AUTOMATIZACIÓN DE MÁQUINA DE TORREFACCIÓN DE CAFÉ PARA EL LABORATORIO DEL PROGRAMA DE INGENIERÍA AGRÍCOLA DE LA UNIVERSIDAD SURCOLOMBIANA

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UNIVERSIDAD SURCOLOMBIANA
FACULTAD DE INGENIERÍA
PROGRAMA DE INGENIERÍA ELECTRÓNICA
NEIVA – HUILA
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Proyecto de grado presentado como requisito para optar al título de Ingeniero Electrónico

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UNIVERSIDAD SURCOLOMBIANA
FACULTAD DE INGENIERÍA
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NEIVA – HUILA
2012

Nota de aceptación:

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Firma del director del proyecto

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Firma del segundo jurado

Neiva, __ de Noviembre de 2012

A Dios por el don de la vida;

A mis padres Gloria y Darío, pues han sido mi mayor inspiración y mi mejor ejemplo de perseverancia y constancia;

A mis hermanas Jessica, Angie y Tatiana, quienes han sido mi apoyo constante;

A mis familiares y amigos, por creer en mí.

ANGÉLICA MARÍA CÁRDENAS CASTAÑO

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GLOSARIO

ADC. La conversión analógica-digital consiste en la transcripción de señales analógicas en señales digitales, con el propósito de facilitar su procesamiento (codificación, compresión, etc.)

AISLAMIENTO. Procedimiento en el que se separa eléctricamente el transductor y el ordenador, para proteger al mismo de transitorios de alta tensión que puedan dañarlo.

AMPLIFICACIÓN. Para conseguir la mayor precisión posible la señal de entrada debe ser amplificada de modo que su máximo nivel coincida con la máxima tensión que el convertidor pueda leer.

EXACTITUD. Capacidad de un instrumento de acercarse al valor de la magnitud real.

FILTRADO. El fin del filtro es eliminar las señales no deseadas de la señal que estamos observando.

IDENTIFICACIÓN. Creación de modelos matemáticos de sistemas dinámicos a partir de valores medidos usando métodos estadísticos

LABVIEW. (Acrónimo de Laboratory Virtual Instrumentation Engineering Workbench) es una plataforma y entorno de desarrollo para diseñar sistemas, con un lenguaje de programación visual gráfico.

LCD (*liquid crystal display*). Una pantalla de cristal es una pantalla delgada y plana formada por un número de píxeles en color o monocromos colocados delante de una fuente de luz o reflectora

PRECISIÓN. Capacidad de un instrumento de dar el mismo resultado en mediciones diferentes realizadas en las mismas condiciones.

TORREFACCIÓN. Es la operación en la cual son tomados, bajo la acción del calor, los principios aromáticos que no existen previamente, en su mayoría, en la semilla del café.

RESUMEN

Este trabajo consistió en el control y la automatización de una máquina de torrefacción de laboratorio del programa de Ingeniería Agrícola de la Universidad Surcolombiana, la cual fue dotada con celdas de carga y los arreglos adecuados al sensor de temperatura con el fin de hacer su control, por tanto se monitorean variables tales como peso y temperatura de manera inalámbrica desde el computador por medio del software Labview e igualmente se tiene la opción de visualizar dicho monitoreo desde el LCD ubicado en la máquina.

Para el desarrollo de este proyecto fue fundamental conocer completamente el proceso de torrefacción, además de las características de todos los sensores y dispositivos usados en esta, con el fin de obtener medidas precisas, además de un control óptimo.

Como resultado de este trabajo, obtuvimos una tostadora controlada por temperatura, con monitoreo del peso, con visualización de estas variables tanto en un LCD como en una aplicación en Labview que me permite, visualizar, controlar y almacenar todos los cambios que sufre el café en relación a su peso y temperatura durante el proceso de torrefacción.

Palabras clave: Control, automatización, torrefacción, LABVIEW.

ABSTRACT

This work dealt with the control and automation of a laboratory coffee roaster of Agricultural Engineering at Surcolombiana University, which was outfitted by load cells and some modifications to sensor temperature with the purpose of making its control, also were monitored every variables wirelessly through LABVIEW software on the computer, furthermore offers the option of visualizing the monitoring on the LCD that is in the machine.

For the development of this project was essential to know fully the roaster process, also the characteristics of each sensor and device which was used in this machine, for the purpose of acquiring accurate measurements and an optimum control.

As result of this work, we obtained a roast which was controlled by temperature, with monitoring of weight, with visualization of these variables on a LCD and an application on LABVIEW which offers the possibility of visualizing, controlling and saving every changes that the coffee is suffering relation to its weight and temperature during the roast process.

Keywords: Control, automation, roaster, LABVIEW.

INTRODUCCIÓN

Colombia hace parte de los principales productores de café verde en el mundo siendo su producción y comercialización una de las principales fuentes de ingresos para el país, es por ello que es de gran importancia la investigación que se realiza actualmente en este campo con el fin de obtener un café de mejores características constituyéndolo así, como un producto de alta calidad.

Es necesario tener en cuenta que la investigación realizada en el sector cafetero es para la obtención de una mejor materia prima y así mismo de un mejor café como producto final luego de múltiples procesos realizados con el fin de explotar al máximo sus características de sabor, aroma, color y textura.

Actualmente el programa de Ingeniería Agrícola de la Universidad Surcolombiana realiza investigaciones en relación al procesamiento del café, siendo de gran importancia para la región, dado que el departamento del Huila en los últimos años ha mostrado gran avance en cuanto a producción de cafés especiales, catalogándose hoy en día como el primer productor de estos en el país, según el Comité Nacional de Cafeteros de Colombia.

Es preciso destacar la importante labor realizada por el Programa de Ingeniería Agrícola, el cual a través de los años ha avanzado en sus investigaciones en el sector cafetero gracias a la adquisición de maquinaria apropiada para los diferentes procesos realizados al grano como son fermentación, secado y torrefacción.

Aunque el Programa ya contaba con una máquina de torrefacción de café diseñada e implementada por un estudiante del programa de Ingeniería Electrónica de la universidad Surcolombiana en el año 2004, la cual contaba con un sistema de control de temperatura On-Off por medio de una termocupla y un sistema de descarga y enfriamiento; lo que se desarrolla en esta tesis es el mejoramiento de dicho sistema de control , además de monitorear el peso y la temperatura del grano de manera inalámbrica y su posterior visualización en el software Labview.

En relación a lo anterior, el desarrollo de este trabajo hace un aporte importante a la investigación de este proceso en el sector cafetero, puesto que permite a los investigadores acceder de una manera más fácil a los datos relacionados con el proceso, con el fin de observar la dinámica de estas y determinar posteriormente algunas características que permitirán aportar en el mejoramiento de la producción del café como materia final.

1. OBJETIVOS

1.1. OBJETIVO GENERAL

- Diseñar e implementar la automatización de una máquina de torrefacción de café del laboratorio del Programa de Ingeniería Agrícola de la Universidad Surcolombiana.

1.2. OBJETIVOS ESPECÍFICOS

- Determinar la variable más adecuada a controlar dentro del proceso.
- Crear una aplicación en el software LABVIEW que permita interactuar de forma inalámbrica entre el usuario y la máquina, permitiendo de esta manera la posibilidad de procesar y almacenar los correspondientes datos.

2. REVISION BIBIBLIOGRÁFICA

2.1. TORREFACCIÓN DEL CAFÉ

Desde la recolección hasta la obtención del café como producto final, observamos diversos procesos los cuales siendo desarrollados de una manera adecuada, conllevan a la obtención de un producto final de excelente calidad. Dentro de estos procesos encontramos la torrefacción que es el proceso en donde se explotarán al máximo las características desabor, aroma, color y textura del café, debido a que este es sometido a altas temperaturas.

2.1.1. Definición.

La torrefacción del café es un proceso en el cual intervienen mecanismos de transferencia de calor y de masa simultáneamente. Depende del tiempo y la temperatura donde se inducen los cambios en el café verde, produciendo los compuestos que originan el aroma característico, sabor, olor y cuerpo del café.[1]

2.1.2. Condiciones de tostión.

Durante el proceso de torrefacción es importante que tanto el café como la maquinaria cumplan con algunas condiciones para lograr obtener un tostado de excelente calidad, por lo tanto encontramos que se deben seguir las siguientes indicaciones:

- Café trillado y limpio de impurezas, libre de granos defectuosos.
- Café seco con humedad entre 10% y 12 %.
- Homogeneidad en el tamaño de los granos.
- En necesario que el recipiente en el que se realiza la tostión esté en constante movimiento para evitar la sobre torrefacción de los granos con el fin de que no hayan pérdidas en sus condiciones óptimas de olor y sabor.
- La tostión se debe hacer bajo calor uniforme y gradual.

[1] FEDERACIÓN NACIONAL DE CAFETEROS DE COLOMBIA. Revista cafetera de Colombia. Torrefacción o tostada del café. Bogotá 1932

- El tiempo y grado de tostión varían según el tipo de café, el tipo de equipo utilizado, la intensidad de calor aplicado y de la forma en la que se transfiere el calor.

- Debido a algunos cambios físicos y químicos que más adelante se explicarán detalladamente, el café sufre un aumento de volumen de hasta 2 veces su volumen inicial, por lo tanto el equipo de tostión debe de quedar lo suficientemente vacío para prever dicho aumento y facilitar el movimiento de los granos.

- Una vez terminada la tostión se debe contar con un sistema de enfriamiento ya sea por medio de una corriente de aire frio a través de una malla o por aspersión de agua conocido como Quenching, para impedir la sobre torrefacción.

- Al finalizar el proceso de torrefacción en muy importante que el café sea almacenado en un lugar con condiciones adecuadas de temperatura y humedad, para que no pierda sus características de aroma y sabor.

2.1.3. Fases de la torrefacción.

Debido a que la principal variable que interviene en este proceso es la temperatura además de tener la mayor influencia sobre las cualidades del café, es esta la que me indica con mayor exactitud las fases de la torrefacción, es así que:

Cuando la temperatura supera los 90º C el café comienza a sufrir cambios de color pasando de verde a amarillo, además de iniciar también el desprendimiento de vapor de agua; al llegar al punto de ebullición del agua, es decir a los 100ºC, el agua que contiene el grado se evapora, por lo tanto hay una pérdida de peso. Cerca de los 120ºC y 130ºC el grano se torna castaño y se empiezan a formar algunos compuestos químicos. A partir de los 150ºC el olor es más característico y se evidencia el aumento de volumen del grano; sobre los 180 ºC los azúcares y almidones empiezan a transformarse, por lo tanto se empiezan a evidenciar mejor sus características de aroma y sabor. A partir de los 200 ºC los gases de combustión se desprenden, los granos se tornan marrón y tienen un aumento de volumen de entre 40% y 60% debido a la crepitación de los granos como reacción espontanea a su exposición a altas temperaturas. La temperatura óptima para la tostión es la comprendida entre los 210ºC y 230ºC, por lo tanto, temperaturas por encima de estas pueden producir sobre torrefacción, haciendo que pierda sus cualidades, debido a que su aroma desaparece, deja de aumentar de volumen y en algunos casos hasta llega a la carbonización. Finalmente para evitar dicha carbonización y detener el proceso de torrefacción es necesario enfriar inmediatamente el café por medio de aire frio o por medio de aspersión de agua.

La *Tabla 1*muestra de manera más clara y resumida el proceso al que es sometido el café:

Tabla 1. Características de tostión de café

Temperatura º C	Color	Volumen	Proceso
100	Amarillo		Desecación y perdida de agua
120-130	Castaño		Reacciones de reducción de azúcares y aminoácidos
130-180	Marrón	Aumenta	Caramelización de azúcares
180-200	Marrón	Aumenta	Producción de CO2 por pirogenación de carbohidratos, proteínas y grasas.
200-230	Marrón	Aumenta	Agrietamiento del grano(crepitación) y afloramiento del aceite en la superficie
250	Negro, sin brillo	Deja de aumentar	Sobre torrefacción, se carboniza y el aroma desaparece.

Fuente: http://www.revistavirtualpro.com/files/TI01_200603.pdf

2.1.4. Cambios característicos del café.

Dentro del proceso de torrefacción y debido a su exposición al calor, el café sufre una serie de cambios físicos y químicos que me pueden ayudar a determinar el mejor punto de torrefacción con el fin de obtener un café con las condiciones deseadas, por tanto dentro de estos cambios tenemos:

- **Pérdida de peso:** esto debido a su exposición al calor sobre los 100ºC que hace que se evapore el agua concentrada en su interior.

- **Aumento de volumen:** debido a la crepitación que produce en el café un efecto de tensión intercelular, es decir los gases debidos a la combustión se expanden.

- **Color:** el color constituye una de las principales formas de determinar el grado de tostión del café, aunque cabe aclarar que esto depende de la intensidad y duración de la exposición del café al calor. Inicialmente alrededor de los 100 grados centígrados, el café inicia su cambios en color tornándose a un poco mas amarillo, posteriormente, con el aumento de temperatura disminuye su peso y aumenta su volumen, así como también su color pasa a ser marrón oscuro. Un indicio de sobretorrefación es un exagerado color marrón u oscuro además de estar acompañado de un olor no característico.

- **Dureza:** debido a los procesos de combustión, el café sufre un cambio en su composición, haciendo que su capacidad de soportar presiones sea menor, debido a que su estructura es más porosa.

- **Contenido de humedad:** es muy importante durante estos procesos conocer la humedad además de controlarla, puesto que si durante su almacenamiento y empacado, su contenido de humedad no es el adecuado, puede conllevar a aparición de hongos lo que significaría pérdida del café, por lo tanto se convierte en un indicador de calidad del café.

- **Cambios químicos:** como resultado de la exposición al calor, el café sufre reacciones químicas que le dan algunas características o atributos a la bebida, es decir son cambios relacionados con compuestos inherentes al olor y al sabor dentro de las que encontramos proteínas, carbohidratos, grasas y aceites, ácidos, taninos, minerales, dióxido de carbono, entre otros.

2.1.5. Máquinas de torrefacción.

Debido a la incorporación de las tecnologías en todos los procesos de producción con el fin de mejorar la calidad además de reducir los tiempos y costos de manufacturación, el proceso de tostado cambió de ser un proceso manual, en el que simplemente el café dentro de un sartén era sometido a fuego y una persona era la encargada de determinar el punto exacto de tostión, a un proceso en el cual es posible, por medio de la medición de la temperatura del grano, determinar con gran exactitud en mejor punto de tostión, además de asegurar que el café no sufra torrefacción debido a que posee sistemas de enfriamiento adecuados.

De acuerdo a lo anterior, en la actualidad encontramos maquinas más robustas, de mayor capacidad y con mejores características de rendimiento; actualmente dichas máquinas son clasificadas comúnmente de acuerdo a su capacidad, por lo tanto, tenemos dos grandes grupos: las de gran capacidad y las de baja capacidad. El primer grupo corresponde a máquinas robustas utilizadas industrialmente por su gran capacidad, utilizan regularmente gas o resistencias calefactoras como medio calefactor, el segundo grupo corresponde a máquinas más pequeñas usadas comúnmente en laboratorio y que usan resistencias calefactoras como medio calefactor.

2.2. MAQUINARIA UTILIZADA

Siendo la torrefacción una de las etapas más importantes dentro del proceso de la obtención del café como producto final, esta se ha convertido en un punto importante de estudio e investigación con el fin de ayudar a mejorar dicho proceso, por lo tanto la adecuación de sensores de temperatura y peso entre otros constituyen un gran avance en el monitoreo y control del proceso de torrefacción.

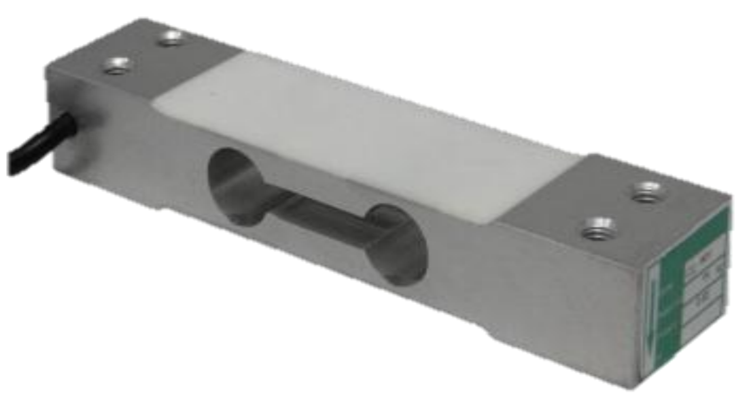
Con el fin de optimizar aun más el proceso de torrefacción y contribuir a la investigación en el país con respecto a este tema, nuestro proyecto tiene como objeto de estudio una máquina de torrefacción diseñada e implementada por el estudiante Yull Heilordt Henao del programa de Ingeniería Electrónica en el año 2004; dicho diseño está basando en la reunión de las características más sobresalientes de algunas máquinas de torrefacción de las empresas más importantes en el país dedicadas a este proceso en aquel año, como resultado de esto, obtuvo una máquina tipo tambor con un sistema de descarga, un sistema de enfriamiento y la integración de una termocupla tipo J para el control On/Off de la temperatura.

Seguidamente veremos las características de los sensores y elementos usados en el desarrollo de este proyecto de grado que serán incorporados a la máquina con el fin de optimizar el proceso de torrefacción.

2.3. CELDAS DE CARGA

Debido a que el peso es un claro indicador en el proceso de tostión, escogimos celdas de carga mono bloque (Ver ANEXO A) con capacidad de 40 kilos como la que se muestra en la *Figura 1*.

Figura 1. Celda de carga mono bloque



Fuente:http://www.bci.co/Pesaje/celdas_de_carga/mono_bloque_max200kg/catalogo_sp06/sp06.pdf

Una celda de carga es un transductor que convierte una fuerza a señales eléctricas, su funcionamiento se basa en la conversión a señales eléctricas de la deformación que sufren 4 galgas extensiométricas debido a la fuerza que se quiere medir. Por tanto su principio de funcionamiento se centra en estas últimas.

2.3.1. Galgas extensiométricas

Estos dispositivos son transductores que al aplicárseles fuerza, responde modificando su resistencia eléctrica. Su principio de funcionamiento se basa en el efecto piezorresistivo de metales y semiconductores, según el cual, su resistividad varía en función de la deformación a la que están sometidos, el material de que esta hecho y el diseño adoptado.

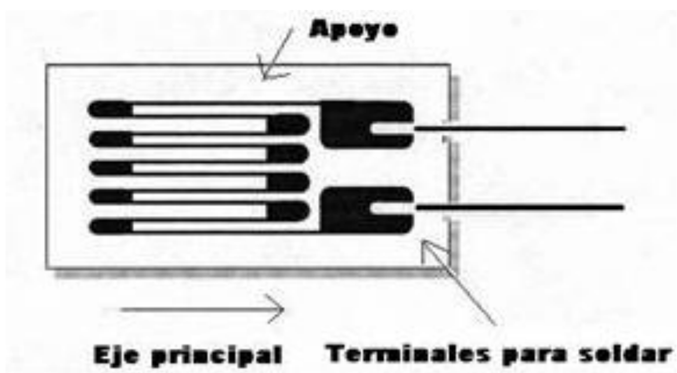
Si se considera un hilo metálico de longitud l, sección transversal A y resistividad ρ, su resistencia eléctrica R es:

$$R = \rho \frac{l}{A}$$

Si se le somete a un esfuerzo en dirección longitudinal, cada una de las tres magnitudes que intervienen en el valor de Rcambia.[2]

El esquema general de una galga extensiométrica se observa en la Figura 2.

Figura 2. Galga extensiométrica

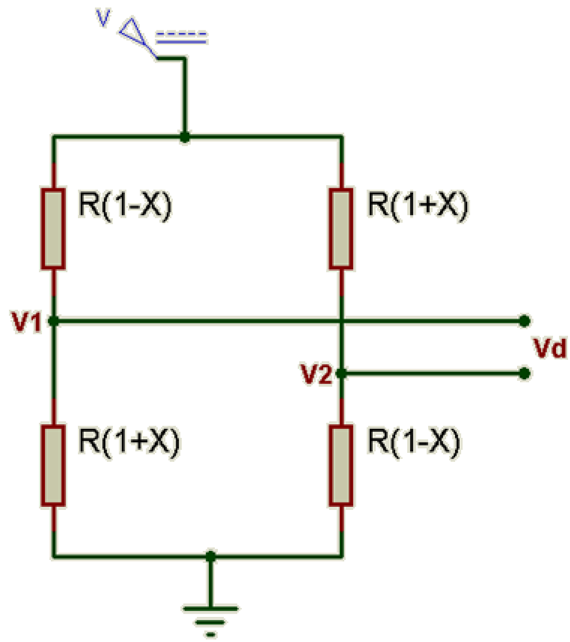


Fuente: http://www.unet.edu.ve/~ielectro/GALGAS1_archivos/image004.jpg

[2] FERRERO, José María. Instrumentación Electrónica, Sensores. Universidad Politécnica de Valencia, España, 1994.

Uno de los métodos más utilizados comúnmente en la medición de la deformación de galgas extensiométricas es el de configuración en puente de Wheatstone con una fuente de excitación de voltaje, bien sea con una o varias galgas brindando mayor o menor sensibilidad según sea el caso. Debido a que una celda de carga es una configuración de 4 galgas extensiométricas, esta configuración se puede apreciar en la *Figura 33* y se utiliza debido a que dichas deformaciones que se ven reflejadas en la resistencia son muy pequeñas, debido a que se cuadruplica la sensibilidad.

Figura 3. Puente de Wheatstone



Si la resistencia nominal de la galga de tensión se señala como R, entonces hay un cambio de tensión inducido en la resistencia señalada como X que puede tener signo positivo cuando la galga se encuentra en tensión y negativo cuando esta se encuentra en compresión, de esta forma el puente se encuentra balanceado.

2.4. TERMOCUPLA

La termocupla es el sensor de temperatura más común utilizado industrialmente. Una termocupla consta de dos alambres de distinto material unidos en un extremo (soldados generalmente). Al aplicar temperatura en la unión de los metales se genera un voltaje muy pequeño (efecto Seebeck) del orden de mili voltios el cual aumenta con la temperatura. Normalmente las termocuplas industriales se consiguen encapsuladas dentro de un tubo de acero inoxidable u otro material (vaina), en un extremo está la unión caliente y en el otro el terminal eléctrico de la unión fría, protegido dentro de una caja redonda de aluminio (cabezal).[3]

Existen gran variedad de tipos de termocuplas, en la *Tabla 2* aparecen algunas de las más comunes, pero casi el 90% de las termocuplas utilizadas son del tipo J ó del tipo K.
Debido a que esta tostadora es de uso en investigación en el laboratorio del programa de Ingeniería Agrícola de la Universidad Surcolombiana, el grano de café será sometido a calor comprendido entre 0 y 500 grados centígrados para determinar cómo es la relación de olor, color y textura a dichas temperaturas y contribuir como ya se mencionó, a la investigación en el sector de la tostación de café, es por ello que la termocupla que hace parte de la tostadora es tipo J la cual tiene un límite máximo de trabajo de 760ºC aunque debido a su naturaleza no lineal es indispensable realizar la correspondiente compensación y linealización.

Tabla 2. Termocuplas

Tipo	Cable + Aleación	Cable + Aleación	ºC	Volts Max
J	Hierro	Cobre – Níquel	(-180, 750)	42.2
K	Níquel - Cromo	Níquel – Aluminio	(-180, 1372)	54.8
T	Cobre	Cobre – Níquel	(-250, 400)	20.8
R	87% Platino 13% Rodio	100% Platino	(0, 1767)	21.09
S	90% Platino 10% Rodio	100% Platino	(0, 1767)	18.68
B	70% Platino 30% Rodio	94% Platino 6% Rodio	(0, 1820)	13.814

Fuente: http://www.arian.cl/downloads/nt-002.pdf

La compensación de cero es necesario debido al error de voltaje proporcional a la temperatura ambiente que se produce en el momento de unir los conectores de la termocupla junto con un conductor de cobre común; para solucionar este problema inicialmente se recurría a poner la unión de los cables a una temperatura de 0ºC, lo cual no era la solución más eficaz, por lo tanto se optó por medir la temperatura

[3] ARIAN, Control and Instrumentación. [En Línea]. [Citado el 28 de Junio de 2012]. <Disponible en http://www.arian.cl/downloads/nt-002.pdf>

ambiente por medio de un sensor de temperatura LM35, y restarlo a la suministrada por la termocupla después de la linealización.

La linealización de la termocupla se realiza debido a que la relación entre el voltaje generado por la termocupla y la temperatura medida no es lineal; por tanto se pueden encontrar dos medios para dar solución a esto, conociendo el voltaje entregado por la termocupla y el tipo de termocupla, se observan las tablas correspondientes y se encuentra el valor de temperatura aproximado para estos valores de voltaje o se aplican estos a una expresión matemática en donde sus coeficientes varían para cada tipo de termocupla, en este caso usamos los polinomios del National Institute of Standards and Technology (NIST), como se observa en la *Tabla 3*.

$$T = a_0 + a_1 v + a_2 v^2 + a_3 v^3 + \cdots + a_n v^n$$

Donde:

T= temperatura de la termocupla
a_n = coeficientes de los polinomios NIST.
v = voltaje entregado por la termocupla.

Tabla 3. Coeficientes polinomio NIST

TERMOCUPLA TIPO J	
RANGO	0º A 500ºC
a_0	0
a_1	1,978425E-02
a_2	-2,001204E-07
a_3	1,036969E-11
a_4	-2,549687E-16
a_5	3,585153E-21
a_6	-5,344285E-26
a_7	5,099890E-31
error	±0,05ºC

2.5. AMPLIFICADORES DE INSTRUMENTACIÓN

Debido a que la señal que envían las celdas de carga es del orden de los mili voltios, se debe hacer la adecuación de dicha señal para que esté dentro del rango de los 0 a 5 voltios; dicha adecuación se hace con la ayuda del amplificador de instrumentación AD602 el cual por medio de una resistencia proporciona la amplificación necesaria.

En nuestro sistema de pesaje contamos con 4 celdas de carga de características especificadas en el ANEXO B*;* la señal eléctrica que proporciona cada una de estas es debidamente amplificada, es decir dicha adecuación se realiza de igual forma para las cuatro celdas de carga con el fin de hacer que el sistema sea balanceado.

2.5.1. Amplificador de instrumentación AD602

Características[4]:

Fácil uso:

- Requiere solo una resistencia externa para ajustar la ganancia de 1 a 1000.
- Amplio rango de alimentación (+- 2.3 V a +- 18 V).
- Mayor rendimiento que tres Amplificadores operacionales.
- Bajo consumo, 1.3 mA corriente de alimentación máxima.

Excelente rendimiento en DC:

- Voltaje offset de salida máximo de 50uV
- Relación de cambio de la intensidad de polarización de entrada en función de la temperatura: máx. 0.6 uV/ºC

Bajo ruido

Excelentes especificaciones AC:

- Ancho de banda de 120 KHz para una ganancia de 100.

Aplicaciones:

- Balanzas.
- ECG e instrumentación medica.
- Sistemas de adquisición de datos.

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[4]ANALOG DEVICES, Semiconductors and Signal Processing. [En Línea]. [Citado el 28 de Junio de 2012.]. <Disponible en http://users.ece.utexas.edu/~valvano/Datasheets/AD620.pdf>

La ganancia del amplificador está dada por la siguiente ecuación:

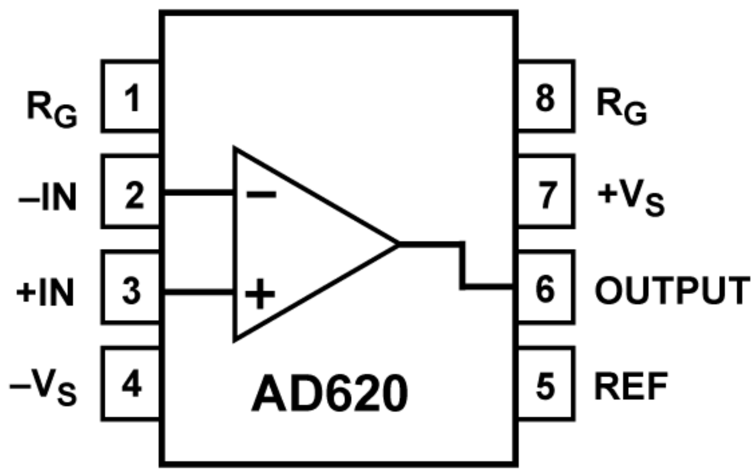
$$G = \frac{49.4\ \mathrm{K\Omega}}{R_G} + 1$$

Por lo tanto la resistencia necesaria para ajustar a la ganancia deseada está dado por la siguiente ecuación:

$$R_G = \frac{49.4\ \mathrm{K\Omega}}{G - 1}$$

La *Figura 4* muestra el diagrama de conexión del amplificador de instrumentación AD620.

Figura 4. Diagrama de conexión AD620



Fuente:http://t0.gstatic.com/images?q=tbn:ANd9GcRA5EbGI1mTR9NLvDcWydIRsuBkhpJ4y-httAEbt2Yg4OiPtWWdrg

2.5.2. Circuito de amplificación para celdas de carga.

Debido a que en nuestro sistema de pesaje usamos cuatro celdas de carga y por tanto el máximo de la suma de las señales es de 5 voltios, cada una debe proporcionar una cuarta parte del total de la señal, es decir 1.25 voltios, la sensibilidad de las celdas de cargas es de 2mV/V, por tanto, al ser alimentadas con 12 voltios, la máxima salida que tendremos es de 24mV. Es decir que para obtener un máximo de 1.25 voltios a 24 mV, la ganancia debe de ser de 52.0833.

Así que la resistencia que debemos usar para obtener una medida exacta debe ser:

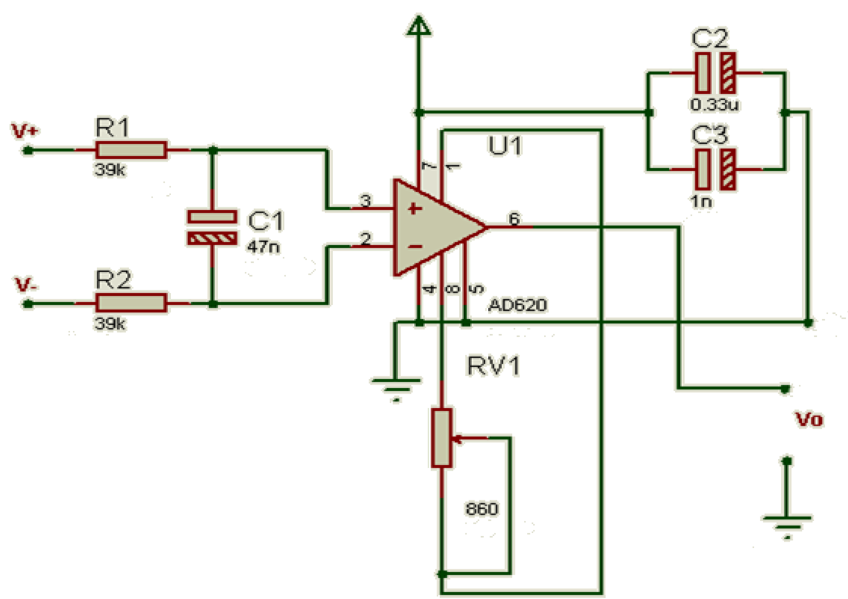
$$R_G = \frac{49.4\ \text{K}\Omega}{G - 1}$$

$$R_G = \frac{49.4\ \text{K}\Omega}{52.0833 - 1}$$

$$R_G = 967{,}05\ \Omega$$

Finalmente obtenemos que el valor de la resistencia que se debe usar en el ADC620 es de $967{,}05\ \Omega$ y como observamos en la *Figura 5* logramos ajustar este valor mediante un potenciómetro de precisión, además de incluir un arreglo de capacitores con el fin de evitar posibles ruidos provenientes de fuentes de alimentación y de la señal de la red de 120 voltios a 60 Hz.

Figura 5. Circuito para amplificación de celdas de carga



2.5.3. Circuito sumador para celdas de carga.

Para obtener la medida total del sistema de pesaje compuesto por las 4 celdas de carga, debemos usar un circuito sumador, que reúna las señales de salida de los amplificadores de instrumentación. Para dicho sumador se utilizó un amplificador operacional AO TLC084 que trae integrados 4 amplificadores operacionales de los cuales sólo se usó uno para la implementación del circuito sumador, los 3 restantes se usarán en otras aplicaciones más adelante.

La salida del sumador no inversor de la *Figura 6* está dado por la siguiente ecuación:

$$V_{sal} = \left(1 + \frac{R25}{R24}\right) * (R20//R21//R22//R23) * (\frac{V_{O1}}{R20} + \frac{V_{O2}}{R21} + \frac{V_{O3}}{R22} + \frac{V_{O4}}{R23})$$

Debido a que las señales provenientes de las celdas de carga no deben ser alteradas, el sumador debe ser de ganancia unitaria, por tanto, haciendo iguales las resistencias de entrada$R20 = R21 = R22 = R23$ tenemos:

$$V_{sal} = \left(1 + \frac{R25}{R24}\right) * (\frac{V_{O1}}{4} + \frac{V_{O2}}{4} + \frac{V_{O3}}{4} + \frac{V_{O4}}{4})$$

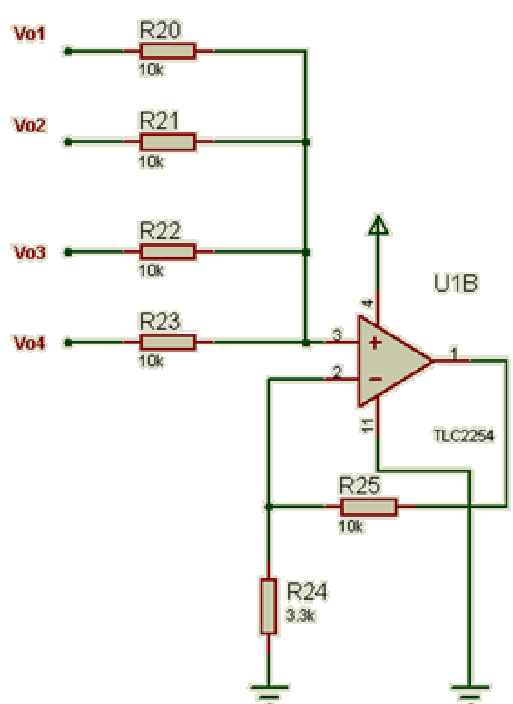
El operador $(1 + \frac{R25}{R24})$debe ser igual a 4 para lograr la ganancia unitaria, es decir

$$\frac{R25}{R24} = 3$$

Si hacemos $R20 = R21 = R22 = R23 = R25 = 10k\Omega$ obtenemos:

$$R24 = \frac{R25}{3} = 3.33\ k\Omega$$

Figura 6. Circuito sumador



2.6. FILTROS ACTIVOS

Debido a que es muy probable que haya ruido en la adquisición de los datos de peso insertado por las celdas de carga, además de eso amplificado y sumado debido a las etapas implementadas para la adecuación de las celdas de carga, es necesario y recomendable implementar un filtro activo que filtre dicha señal y que proporcione como salida, sólo la componente DC de dicha señal.

2.6.1. Diseño de un filtro pasa bajo

Se diseño para este caso un filtro pasa bajo con frecuencia de corte de 1 Hz; para el diseño de este filtro se utilizó el software Filter Wiz Pro en el cual introducimos datos tales como frecuencia de corte y orden del filtro; este programa es de gran ayuda debido a que proporciona las gráficas de respuesta del filtro además de brindar los valores comerciales de los elementos a utilizar y finalmente el diagrama circuital a implementar.

La Figura 7 muestra el panel de especificaciones del filtro a diseñaren el software Filter Wiz Pro, en la Figura 8 se observa una aproximación de la respuesta del filtro diseñado, en la Figura 9 se observa la primera etapa del circuito a implementar y finalmente en la Figura 10 se observa la etapa final del circuito.

Figura 7. Panel de especificaciones

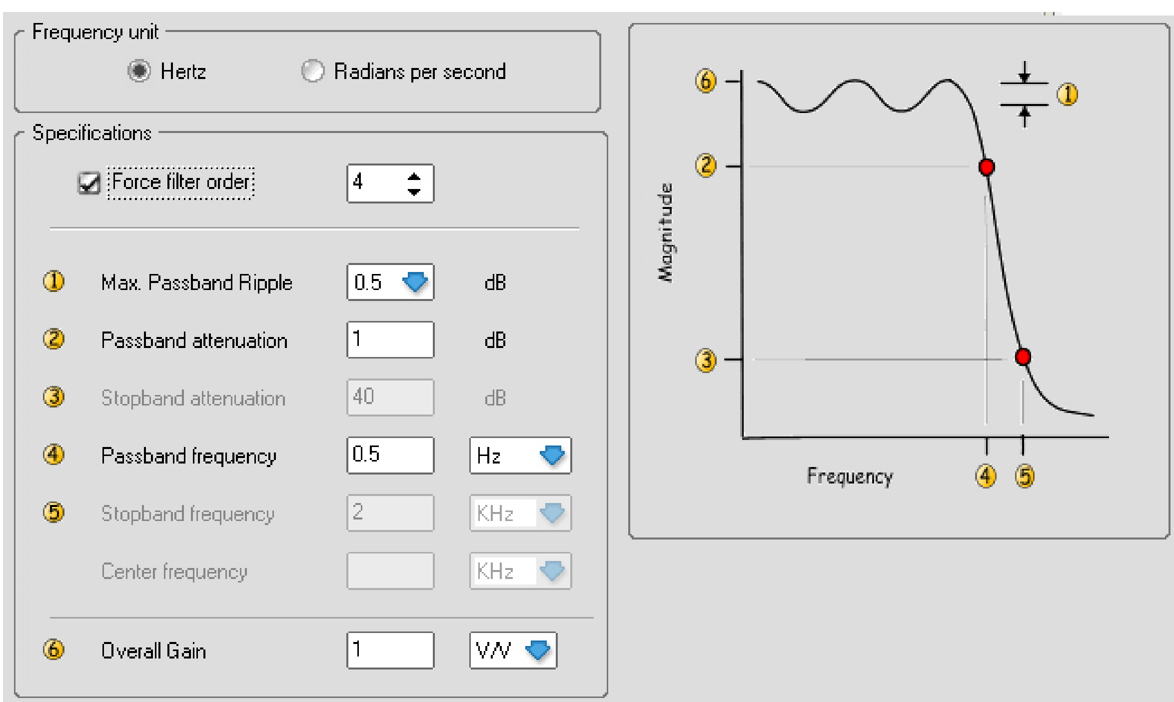


Figura 8. Aproximación de la respuesta en magnitud del filtro

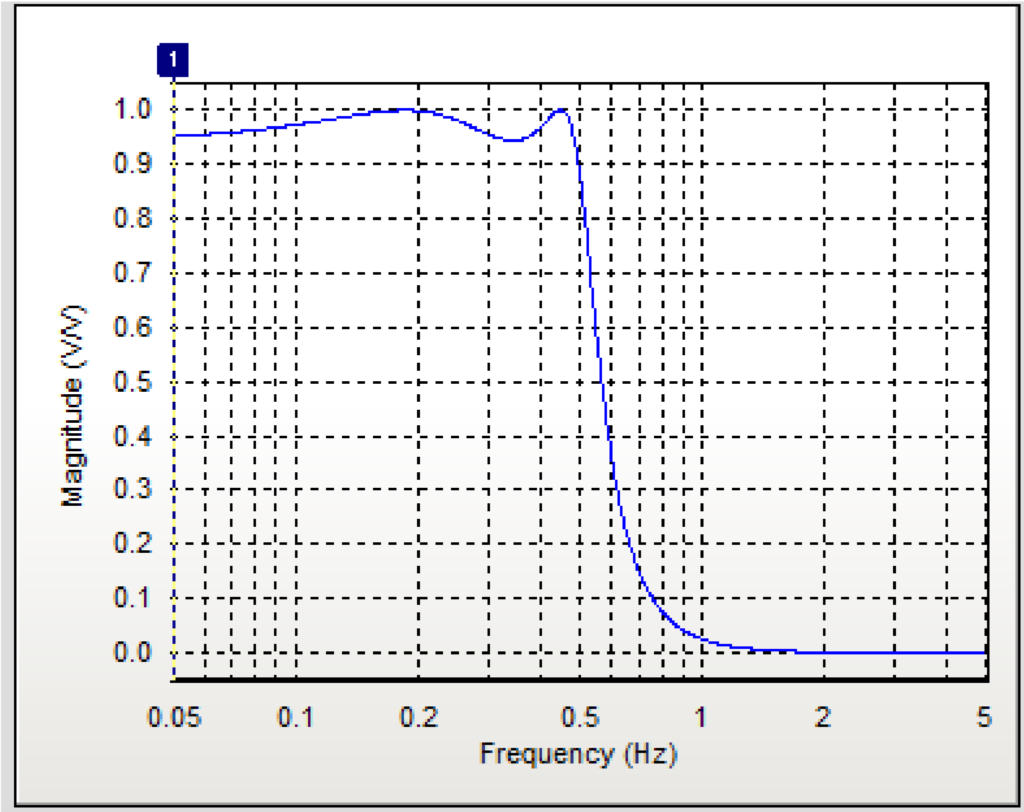
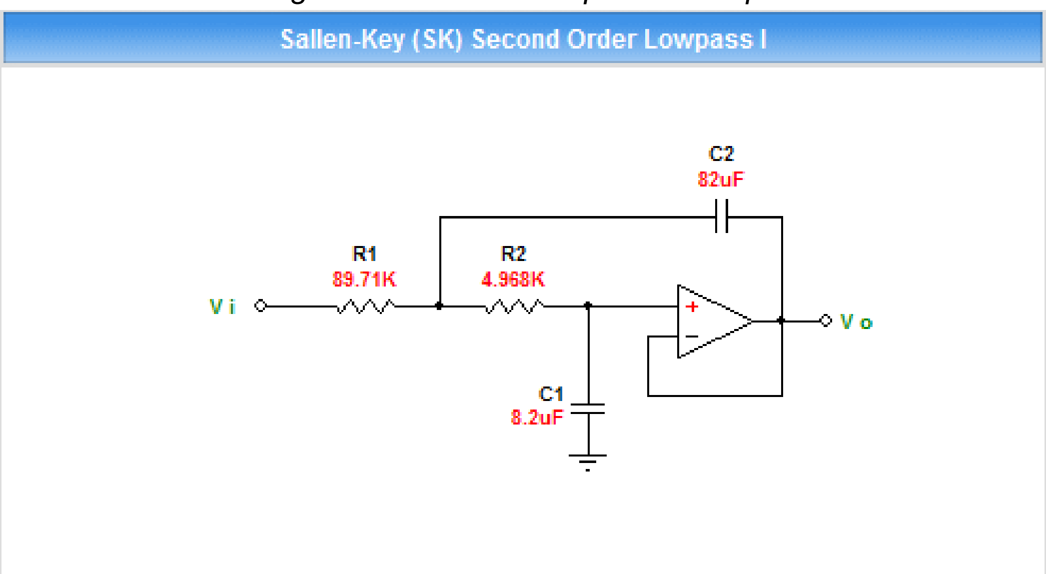
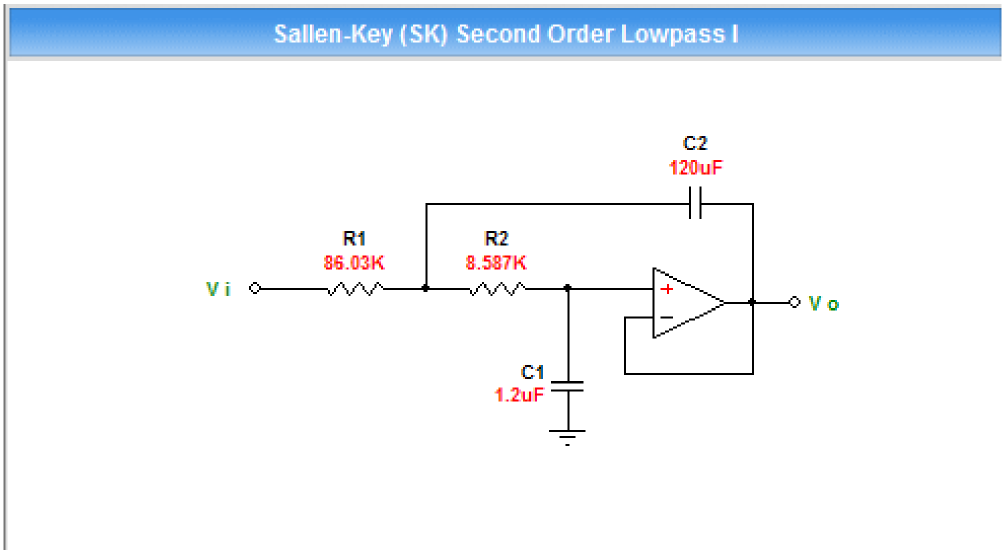


Figura 9. Circuito final primera etapa



Stage gain (V/V):	1.000	[1.000]	wp	0.291Hz
Overall filter gain (V/V):	1.000	[1.000]	Q	0.71
Opamp GBW (MHz):	1	[~1]	wz	---

Figura 10. Circuito final segunda etapa



Stage gain (V/V):	0.944	[0.944]	wp	0.502Hz
Overall filter gain (V/V):	1.000	[1.000]	Q	2.94
Opamp GBW (MHz):	1	[~1]	wz	---

2.7. MÓDULOS INALÁMBRICOS

Como innovación en el desarrollo de este proyecto se incorporó la comunicación inalámbrica de bajo consumo, para lograr este objetivo se usó tecnología ZigBee, que es un protocolo de comunicación inalámbrica basado en el estándar 802.15.4 que es ideal para aplicaciones de baja velocidad entre dos o más dispositivos, bajo coste en implementación, bajo consumo energético, fiabilidad y para redes inalámbricas basadas en un estándar global abierto, lo que significa que cualquier dispositivo de un fabricante que soporte este estándar de comunicaciones y pase la certificación correspondiente, podrá comunicarse con otro dispositivo de otro fabricante distinto.

ZigBee permite comunicaciones robustas y opera en la frecuencia **ISM**(Industrial, Scientific and Medical) en Europa, lo que significa que dichas bandas están reservadas para uso no comercial, su uso está abierto a todo el mundo (siempre que no se pasen los límites de potencia) y son gratuitas en cuanto a la necesidad de usar protocolos normalizados; a 915 MHz en los Estados Unidos y 2,4 GHz en otras partes del mundo, además de no necesitar licencia para operar, las redes

ZigBee ofrecen una excelente inmunidad contra las interferencias, y la capacidad para albergar miles de dispositivos en una red (más de 65.000), con tasas de transferencia de datos que van desde 20kbps a 250Kbps.[5]

Es de esta forma como dentro de esta tecnología se buscó un dispositivo que además de brindar las características anteriormente mencionadas fuera económico, por lo tanto se optó por módulos XBee PRO, como se observa en la *Figura 11* los cuales son módulos inalámbricos fabricados para ser compatibles con dispositivos ZigBee, en el ANEXO C se encuentran las especificaciones técnicas de estos dispositivos.

Figura 11. Módulo XBee PRO

Fuente:http://t0.gstatic.com/images?q=tbn:ANd9GcSBD7tqrMhmAxD_IBAgjp4zTNbfvpt81zywN_vWBCn0G2Y1_WzrCKEFWUVyng

2.7.1. Características de los módulos Xbee PRO

Dichos módulos presentan las siguientes características:

- Alcance: 100 m;
- Sensibilidad del receptor: 100 dBm (1%)
- Frecuencia de operación: ISM de 2,4 GHz;
- Alimentación: 2,8 a 3,4 V;
- Temperatura de funcionamiento: -40 a 85 º C (industrial)
- Rango de frecuencia: 2.4000 - 2.4835 GHz;

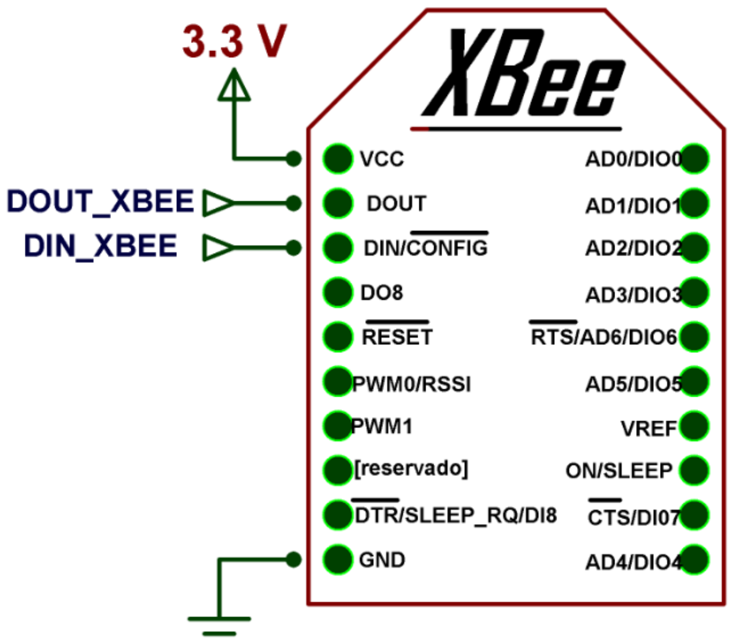
[5]ZigBee Alliance, Wireless Control [En Línea]. [Citado el 1 de Julio de 2012.].<Disponible en https://docs.zigbee.org/zigbee-docs/dcn/08-0034.pdf>

- Bajo consumo <50mA cuando está en funcionamiento y <10uA cuando están en modo sleep.
- Interfaz serial.

2.7.2. Configuración física de los módulos Xbee PRO

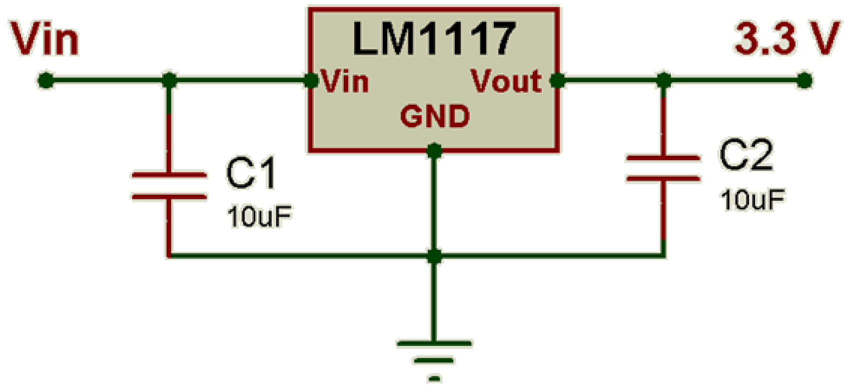
En cuanto a la configuración física del dispositivo Xbee PRO es necesario realizar las siguientes conexiones básicas de funcionamiento, como se observa en la *Figura 12*.

Figura 12. Configuración básica de módulos Xbee



Para obtener los 3.3 voltios necesarios para alimentar el módulo transmisor inalámbrico Xbee PRO usamos un regulador a 3.3 voltios de referencia LM1117 como se observa en la Figura 13.

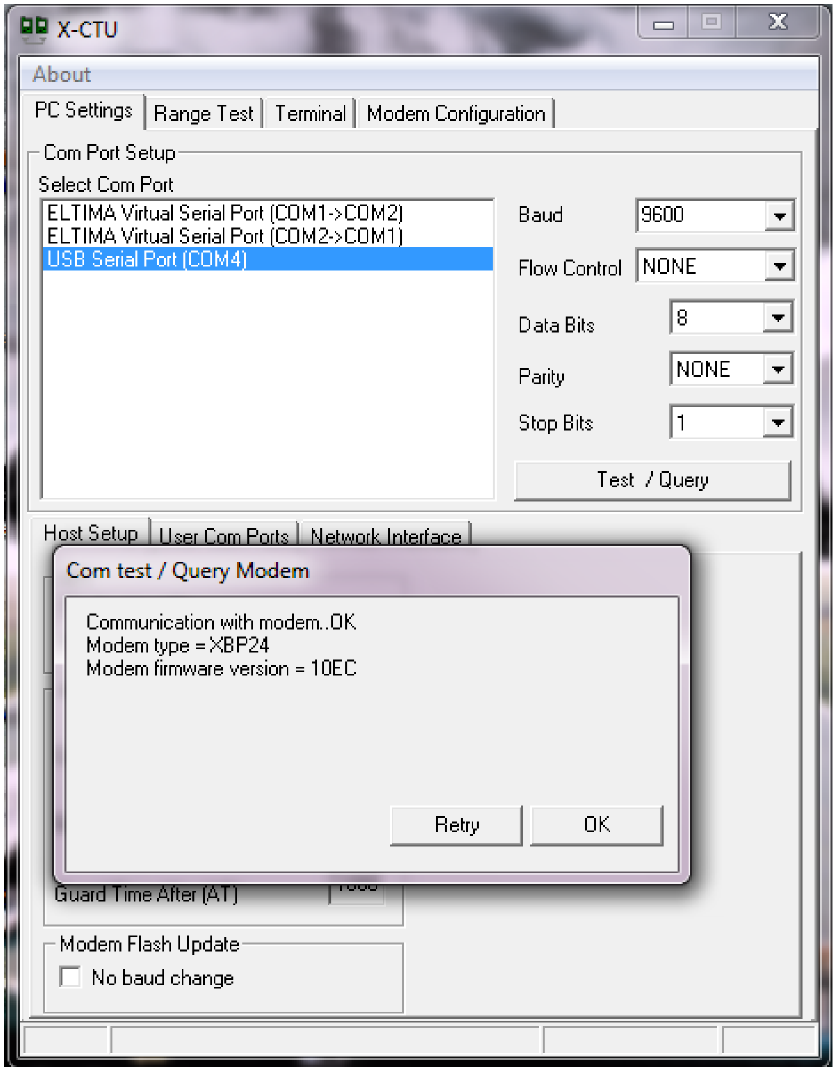
Figura 13. Regulador a 3.3 voltios



2.7.3. Configuración por software de los módulos XBee PRO

Los dispositivos XBee son de fácil configuración, puesto que sólo es necesario un cable mini-usb para realizar la comunicación entre los módulos y el computador, además de realizar el envío de datos de manera serial y configurar los módulos por medio del software X-CTU de DIGI de modo coordinador y modo receptor, como se observa en la Figura 14.

Figura 14.Configuración módulo Xbee PRO por medio de X-CTU



En la Figura 15 se observa la adquisición de datos inalámbricamente por medio del software mencionado.

Figura 15. Adquisición de datos inalámbricamente por X-CTU

2.8. ESTADO INICIAL DE LA TOSTADORA

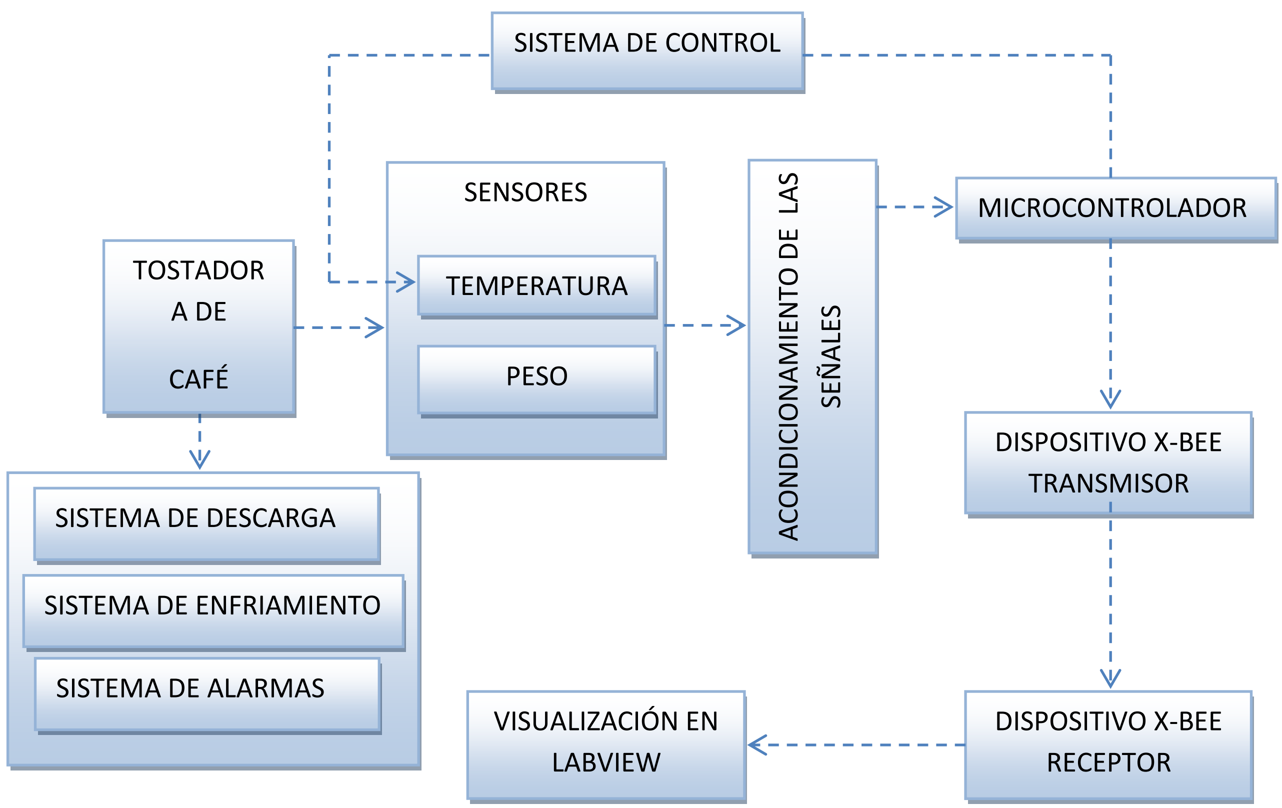
Esta tostadora fue diseñada e implementada por el estudiante Yull Heilordt Henao Roa del programa de Ingeniería Electrónica de la Universidad Surcolombiana como trabajo de grado en el año 2004. Dicha tostadora está basada en las características más relevantes de las tostadoras que se encontraban en el mercado de esos años, posee una resistencia calefactora como medio calefactor; las ordenes son dadas por medio de pulsadores ubicados en la máquina, que brinda las opciones de ajustar la temperatura deseada y el tiempo de tostión; la temperatura es censada por una termocupla y el control es tipo On/Off, es decir, cuando la temperatura alcanza la temperatura introducida por teclado, se envía la señal de apagar la resistencia calefactora, luego, si la temperatura excede el rango asignado, la resistencia calefactora de nuevo se enciende y así es el ciclo sucesivo. Además de esto posee un sistema de descarga que se activa cuando se ha llegado al tiempo de tostión introducido por medio del teclado y un sistema de enfriamiento que se enciende cuando el café es sacado del tambor. En la Figura 16 se observa el estado inicial de la máquina.

Figura 16. Tostadora del laboratorio

3. DISEÑO E IMPLEMENTACION

La Figura 17 ilustra el diagrama general en bloques del proyecto, es de esta manera como se llevó a cabo el desarrollo de este trabajo:

Figura 17. Diagrama general en bloques del proyecto



3.1. DISEÑO DEL HARDWARE

En el desarrollo de este proyecto se adecuaron una termocupla y 4 celdas de carga, para estas últimas fue necesario implementar una base metálica que sirve de soporte tanto a la tostadora como al sistema de pesaje. La sección de adquisición de datos fue ubicada en una caja de acrílico como panel frontal en la tostadora, con el fin de servir de interfaz con los usuarios, dicha caja contiene el PIC 18F4550, el LCD Back light azul de 16X2 caracteres, el teclado matricial de 4X3, el modulo inalámbrico transmisor Xbee PRO, entre otros componentes como amplificadores operacionales usados en la adecuación de la señal de la termocupla, integrados 555 para el manejo de las señales de alarmas y los opto acopladores usados para aislar el circuito de control con el circuito de la carga. Adicionalmente, fue necesaria la implementación de una nueva caja que me permite ubicar de forma segura el modulo inalámbrico receptor de datos.

3.1.1. Adquisición de datos.

Los datos de temperatura para el control de temperatura de la resistencia calefactora, los datos del peso y las señales provenientes de los sensores ópticos de inicio y fin de carrera para el sistema de descarga son adquiridos por medio del PIC 18F4550.

Aunque la tostadora de café inicialmente traía adecuada la señal de la termocupla, decidimos implementar una nueva, debido a que la existente poseía algunos problemas en las lecturas debido al deterioro de los elementos, de tal forma que lográramos medidas más precisas y exactas. La señal que entrega la termocupla es de 51µV/ºC y la temperatura máxima de trabajo de la resistencia calefactora es de 480ºC, por lo tanto para obtener una señal máxima de 5 voltios a esta temperatura se amplificó la señal 204 veces. Para lograr dicha amplificación se utilizó un amplificador operacional LM358 que trae encapsulados dos amplificados que fueron usados en configuración no inversora y en cascada, como se observa en la Figura 18.

Debido a que es necesario realizar la compensación de la temperatura ambiente, se usó un sensor LM35 que entrega una señal lineal de 10mV/ºC, si bien, el café será sometido a temperaturas comprendidas entre 0 y 500ºC, dicha señal no necesita amplificación debido a que para la temperatura máxima, 500ºC, la señal será de 5 voltios, la cual es adecuada para ser leída por el PIC, adicionalmente se agregó un arreglo RC a la salida del sensor que previene interferencias en el normal funcionamiento del dispositivo, como se observa en la Figura 19.

Además de la señal proveniente de la termocupla y del LM35, el PIC recibe la señal del sistema de pesaje que está compuesto por un arreglo de 4 celdas de carga cada una acondicionada debidamente, mediante la amplificación y la posterior suma de las señales que entrega cada una, además de la adición de un filtro pasa bajo que elimina posibles ruidos, todo esto como se observa en la sección 2.5. En la Figura 20 se observa el diagrama esquemático completo del sistema de pesaje y en la Figura 21 la placa o impreso a implementar.

Figura 18. Amplificación de la señal de la termocupla.

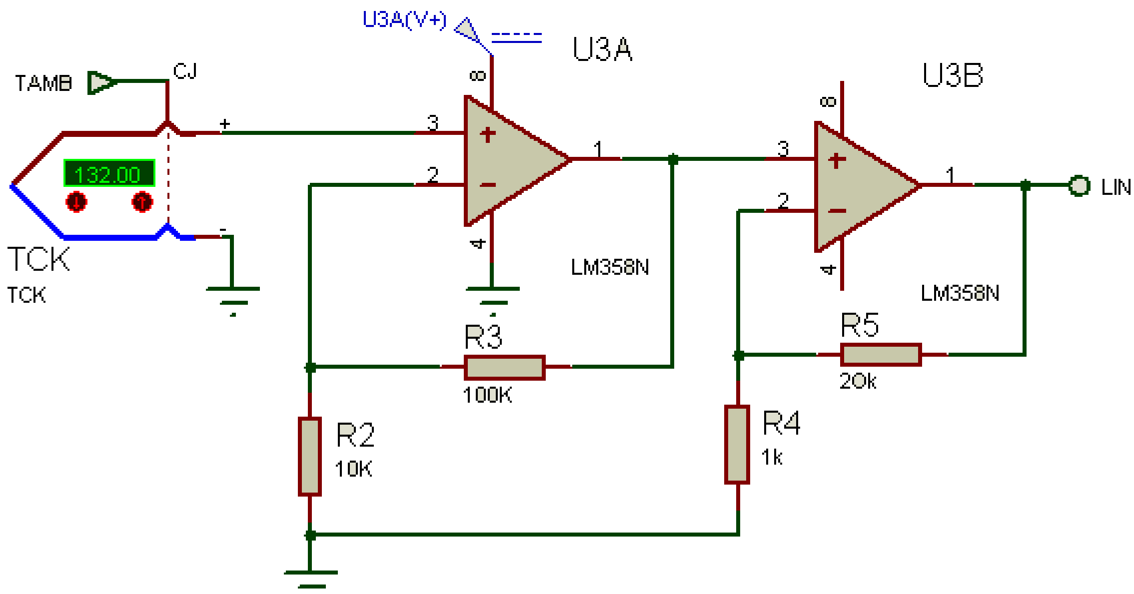


Figura 19.Configuración LM35

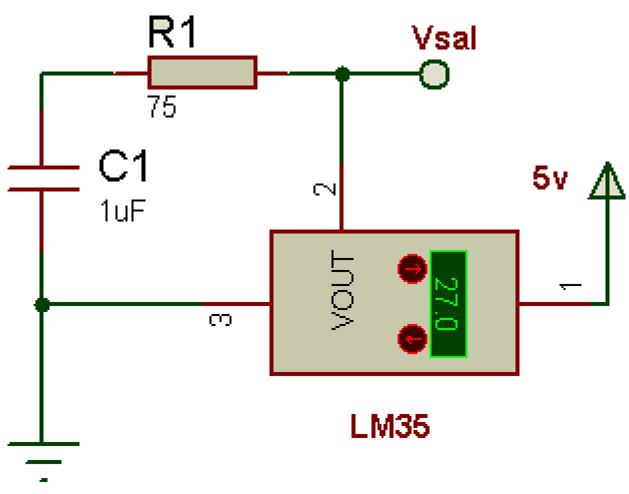


Figura 20. Circuito completo sistema de pesaje

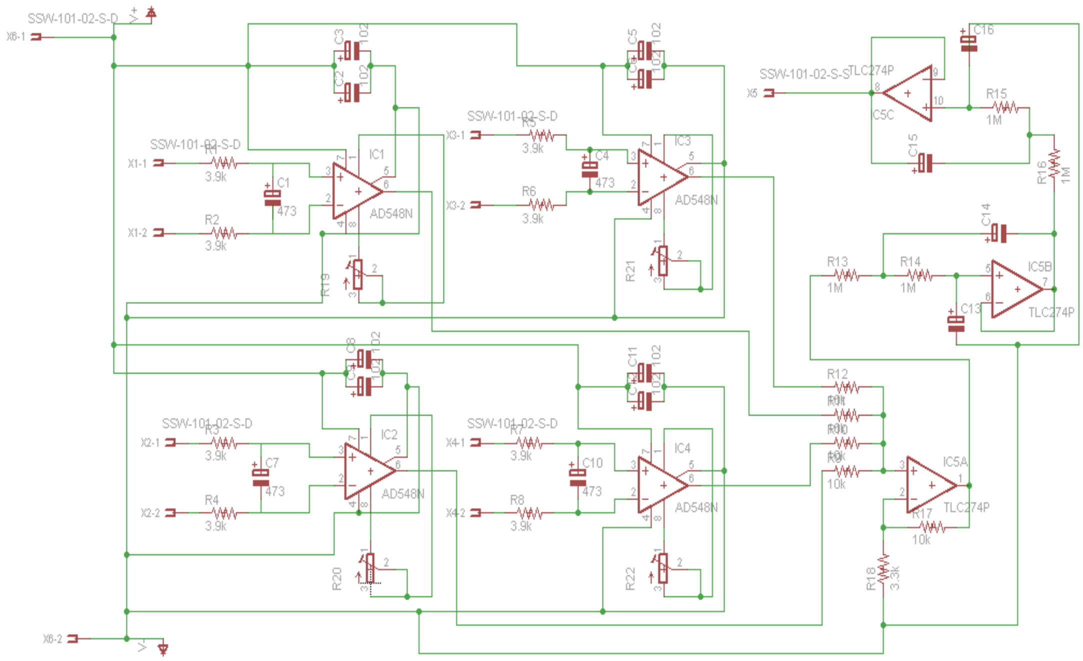
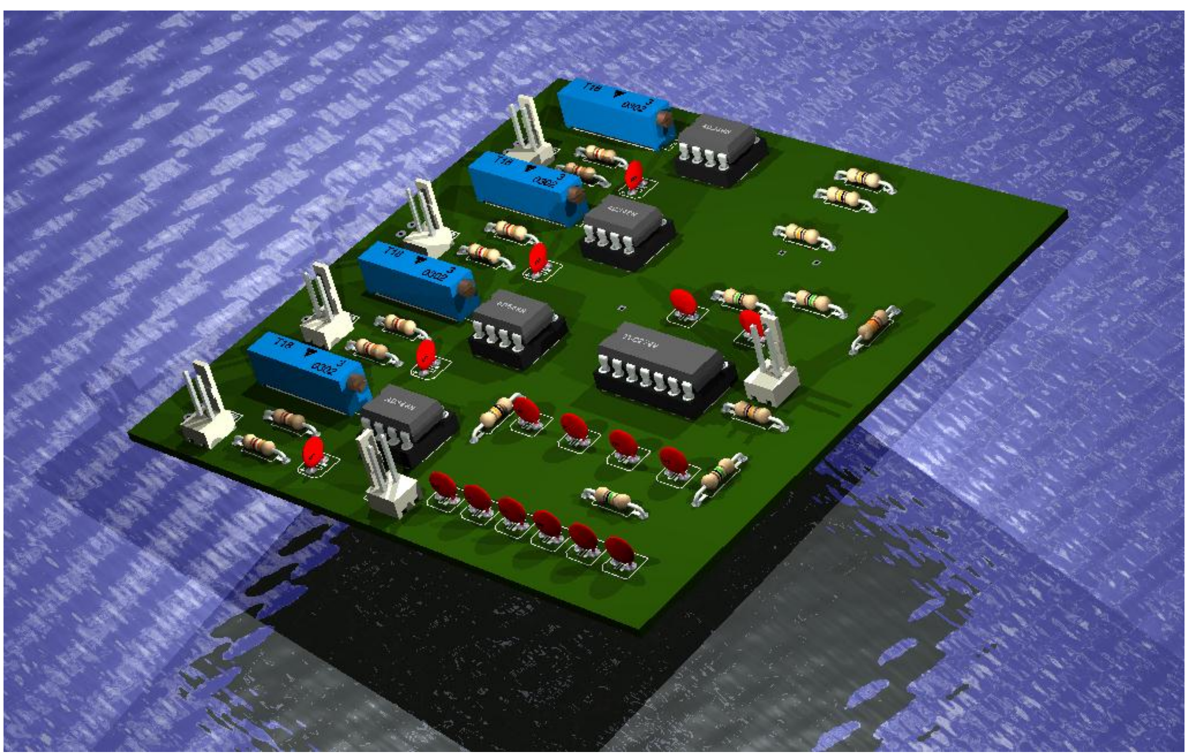


Figura 21. Sistema de pesaje



3.1.2. Alarmas

En esta sección, se le informa al usuario por medio de alarmas sonoras que el proceso de tostión ha terminado, además de informar lumínicamente el giro del cilindro, el proceso de tostión, la puesta en marcha del extractor, la comunicación inalámbrica y el proceso de precalentamiento como se observa en la *Figura 22* que corresponde a una sección del panel frontal de la máquina de torrefacción.

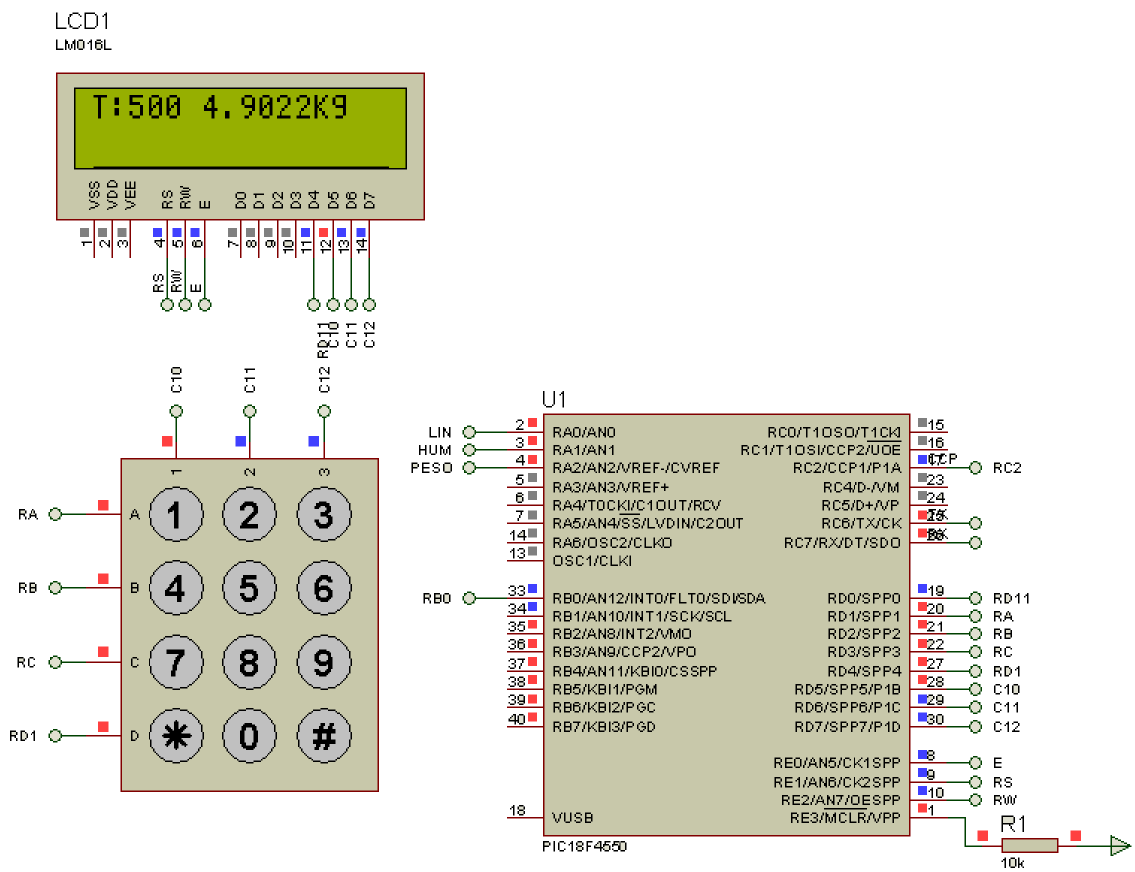
Figura 22. Alarmas en panel frontal

3.1.3. Teclado y LCD

Estos dos dispositivos se encuentran ubicados en el panel frontal de la tostadora al igual que las alarmas luminosas; el teclado matricial de membrana de 3X4 permite al usuario interactuar con la máquina de modo que se puedan configurar tanto la temperatura como el tiempo de tostión y el LCD permite visualizar el menú del proceso además de los datos de temperatura y peso que se monitorean durante el proceso.

La programación de estos dos dispositivos se realizó en el mismo puerto con el fin de ahorrar espacio como se ilustra en la Figura 23.

Figura 23. Conexión Teclado y LCD



3.1.4. Sistema de descarga

El sistema de descarga ya estaba implementado, este se compone de un motor que hace girar un tornillo en un sentido y este mueve la tuerca, la cual a su vez mueve el cilindro subiéndolo o bajándolo según sea el sentido de giro de motor, además de poseer dos sensores ópticos de barrera de inicio y fin de carrera; lo que se hizo fue que por medio del micro controlador se leyeran las señales provenientes de estos sensores y enviaran las respectivas señales de control de descarga, por tanto cuando el proceso de tostión ha terminado, el PIC envía la señal al motor para que el cilindro empiece a subir y el café caiga en la bandeja y el sistema de enfriamiento empiece a funcionar.

Por tanto tenemos que el sistema verifica la posición del cilindro y actúa según sea su ubicación, es decir que si el cilindro está en la parte alta lo regresa a su posición inicial y si se encuentra en un punto intermedio termina de subir el cilindro, esto para garantizar que si ocurrió un corte de energía durante una tostión previa y el cilindro quedo en la mitad del recorrido, la tostadora termina la descarga anterior y regresa el cilindro a la posición inicial.

3.1.5. Sistema de enfriamiento

La tostadora de café está dotada con un sistema de enfriamiento el cual consta de un conducto con dos recamaras (tolvas) que se conectan a un extractor. La primera recamara es donde se enfría el grano y la segunda está ubicada debajo de la resistencia y el cilindro donde se realiza la tostión. Se acondicionó un pequeño motor DC, el cual viene adecuado para sacar un pequeño pistón de unos 4 cm aproximadamente cuando se polariza en directo (+ 12 V DC) y regresa a su posición original con una polarización inversa.

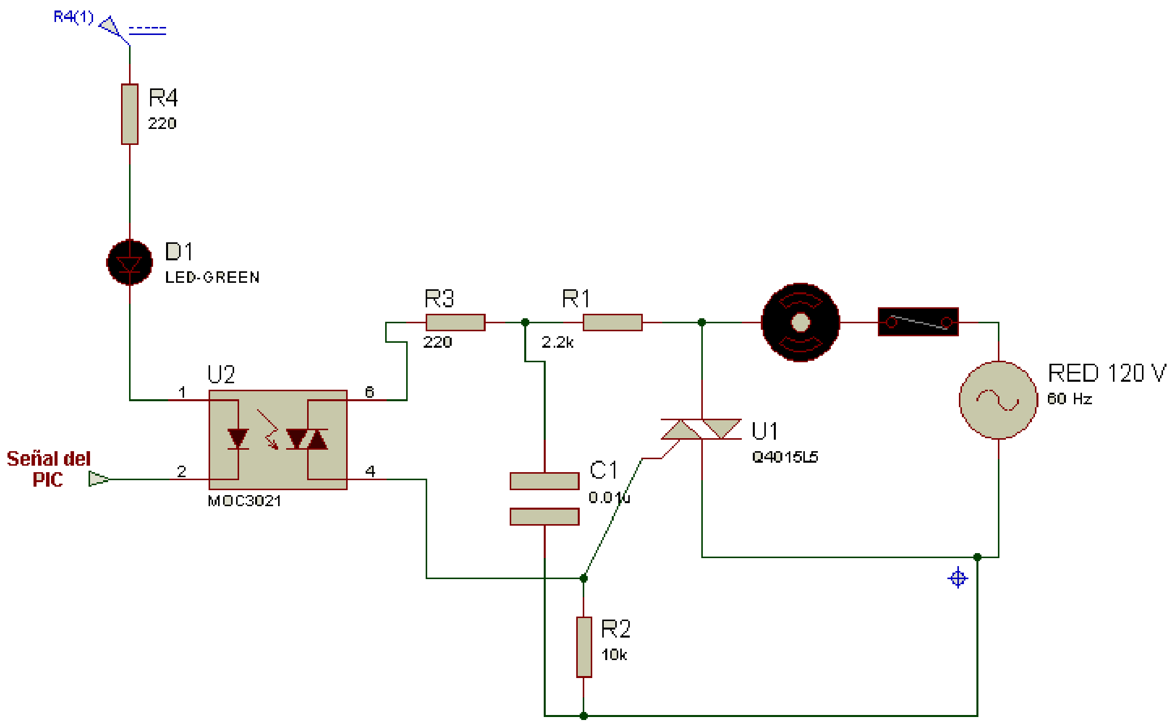
El funcionamiento del sistema consiste en abrir la compuerta 1 y encender el extractor en el momento en que el café tostado se encuentre en la bandeja (posición 1) de tal manera que la muestra de café se enfrié rápidamente y pueda ser retirada de la tostadora. La compuerta 2 permanece cerrada durante este proceso para no tener pérdidas de calor en el cilindro de tostión.

La posición 2 del sistema de enfriamiento, se caracteriza porque la compuerta 2 está abierta y las compuerta 1 se encuentre cerrada, se utiliza cuando se desea hacer una limpieza en la tolva de tostión y para hacer la aspiración de humo durante la tostión.

El control del sistema de enfriamiento consta de dos partes, la primera es el control del motor de apertura y cierre de paso del aire y el segundo es el control del encendido y apagado del extractor.

Para la primera parte se utilizó un puente H gobernado por dos señales de control que provienen del micro controlador. Para la segunda se utilizó un motor monofásico. Una salida del micro controlador se conecta a un opto acoplador y luego a un TRIAC de potencia para manejar el motor del extractor al igual que se hace con el motor del giro del cilindro, como se observa en la Figura 24.

Figura 24. Manejo de motor extractor del sistema de enfriamiento



Con la ayuda de software Eagle se desarrollaron los circuitos antes explicados, como resultado obtuvimos 3 placas que componen el total del proyecto, es así como tenemos:

Panel Lateral, Figura 25, este contiene el circuito de potencia; Triacs, transistores y puente H para manejo de motores,

Panel Frontal, Figura 26, este contiene el PIC, el acondicionamiento de la señal de la termocupla, los opto acopladores, el módulo Xbee y su debido acondicionamiento, el teclado, el LCD y el circuito de alarma.

Panel Sistema de pesaje, Figura 21, que contiene el acondicionamiento de las señales de las celdas de carga.

Figura 25. Panel Lateral

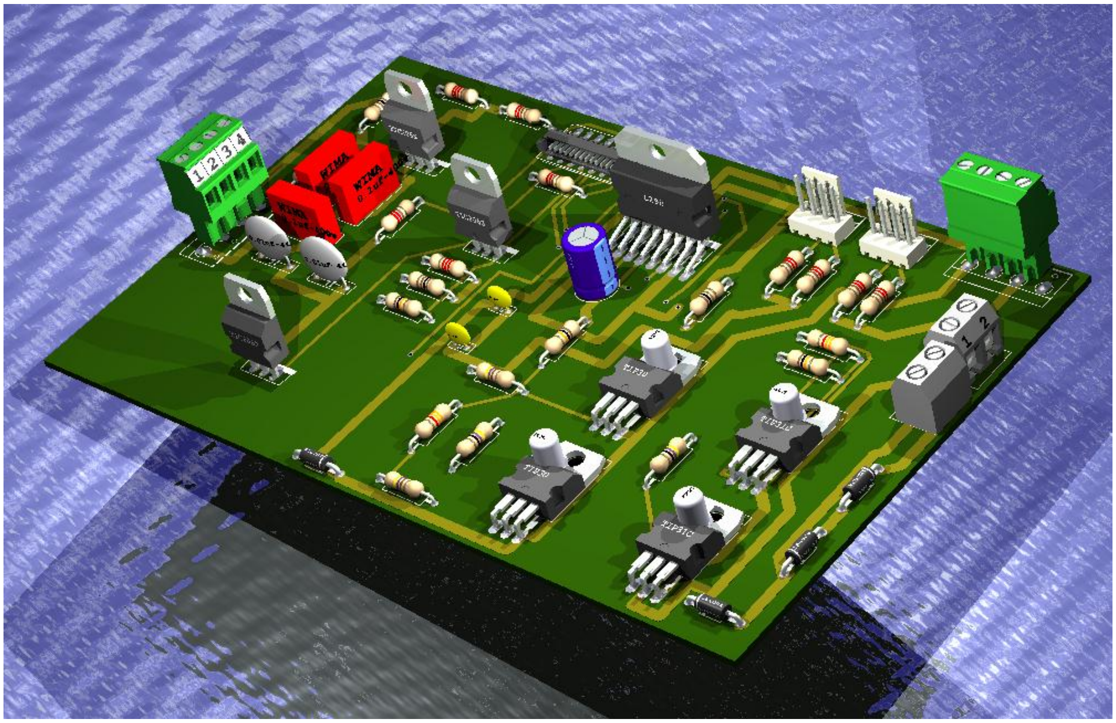
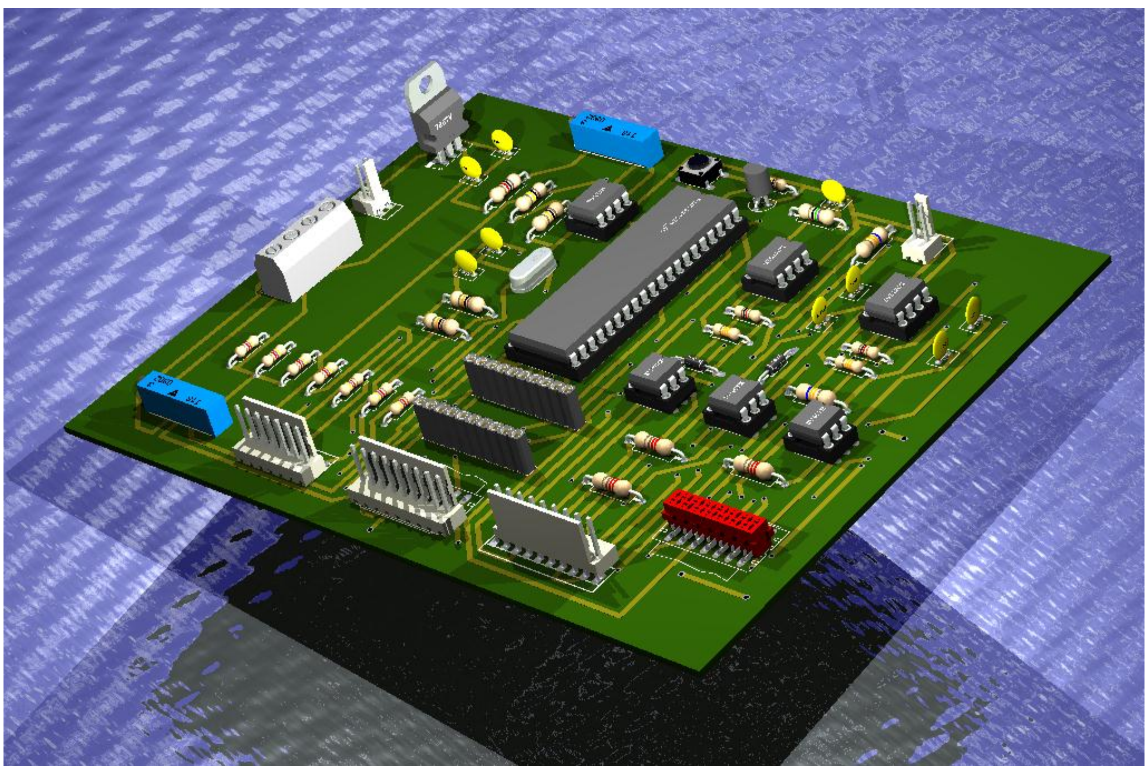


Figura 26. Panel Frontal



3.2. IDENTIFICACION DEL SISTEMA

Para realizar el diseño del control de temperatura, es necesario efectuar la identificación del sistema, es decir construir un modelo matemático del comportamiento del sistema a controlar, en este caso se halló el modelo matemático que caracteriza el comportamiento o la relación entre la temperatura en el tambor, siendo esta la salida del sistema y el voltaje aplicado a la resistencia calefactora, por tanto siendo esta última la entrada del sistema.

Para lograr determinar el modelo, excitamos la resistencia calefactora con 120 voltios y adquirimos los datos de temperatura en el tambor por medio de nuestra aplicación en Labview durante 30 minutos como se observa en la Figura 27, dichos datos fueron almacenados en nuestra base de datos MYSQL y posteriormente procesados en Matlab. Debido a que la entrada al sistema fue constante, decidimos optar por la identificación por el método de Van Der Grinten o método de los 4 parámetros ilustrados en la Figura 28.

Figura 27. Voltaje de alimentación y temperatura

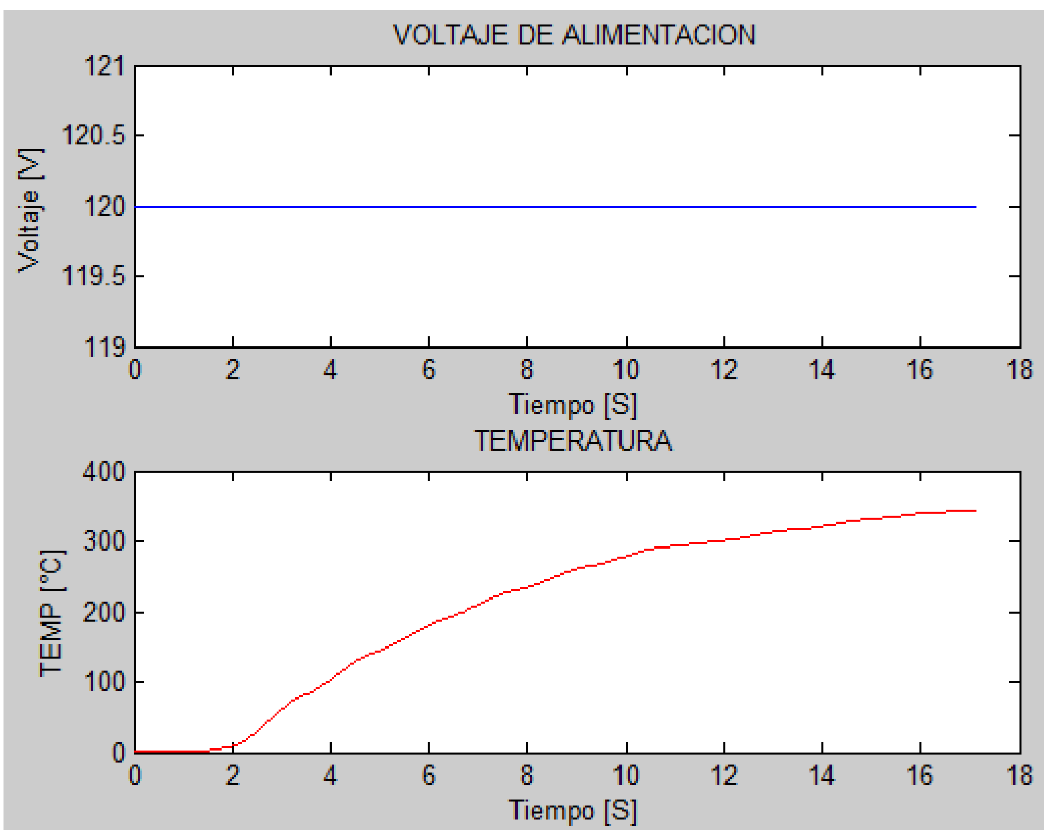
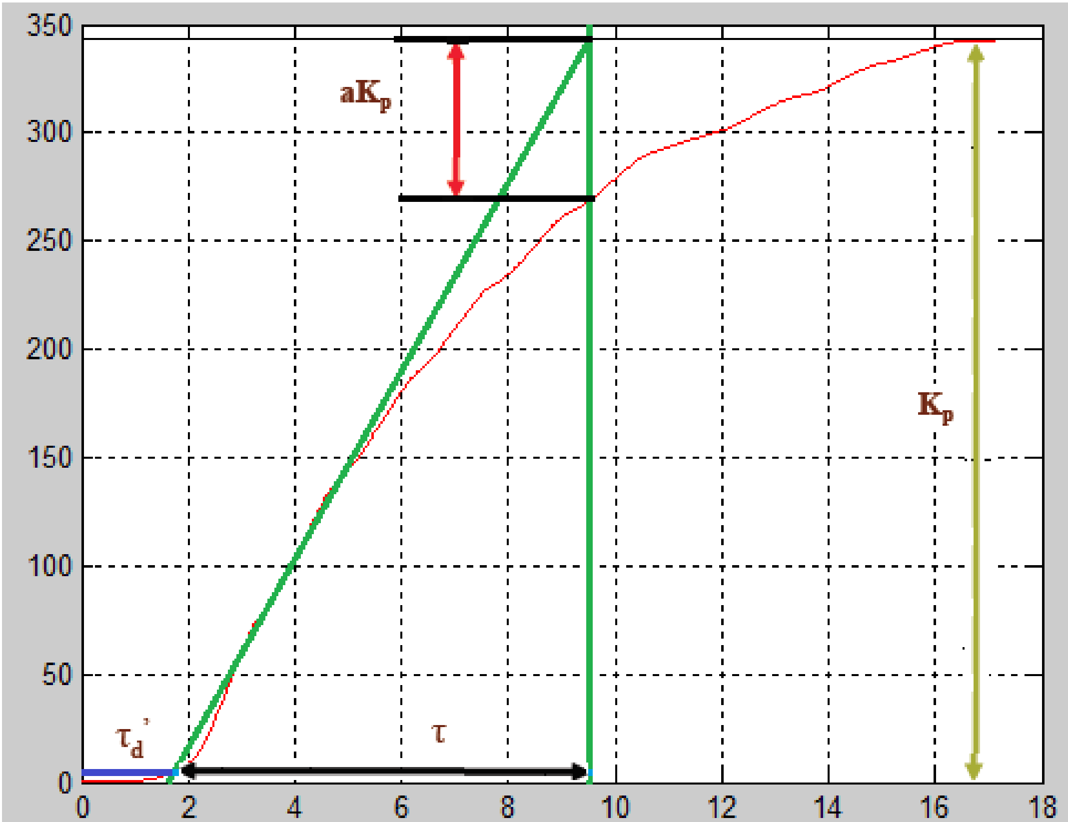


Figura 28. Método De Van Der Grinten



$a * k_p = 71.5$ $k_p = 342.5$ $\tau_d' = 1.536$ $\tau = 8.096$

$$a = \frac{1}{e} \rightarrow G(s) = k_p \frac{e^{-\tau_d s}}{\tau s + 1}$$

$$\tau_d = \tau_d{}' - \frac{\tau_1 \tau_2}{\tau_1 + 3\tau_2}$$

$$\tau_1 = \tau \frac{3ae - 1}{1 + ae}$$

$$\tau_2 = \tau \frac{1 - ae}{1 + ae}$$

Luego de aplicar las respectivas ecuaciones determinamos:

$\tau_1 = 3.309$ $\tau_2 = 2.3934$ $\tau_d = 0.7809$ $a = 0.2$

Dado que el valor de a se encuentra muy alejado de $\frac{1}{e}$ aplicamos la siguiente ecuación:

$$a \neq \frac{1}{e} \rightarrow G(s) = k_p \frac{e^{-\tau_d s}}{(\tau_1 s + 1)(\tau_2 s + 1)}$$

$$G(s) = 342.5 \frac{e^{-0.7809s}}{(3.309s + 1)(2.3934s + 1)}$$

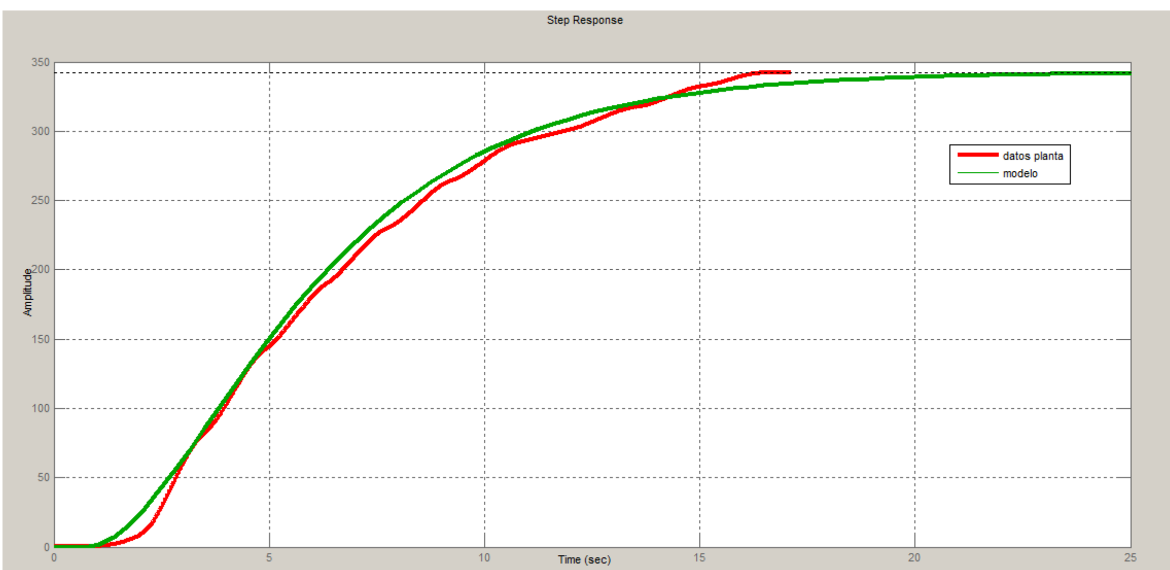
$$G(s) = \frac{342.5e^{-0.7809s}}{7.919s^2 + 5.7024s + 1}$$

Mediante la ayuda de Matlab obtenemos el modelo digital de la planta como sigue:

$$G(z) = \frac{0.2111\,z + 0.2061}{z^2 - 1.929\,z + 0.9305} T_s = 0.1\,s$$

Al graficar el anterior polinomio en MATLAB y compararlo con el comportamiento real del sistema, como se observa en la Figura 29, determinamos que es el modelo más aproximado a dicha respuesta.

Figura 29. Validación del modelo de la planta

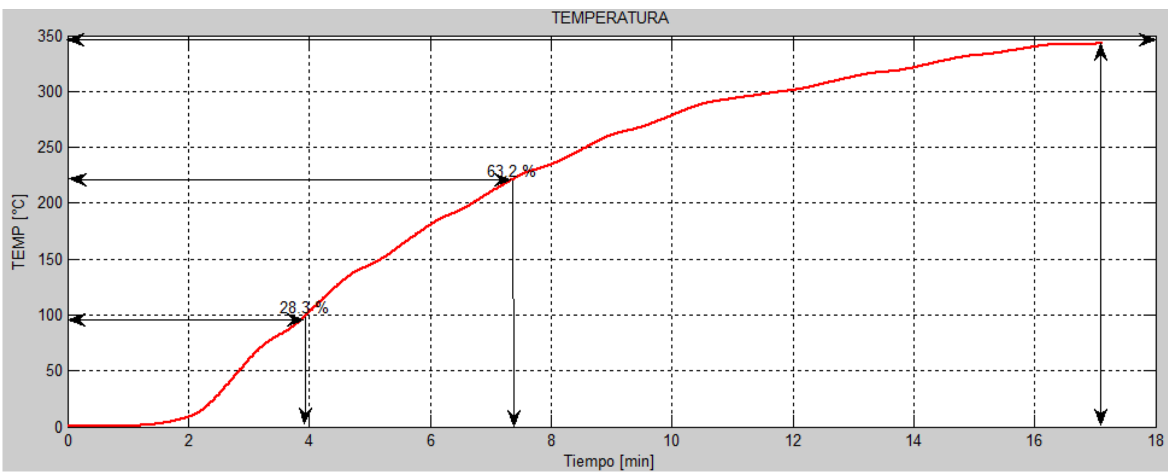


3.3. CONTROL DE TEMPERATURA

Debido a que la temperatura es la variable que define el proceso, el control se enfoca hacia esta variable. Posteriormente, mediante la ayuda de Matlab observamos el comportamiento de la planta con realimentación unitaria, con el fin de determinar qué tipo de control aplicar, es así, como se optó por implementar un controlador PID, debido a que el sistema realimentado presentaba inestabilidad y un error muy grande además de que queremos mejorar el tiempo de respuesta, con esto logramos mejorar el error actual, corregir proporcionalmente la integral del error, es decir asegurar que aplicando un esfuerzo de control suficiente, el error de seguimiento se reduce a cero, además de mejorar la reacción del tiempo en el que el error se produce.

En este caso se utilizó el método de Ziegler-Nichols basado en la respuesta en frecuencia haciendo una estimación en lazo abierto, es decir estimando los parámetros $\boldsymbol{K}, \boldsymbol{T_p}, \boldsymbol{T_0}$ que mejor aproximan las características de la respuesta como se observa en la Figura 30.

Figura 30. Respuesta del sistema a una entrada de 5 voltios



Característica al 28.3 %

$$\mathbf{0.283(350) = 99.05}$$

$$\boldsymbol{t_1 = 3.92\ min}$$

Característica al 63.2 %

$$\mathbf{0.632(350) = 221.2}$$

$$\boldsymbol{t_2 = 7.344\ min}$$

$$T_p = 1.5(t_2 - t_1) = 5.136$$

$$T_0 = t_2 - T_p = 2.208$$

$$K = \frac{cambio\ en\ la\ temperatura}{cambio\ en\ la\ apertura} = \frac{350}{5} = 70$$

Ahora mediante las formulas de sintonía de Ziegler-Nichols y con los anteriores parámetros hallados, determinamos las constantes proporcional K_p, integral T_I y derivativa T_D.

$$K_p = \frac{1.2T_P}{KT_0} = \frac{1.2(5.136)}{(70)(2.208)} = 0.042$$

$$T_I = 2\,T_0 = 4.416$$

$$T_D = 0.5\,T_0 = 1.104$$

Por tanto la función de transferencia del controlador PID es:

$$\frac{U(z)}{E(z)} = \frac{q0z^2 + q1z + q2}{z(z-1)}$$

Donde:

$$q0 = K_P\left[1 + \frac{T}{T_I} + \frac{T_D}{T}\right] = 0.5066$$

$$q1 = -K_P\left[1 + 2\frac{T_D}{T}\right] = -0.96936$$

$$q2 = K_P\left[\frac{T_D}{T}\right] = 0.46368$$

$$Gc(z) = \frac{0.5066z^2 - 0.96936z + 0.46368}{z(z-1)}$$

3.3.1. Algoritmo a implementar en el PIC

Para implementar el controlador PID en el PIC, es necesario pasar el controlador que se encuentra en el dominio Z a una ecuación en diferencia, que permite introducir una función de transferencia en un sistema digital, en este caso un PIC; para lograr este fin, aplicamos las propiedades de la transformada Z como sigue:

$$Gc(z) = \frac{0.5066z^2 - 0.96936z + 0.46368}{z(z-1)}$$

$$\frac{Y(z)}{U(z)} = \frac{0.5066 - 0.96936z^{-1} + 0.46368z^{-2}}{(1 - z^{-1})}$$

$$Y(z) - z^{-1}Y(z) = U(z)(0.5066 - 0.96936z^{-1} + 0.46368z^{-2})$$

$$Y(z) = 0.5066U(z) - 0.96936z^{-1}U(z) + 0.46368z^{-2}U(z) + z^{-1}Y(z)$$

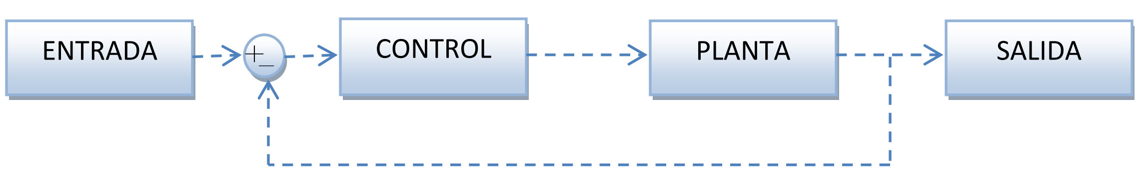
$$Y(n) = 0.5066U(n) - 0.96936U(n-1) + 0.46368U(n-2) + Y(n-1)$$

En el PIC, tenemos:

```
// TempRef: temperatura deseada (introducida por teclado)
// TempReal: temperatura sensada en el cilindro tostador

eT=TempRef-TempReal; //Cálculo del error
uT=q0*eT_1+q2*eT_2+uT_1; //ecuación en diferencia


// Guardar variables para próximo estado

eT_2=eT_1;
eT-1=eT;
uT_1=uT;
```

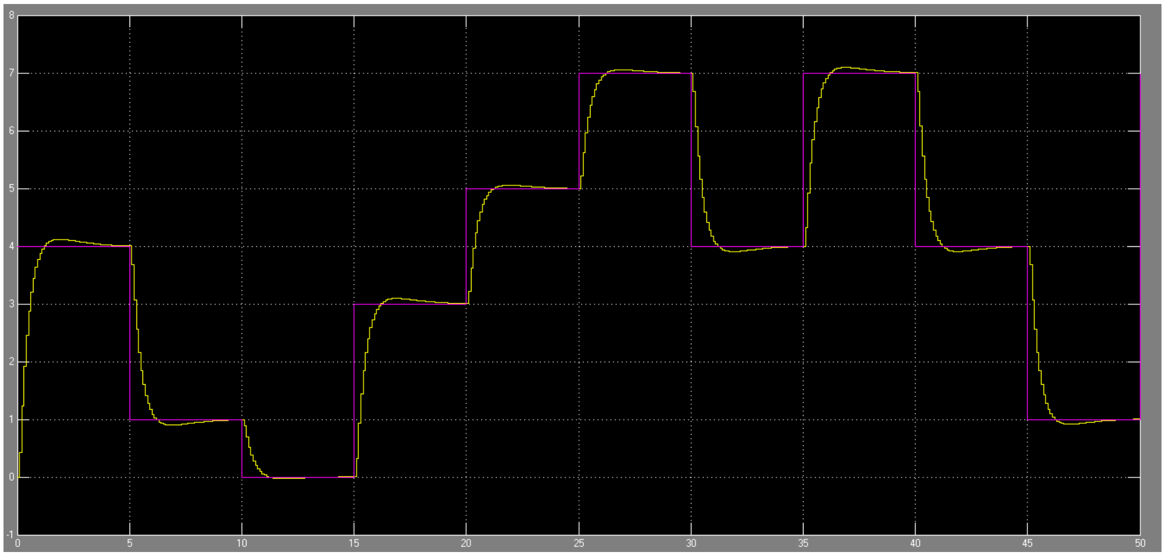
Luego de obtener la respectiva ecuación del controlador con sus constantes, podemos observar el diagrama completo del sistema como observamos en la Figura 31.

Figura 31. Diagrama en bloque del sistema controlado



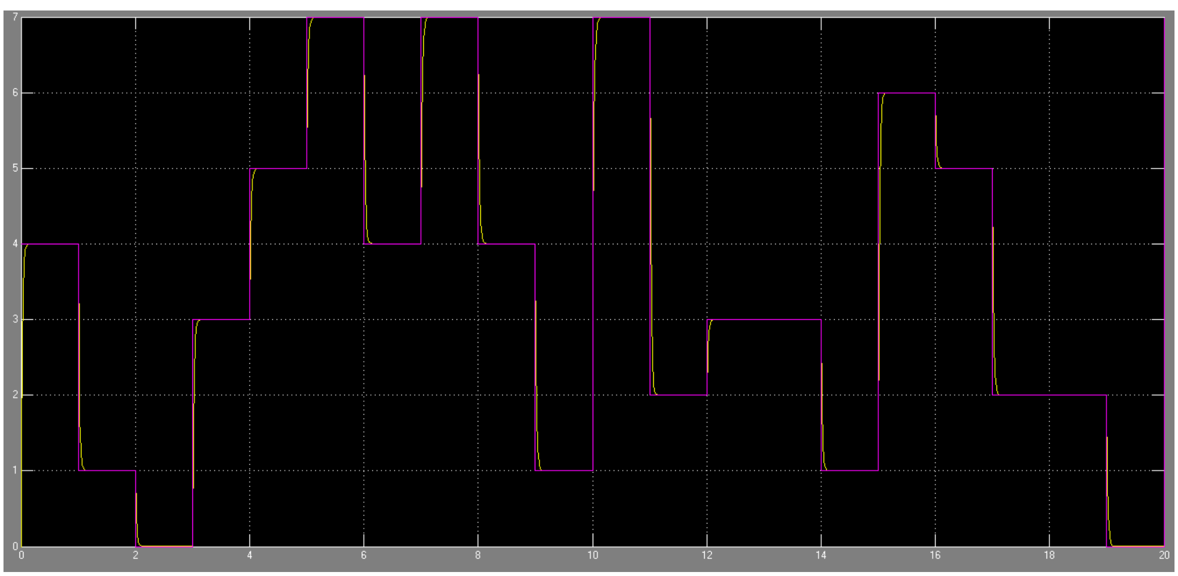
Así mismo procedemos a evaluar la respuesta de la planta con el respectivo controlador para diferentes valores de entrada lo cual se puede observar en la Figura 32.

Figura 32.Respuesta del sistema controlado



Para lograr una mejor respuesta, se decidió sintonizar mediante Matlab los parámetros del controlador, se esta forma se obtuvo una mejor respuesta como se observa en la Figura 33.

Figura 33. Sintonización de parámetros



3.4. CONTROL DE FASE

El control de fase consistió en hacer que la resistencia calefactora alimentada con corriente alterna, es decir la señal de 60 Hz a 120 voltios, en lugar de recibir todo el ciclo senoidal de la tensión de la red, reciba solo parte. Para lograr esto se dispone la resistencia calefactora en serie con un semiconductor capaz de conducir la corriente alterna (Triac), como se observa en la Figura 36. Para lograr el control, se monitorea la señal de cruce por cero y se carga un valor de tiempo en el PIC, como los tiempos equivalen a ángulos en la corriente alterna, y la diferencia entre ellos se llama ángulo de fase, al controlar el ángulo en que se pone a conducir el semiconductor, se controla la tensión que llega a la resistencia, todo esto con el fin de que en el momento indicado el Triac se dispare y empiece a conducir solo la tensión necesaria hasta el siguiente cruce por cero, haciendo que el proceso se repita cada semi-ciclo.

3.4.1. Cruce por cero

Como punto inicial, se implementó el circuito de cruce por cero como se observa en la Figura 34, el cual consiste en tomar la señal de la red de 120 voltios AC y mediante un transformador reducir este a 12 voltios AC, posteriormente mediante un puente rectificador, se hace que la onda solo tenga ciclos positivos, como se observa en la gráfica azul de la parte superior de la Figura 35, en seguida mediante un amplificador operacional configurado como comparador, referenciado a un voltaje muy cercano a cero, alrededor de 20 mili voltios, se hace que cada vez que la señal de entrada proveniente del puente rectificador sea igual al de la referencia, la salida sea la máxima señal de entrada, por tanto cuando la señal de entrada es diferente a la referencia, la señal de salida es cero, es así como se generan pulsos cada vez que la señal cruza por cero, como se observa en la gráfica amarilla de la parte inferior de la Figura 35.

Figura 34. Circuito cruce por cero

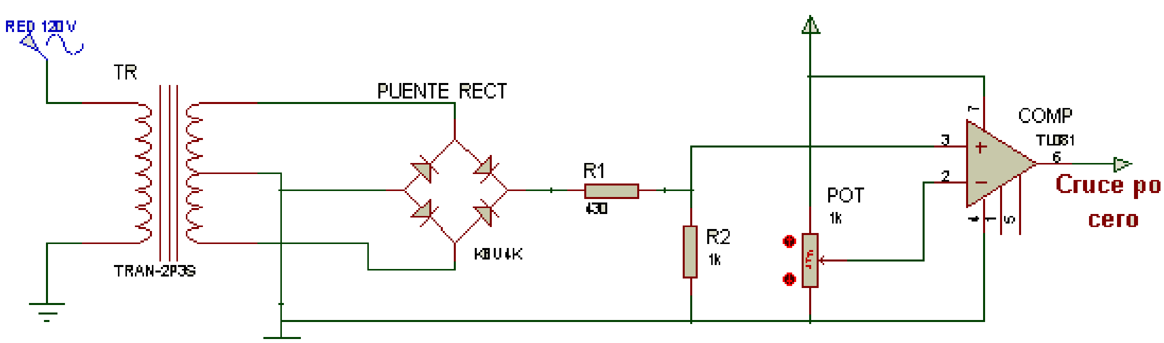
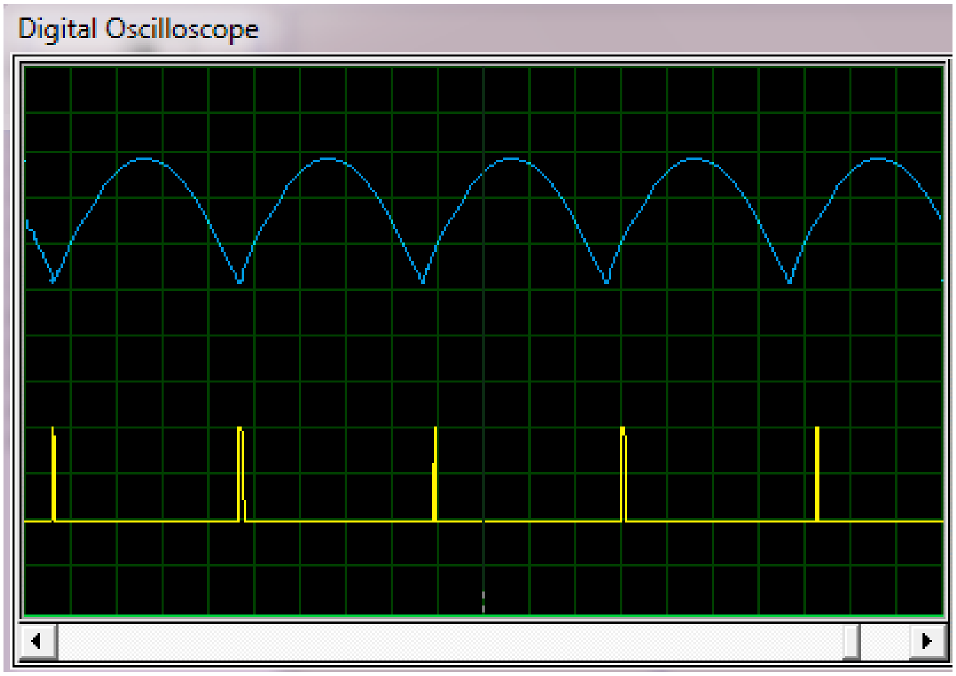


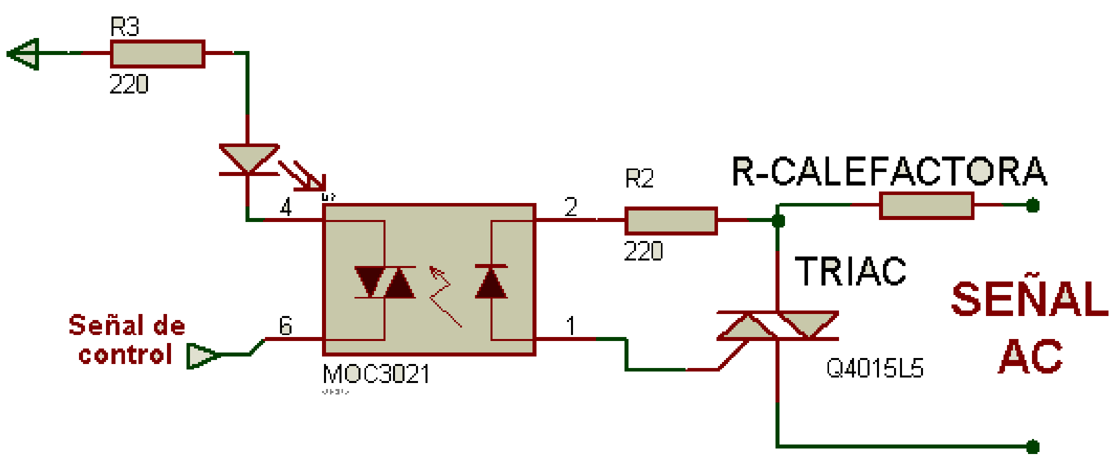
Figura 35. Gráficas señal rectificada y cruce por cero



3.4.2. Acople del circuito de control y el circuito de potencia

Debido a que el PIC proporciona la señal de disparo para el Triac, es decir una señal digital de control, es necesario aislar físicamente dicha señal del circuito de potencia mediante un opto acoplador como se observa en la Figura 36.

Figura 36. Acople entre control y potencia

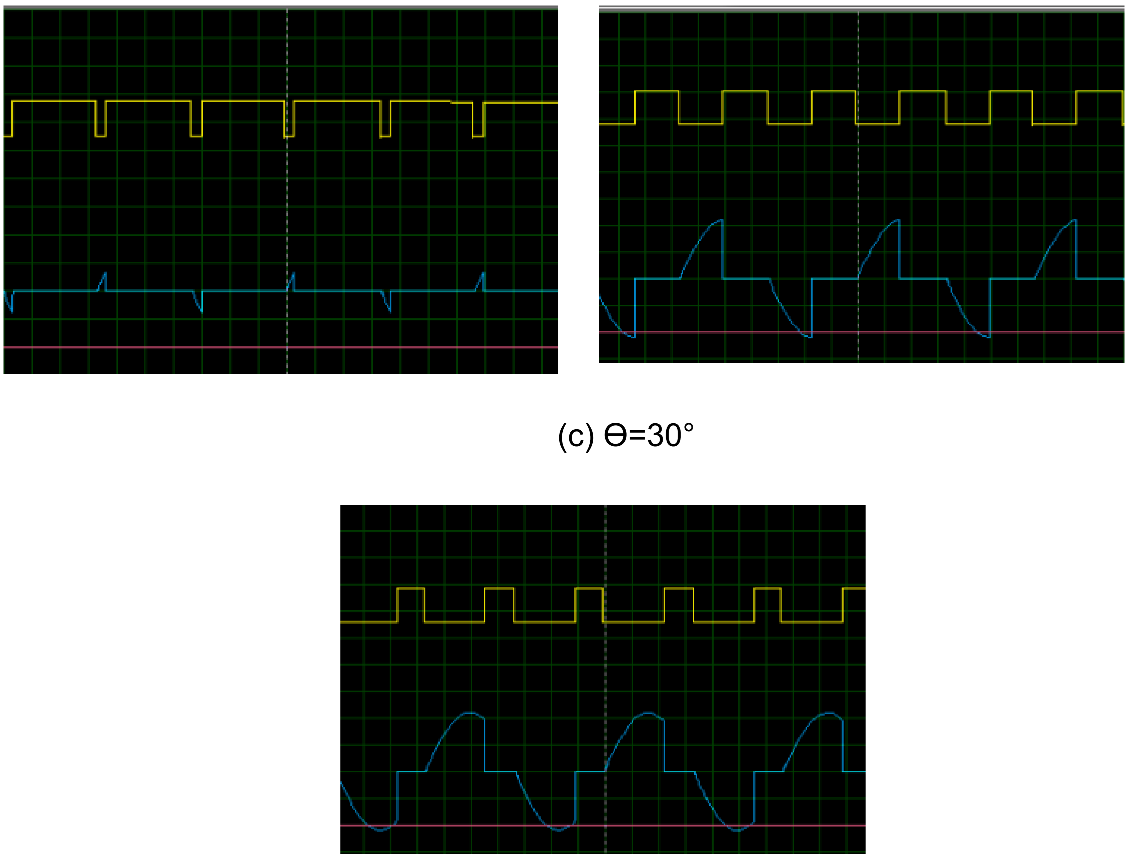


Es de esta forma como la resistencia calefactora no recibe toda la señal de la red, si no la correspondiente a la temperatura deseada por el usuario, como se observa en la Figura 37.

Figura 37. Control de Fase

(a) ϴ=160° (b) ϴ= 90°

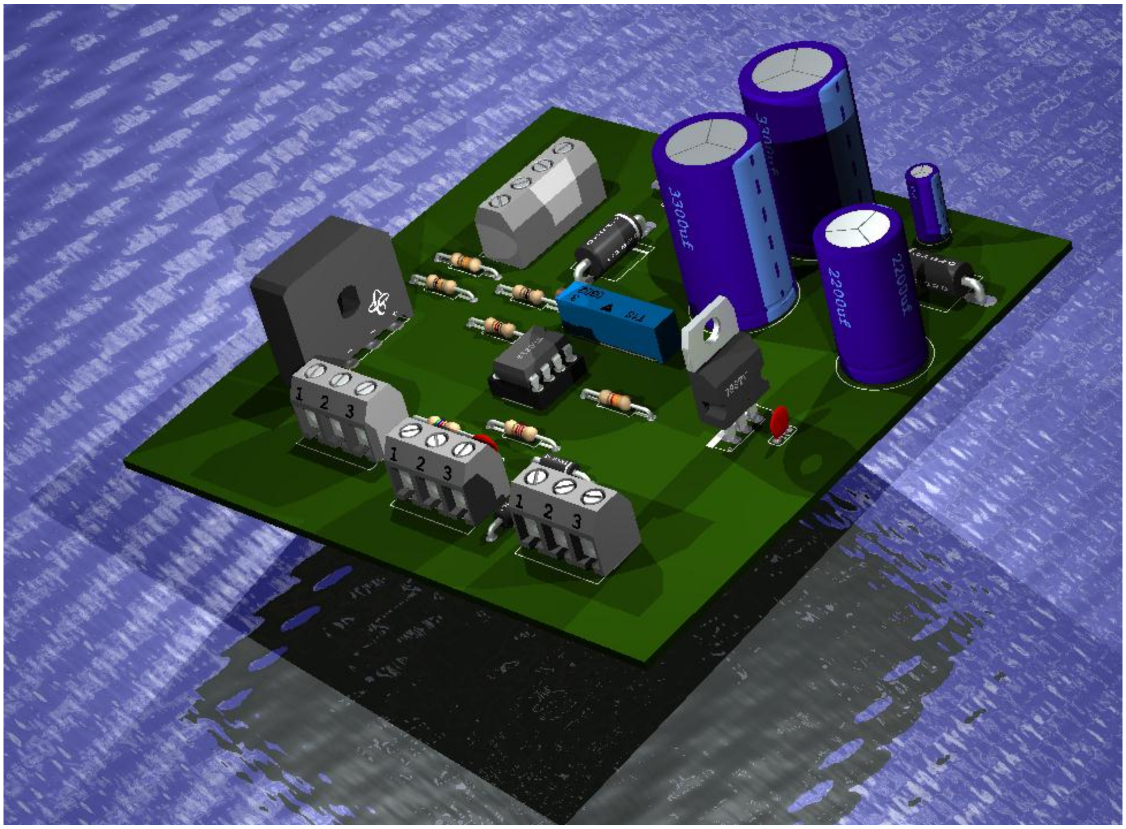
(c) ϴ=30°



3.5. FUENTE DE PODER

Para energizar el panel lateral, el frontal, el sistema de pesaje y el cruce por cero, se implemento una fuente de poder que suministra en voltaje necesario para lograr el funcionamiento de estas, dicha fuente suministra 12 y 5 voltios DC y se observa en la Figura 38.

Figura 38. Fuente de Poder



3.6. DISEÑO SOFTWARE

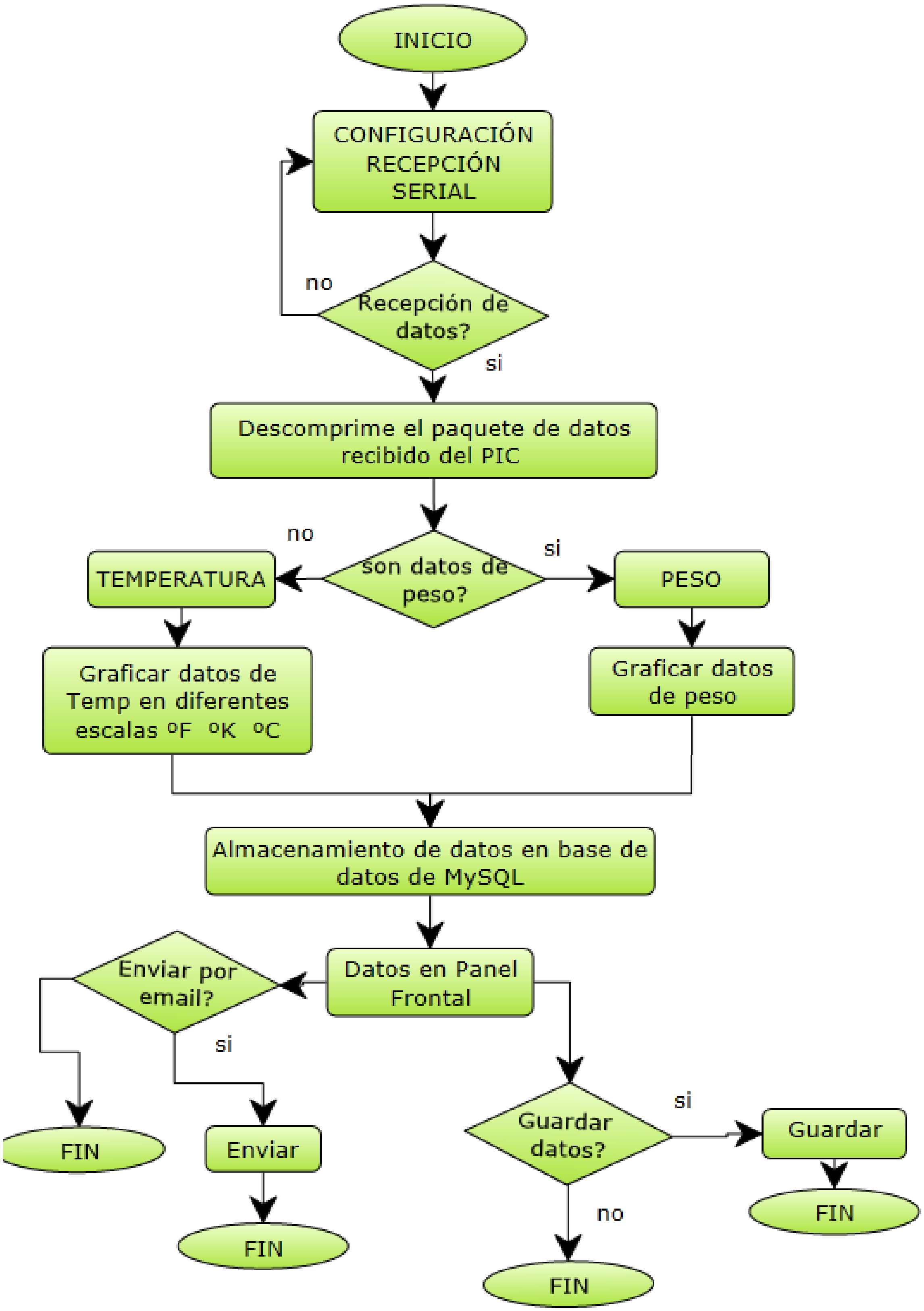
Se desarrolló una interfaz gráfica en el programa Labview de National Instruments, debido a que el programa de Ingeniería Electrónica cuenta con la licencia para operar dicho software.

La interfaz gráfica elaborada permite al usuario visualizar el comportamiento de cada una de las variables censadas en el proceso de tostión de una forma amigable dado que está orientado hacia estudiantes que realizarán investigaciones y practicas sobre la tostión de café en el laboratorio.

En relación a lo anterior, la interfaz gráfica está dividida en los siguientes paneles:

- Inicio
- Temperatura
- Peso
- Base de datos

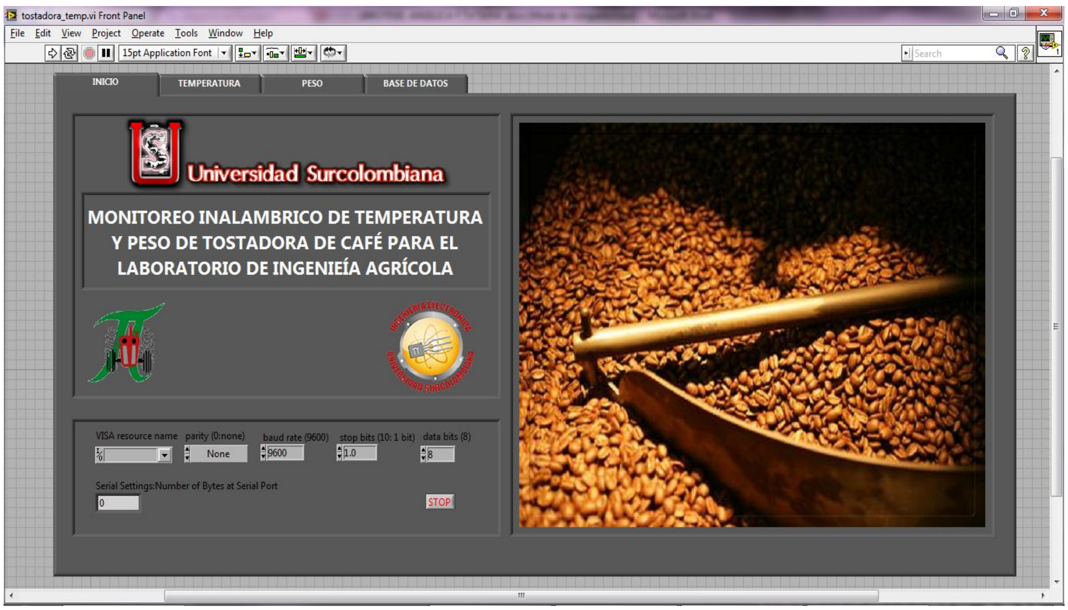
Figura 39. Diagrama de Flujo programación en Labview



3.6.1. Panel de inicio

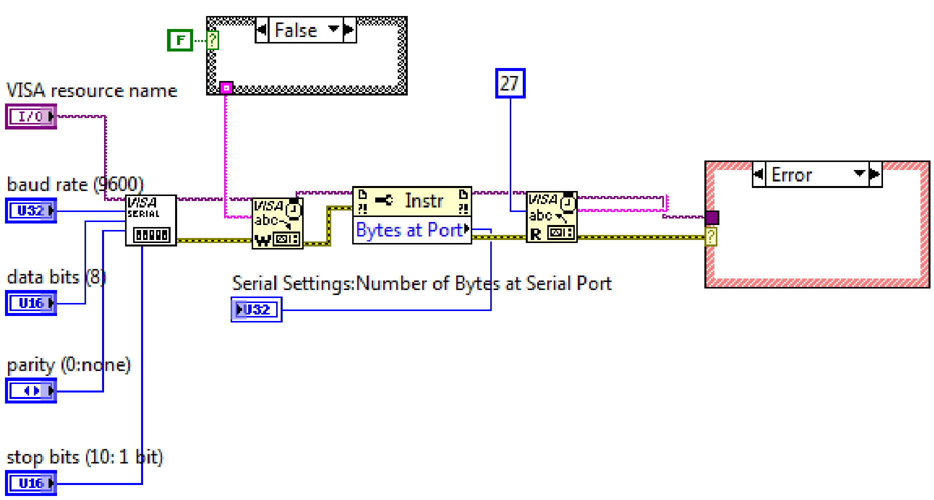
Este panel es de vital importancia pues es en este en el cual se configura el puerto a través del cual se realizará la adquisición de los datos que se están recibiendo por medio del módulo Xbee, al igual que la velocidad de adquisición, este panel se observa en la Figura 40.

Figura 40. Panel frontal de comunicación y adquisición



La adquisición de los datos en LABVIEW fue realizada por medio de los VI de la paleta de serial como VISA Configure Serial Port, VISA write y VISA read como se puede observar en la Figura 41.

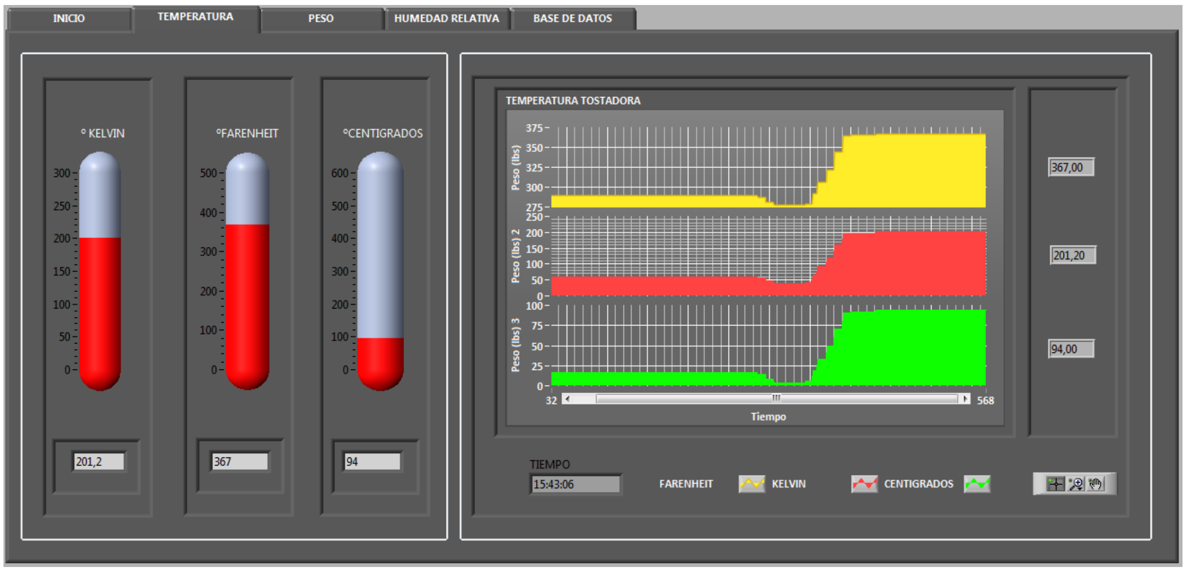
Figura 41. Diagrama de bloques de adquisición



3.6.2. Panel de temperatura.

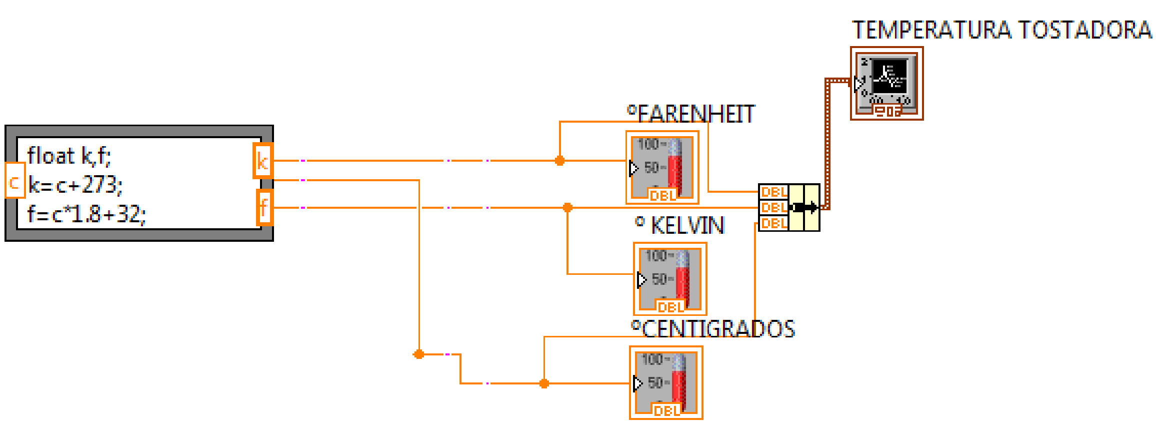
Este panel permite la visualización de la temperatura a la cual está sometido el grano durante la tostión dentro del tambor de la tostadora; es posible observar la temperatura en tres diferentes escalas bien sea por medio de indicadores o en gráficas de temperatura vs tiempo como se observa en la Figura 42.

Figura 42. Panel de monitoreo de temperatura



La visualización de la temperatura en las escalas Kelvin, Fahrenheit y Centígrados se realizó aplicando las respectivas ecuaciones por medio del VI formula node como se muestra en la Figura 43.

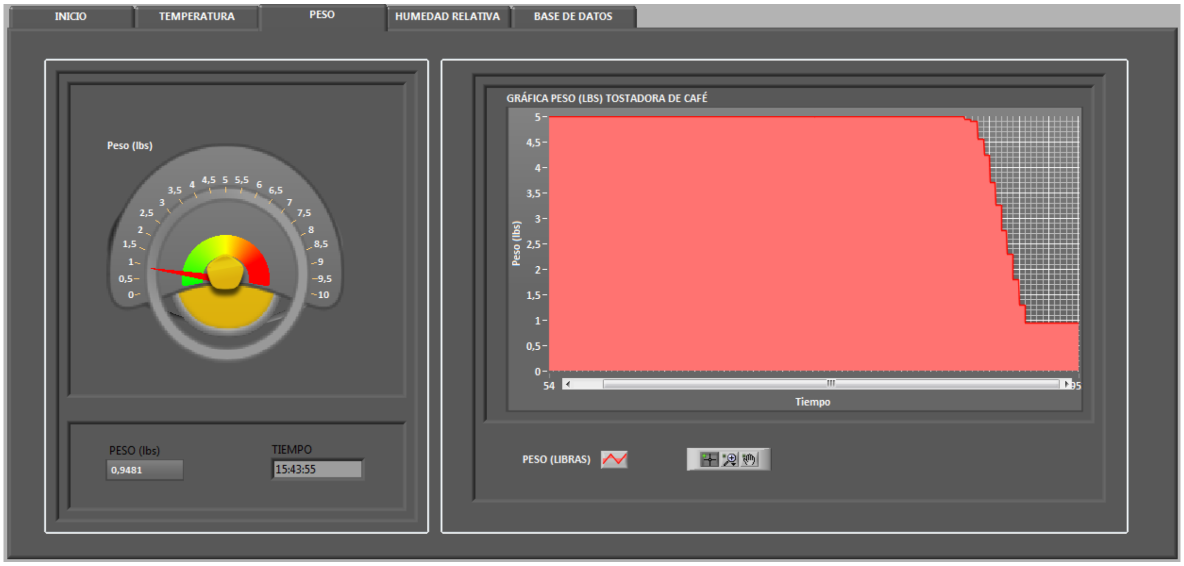
Figura 43. Diagrama de bloque de visualización de temperatura



3.6.3. Panel de peso.

Este panel permite el monitoreo de la variación del peso del grano durante el tiempo de la tostión; esto es posible mediante un indicador numérico o bien por medio de una gráfica que representa la variación del peso en relación al tiempo como se observa en la Figura 44.

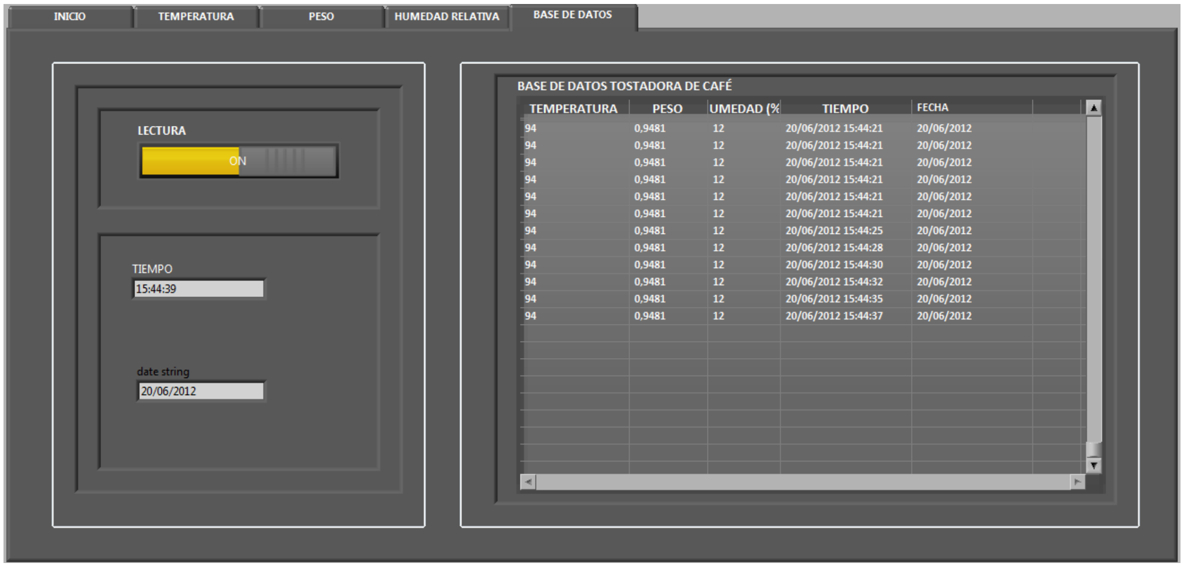
Figura 44. Panel de monitoreo de peso



3.6.4. Panel de base de datos.

Este panel brinda la posibilidad de almacenar y visualizar los datos obtenidos de las diferentes variables en una base de datos, como se observa en la *Figura 45*, esta fue elaborada en MYSQL el cual es un software libre reconocido por su gran capacidad de almacenamiento de datos brindando mayor eficacia y rendimiento durante el manejo de gran cantidad de datos. Para la lectura de dicha base de datos desde LABVIEW fue necesario descargar de forma gratuita los instrumentos virtuales que permiten utilizar el motor de base de datos MYSQL.

Figura 45. Panel de lectura y escritura de datos



La lectura y escritura de la base de datos se realizó mediante los VI's para la interacción de LABVIEW con SQL denominados lab SQLADO como se puede observar en la Figura 46 y Figura 47.

Figura 46. Diagrama de bloques lectura de base de datos

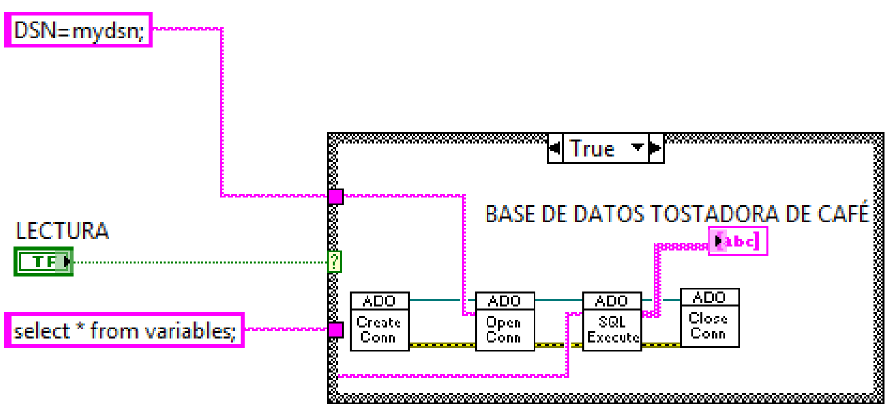
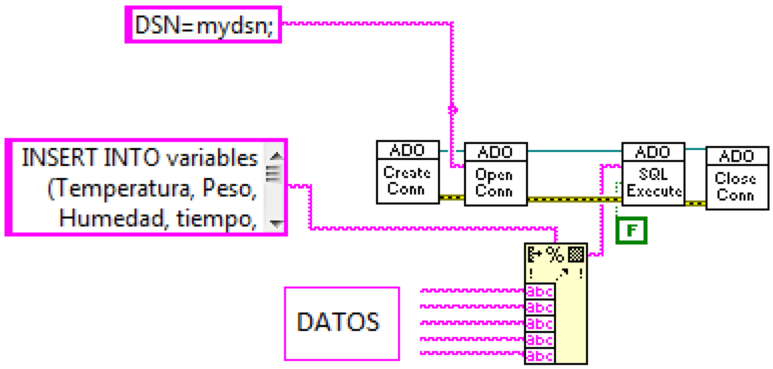


Figura 47. Diagrama de bloques escritura de la base de datos



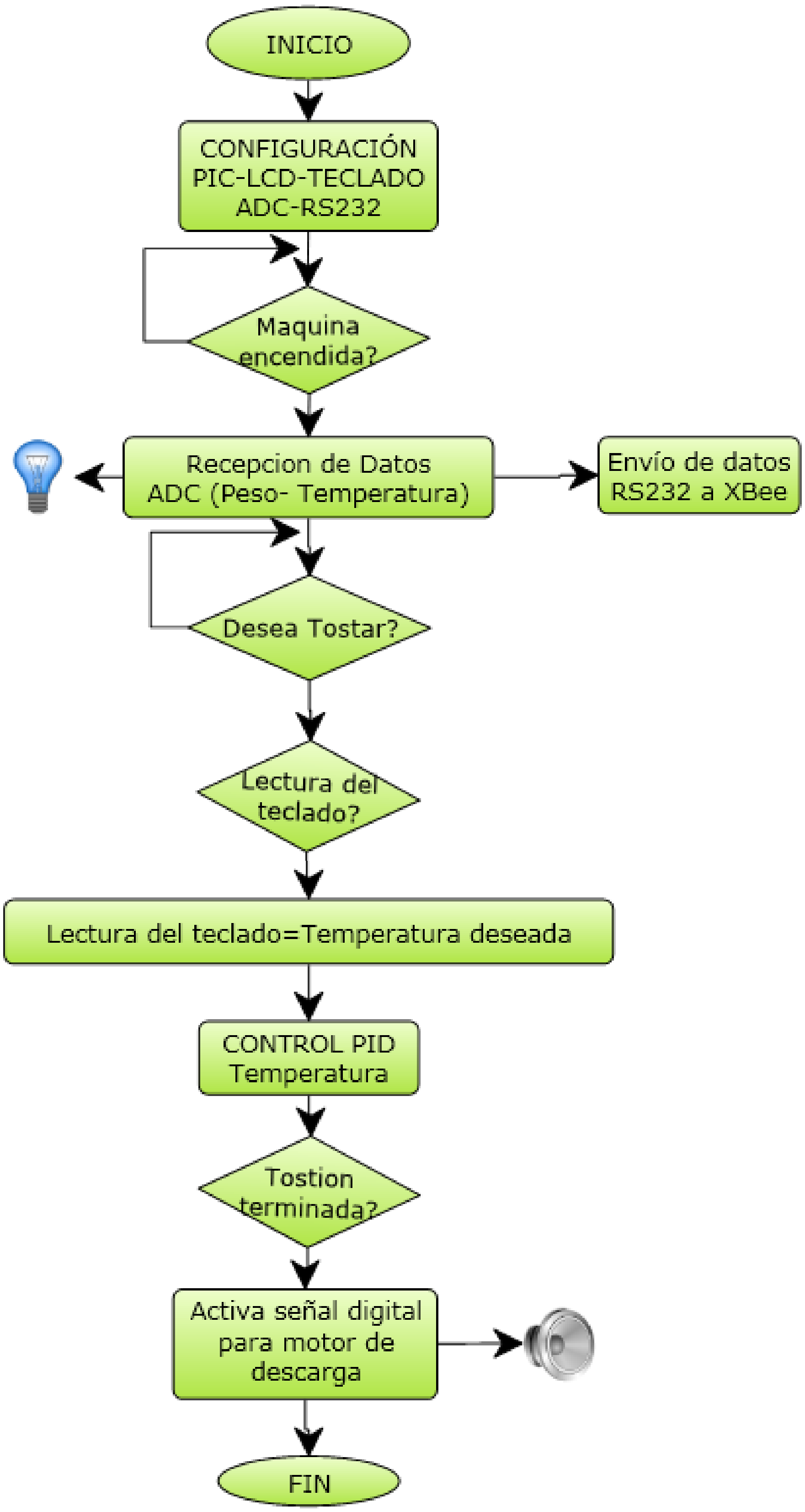
Los datos obtenidos mediante la interacción de LABVIEW con MYSQL además de ser visualizados en el panel frontal y ser almacenados en la respectiva base de datos de MYSQL, pueden ser exportados como archivos de texto con extensión .txt u hoja de datos de Excel con extensión .xlsx que son de gran utilidad para posteriores procesamientos.

3.6.5. Programación del PIC

El firmware fue escrito mediante el compilador C de CCS inc. La Figura 48 muestra el diagrama de flujo de la programación del PIC que está encargado de realizar las siguientes tareas:

- Monitoreo de datos análogos de temperatura de la termocupla y del sensor LM35.
- Monitoreo de los sensores ópticos de barrera de fin e inicia de carrera.
- Proveer las salidas digitales que controlan el ángulo de fase para la resistencia calefactora y los motores del extractor y giro del cilindro.
- Manejo del LCD y teclado.
- Envío de los datos de temperatura y peso de forma serial para que sean transmitidos al computador de manera inalámbrica.
- Implementación del controlador PID de temperatura.
- Control de alarmas.

Figura 48.Diagrama de flujo Programación PIC



4. CONCLUSIONES

- Se diseñó e implementó la automatización de una tostadora de café del programa de Ingeniería Agrícola de la Universidad Surcolombiana, el cual consta de un sistema de pesaje, control PID de temperatura y envío inalámbrico de datos.

- La temperatura es la variable más adecuada a controlar en el proceso de torrefacción de café.

- El peso es una variable importante en el proceso de torrefacción, por lo tanto monitorearla aporta información para la investigación en este sector.

- La aplicación desarrollada en Labview permite al usuario acceder de manera sencilla a los datos que están siendo monitoreados durante el proceso, mediante gráficas y tablas.

- La comunicación inalámbrica implementada por medio de tecnología Zigbee facilita al usuario el acceso a la máquina y a los datos sin necesidad de cableado.

5. RECOMENDACIONES

- Monitorear otras variables en el proceso de torrefacción, como el color, por medio de un instrumento que permita medir la reflectancia del color.

- Realizar periódicamente revisiones y mantenimiento que sean necesarios para que la máquina permanezca en buen estado.

- Integrar la máquina de torrefacción con el laboratorio de Análisis Sensorial del Programa de Ingeniería Agrícola de la Universidad Surcolombiana.

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ANEXOS

ANEXO A. PROGRAMACIÓN PIC

Este anexo se encuentra en el CD que acompaña este libro.

ANEXO B. MÓDULOS INALÁMBRICOS XBEE

Este anexo se encuentra en el CD que acompaña este libro.

ANEXO C. COEFICIENTES DE POLINOMIOS DE NIST

Este anexo se encuentra en el CD que acompaña este libro.

ANEXO D. CELDA DE CARGA MONOBLOQUE SP06

Este anexo se encuentra en el CD que acompaña este libro.

ANEXO E. AMPLIFICADOR DE INSTRUMENTACIÓN AD620

Este anexo se encuentra en el CD que acompaña este libro.

ANEXO F. REGULADOR DE VOLTAJE LM317

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ANEXO G. AMPLIFICADOR OPERACIONAL TL084

Este anexo se encuentra en el CD que acompaña este libro.

ANEXO H. PROGRAMACIÓN EN LAVIEW

Este anexo se encuentra en el CD que acompaña este libro

Automatización de Máquina de Torrefacción de Café para el Laboratorio del Programa de Ingeniería Agrícola de la Universidad Surcolombiana

Automation of a Coffee Roaster Machine of Agricultural Engineering Laboratory at Surcolombiana University

Agustín Soto Otalora[1], Angélica María Cárdenas Castaño[2], Jenifer Tatiana Osorio Guzmán[3]

Resumen

Este trabajo consiste en el control y la automatización de una máquina de torrefacción de laboratorio del programa de Ingeniería Agrícola de la Universidad Surcolombiana, la cual fue dotada con celdas de carga y los arreglos adecuados al sensor de temperatura con el fin de hacer su control, por tanto se monitorean variables tales como peso y temperatura de manera inalámbrica desde el computador por medio del software LabVIEW e igualmente se tiene la opción de visualizar dicho monitoreo desde el LCD ubicado en la máquina. Para el desarrollo de este proyecto fue fundamental conocer completamente el proceso de torrefacción, además de las características de todos los sensores y dispositivos usados en esta, con el fin de obtener medidas precisas, además de un control óptimo. Como resultado de este trabajo, se obtuvo una tostadora controlada por temperatura, con monitoreo del peso, con visualización de estas variables tanto en un LCD como en una aplicación en LabVIEW que me permite, visualizar, controlar y almacenar todos los cambios que sufre el café en relación a su peso y temperatura durante el proceso de torrefacción.

Palabras Claves: Control, automatización, torrefacción, LabVIEW.

Abstract

This work is about the control and automation of a coffee roaster machine of Agricultural Engineering laboratory at Surcolombiana University, which was outfitted by load cells and some modifications to sensor temperature with the purpose of making its control, also were monitored every variables wirelessly through LabVIEW software on the computer, furthermore offers the option of visualizing the monitoring on the LCD that is in the machine. For the development of this project was essential to know fully the roaster process, also the characteristics of each sensor and device which was used in this machine, for the purpose of acquiring accurate measurements and an optimum control.

As result of this work, we obtain a roast which was controlled by temperature, with monitoring of weight, with visualization of these variables on a LCD. We develop an application on LabVIEW which offers the possibility of visualizing, controlling and saving all changes that the coffee is suffering relation to its weight and temperature during the roast process.

Keywords: LabView, ZigBee, Fuzzy control, humidity, temperature.

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1. Introducción

Colombia hace parte de los principales productores de café verde en el mundo siendo su producción y comercialización una de las principales fuentes de ingresos para el país, es por ello que es de gran importancia la investigación que se realiza actualmente en este campo con el fin de obtener un café de mejores características constituyéndolo así, como un producto de alta calidad.

Es necesario tener en cuenta que la investigación realizada en el sector cafetero tiene como objetivo la obtención de una mejor materia prima y así mismo de un mejor café como producto final luego de múltiples procesos realizados con el fin de explotar al máximo sus características de sabor, aroma, color y textura.

Actualmente el programa de Ingeniería Agrícola de la Universidad Surcolombiana realiza investigaciones en relación al procesamiento del café, siendo de gran importancia para la región, dado que el departamento del Huila en los últimos años ha mostrado gran avance en cuanto a producción de cafés especiales, catalogándose hoy en día como el primer productor de estos en el país, según el Comité Nacional de Cafeteros de Colombia.

Es preciso destacar la importante labor realizada por el Programa de Ingeniería Agrícola, el cual a través de los años ha avanzado en sus investigaciones en el sector cafetero gracias a la adquisición de maquinaria apropiada para los diferentes procesos realizados al grano como son fermentación, secado y torrefacción.

Aunque el Programa ya contaba con una máquina de torrefacción de café diseñada e implementada por un estudiante del programa de Ingeniería Electrónica de la universidad Surcolombiana en el año 2004, la cual contaba con un sistema de control de temperatura On-Off por medio de una termocupla y un sistema de descarga y enfriamiento; lo que se desarrolla en esta tesis es el mejoramiento de dicho sistema de control , además de monitorear el peso y la temperatura del grano de manera inalámbrica y su posterior visualización en el software LabVIEW.

En relación a lo anterior, el desarrollo de este trabajo hace un aporte importante a la investigación de este proceso en el sector cafetero, puesto que permite a los investigadores acceder de una manera más fácil a los datos relacionados con el proceso, con el fin de observar la dinámica de estas y determinar posteriormente algunas características que permitirán aportar en el mejoramiento de la producción del café como materia final.

2. Metodología

En El sistema propuesto para esta aplicación consta de varios módulos que pueden ser apreciados en el diagrama de bloques que se muestra en la figura 1.

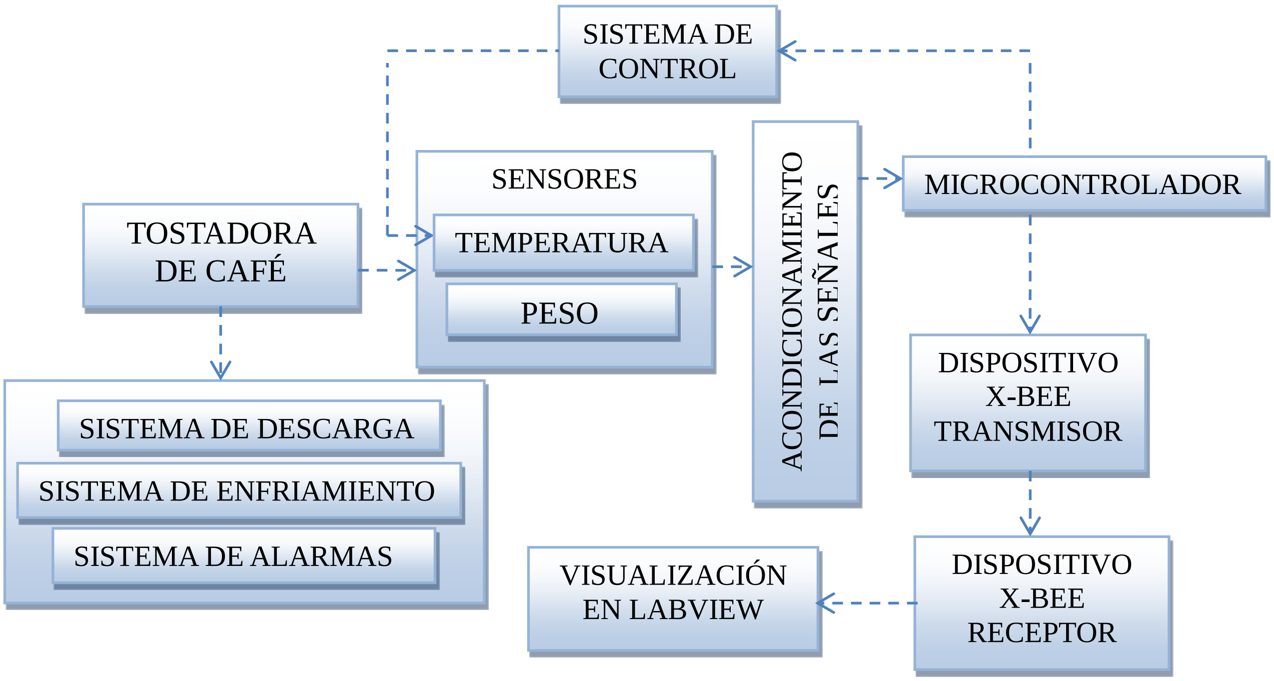

Fig. 1.Diagrama en bloques del sistema.

2.1 Diseño del hardware

2.1.1. Peso. Debido a que el peso es un claro indicador en el proceso de tostión, escogimos celdas de carga mono bloque de referencia SP06 como la que se muestra en la Figura 2 con capacidad de 40 kilos y sensibilidad de 2 milivoltios/voltio, por lo que es necesario el acondicionamiento de la señal.

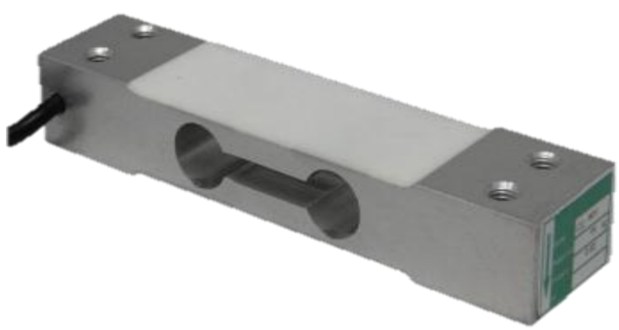

Fig. 2. Celda de carga monobloque SP06

Para cada uno de los sensores, se diseñó una etapa de acondicionamiento con amplificadores operacionales y de instrumentación. Para el sistema de pesaje se implemento un arreglo de 4 celdas de carga con el fin de mejorar la sensibilidad del sistema, por tanto las señales de las 4 celdas se amplifican debidamente cada una y posteriormente se suman con el fin de hallar el peso total, finalmente para evitar ruidos en el sistema, dicha señal pasa por un filtro pasa bajo; su acondicionamiento se observa en el diagrama de bloques de la Figura 3.

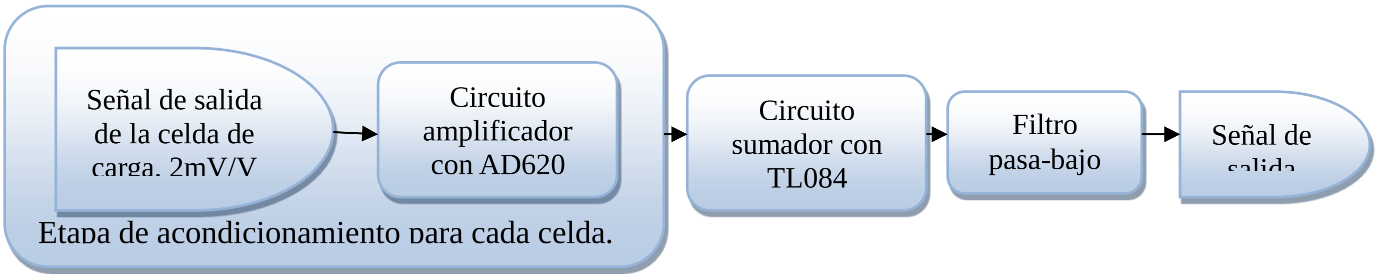

Fig. 3. Diagrama de bloques del acondicionamiento de las celdas de carga.

2.1.2. Temperatura. Además de la celda de carga, se usó una termocupla, el cual es el sensor de temperatura más común utilizado industrialmente. Una termocupla consta de dos alambres de distinto material unidos en un extremo (soldados generalmente). Al aplicar temperatura en la unión de los metales se genera un voltaje muy pequeño (efecto Seebeck) del orden de milivoltios el cual aumenta con la temperatura. Normalmente las termocuplas industriales se consiguen encapsuladas dentro de un tubo de acero inoxidable u otro material (vaina), en un extremo está la unión caliente y en el otro el terminal eléctrico de la unión fría, protegido dentro de una caja redonda de aluminio (cabezal).

Debido a que esta tostadora es de uso en investigación en el laboratorio del programa de Ingeniería Agrícola de la Universidad Surcolombiana, el grano de café será sometido a calor comprendido entre 0 y 500 grados centígrados para determinar cómo es la relación de olor, color y textura a dichas temperaturas y contribuir como ya se mencionó, a la investigación en el sector de la tostación de café, es por ello que la termocupla que hace parte de la tostadora es tipo J la cual tiene un límite máximo de trabajo de 760ºC aunque debido a su naturaleza no lineal es indispensable realizar la correspondiente compensación y linealización.

. La señal que entrega la termocupla es de 51μV/ºC y la temperatura máxima de trabajo de la resistencia calefactora es de 480ºC, por lo tanto para obtener una señal máxima de 5 voltios a esta temperatura se amplificó la señal 204 veces. El diagrama en bloque del acondicionamiento de la señal se observa en la Figura 4. Posteriormente mediante software se realiza la linealización de la señal.

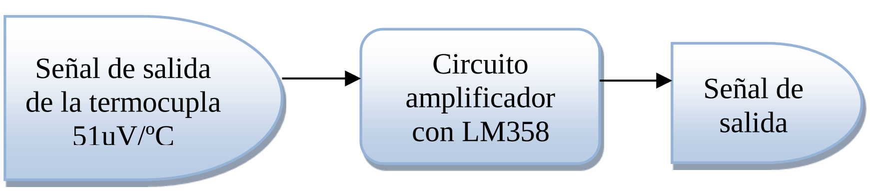

Fig. 4. Diagrama de bloques del acondicionamiento de la termocupla.

2.1.3. Comunicación inalámbrica. Como innovación en el desarrollo de este proyecto se incorporó la comunicación inalámbrica de bajo consumo, para lograr este objetivo se usó tecnología ZigBee, que es un protocolo de comunicación inalámbrica basado en el estándar 802.15.4 que es ideal para aplicaciones de baja velocidad entre dos o más dispositivos, bajo coste en implementación, bajo consumo energético, fiabilidad y para redes inalámbricas basadas en un estándar global abierto, lo que significa que cualquier dispositivo de un fabricante que soporte este estándar de comunicaciones y pase la certificación correspondiente, podrá comunicarse con otro dispositivo de otro fabricante distinto.

Para la configuración física del dispositivo Xbee PRO es necesario realizar las siguientes conexiones básicas de funcionamiento, como se observa en la Figura 5.

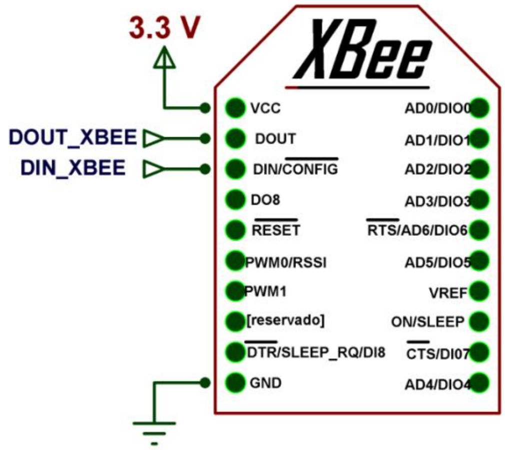

Fig. 5. Configuración básica de módulos Xbee

2.2 Identificación del sistema

Para realizar el diseño del control de temperatura, es necesario efectuar la identificación del sistema, es decir construir un modelo matemático del comportamiento del sistema a controlar, en este caso se halló el modelo matemático que caracteriza el comportamiento o la relación entre la temperatura en el tambor y el voltaje aplicado a la resistencia calefactora.

Para lograr determinar el modelo, excitamos la resistencia calefactora con 120 voltios y adquirimos los datos de temperatura en el tambor por medio de nuestra aplicación en LabVIEW durante 30 minutos como se observa en la **¡Error! No se encuentra el origen de la referencia.**, dichos datos fueron almacenados en nuestra base de datos MYSQL y posteriormente procesados en Matlab. Debido a que la entrada al sistema fue constante, y la salida muestra un retraso, además de ser de orden uno, decidimos optar por la identificación por el método de Van Der Grinten o método de los 4 parámetros, de la q obtuvimos el modelo correspondiente como se muestra en la ecuación 1.

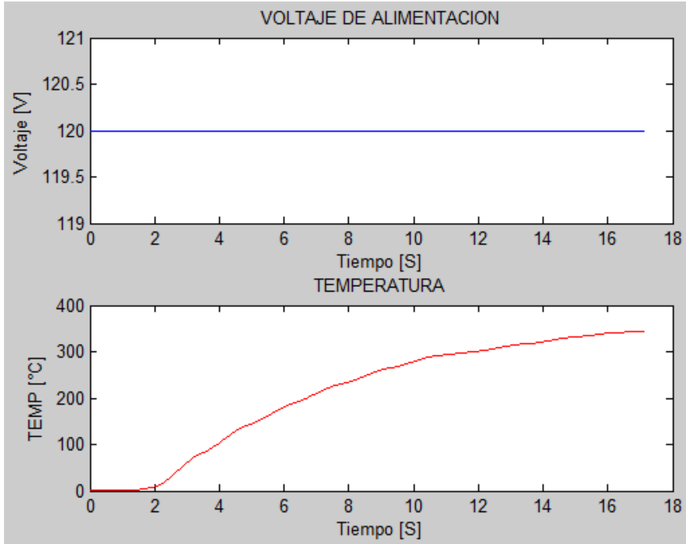

Fig. 6. Voltaje de alimentación y temperatura

$$G(s) = \frac{342.5e^{-0.7809s}}{7.919s^2 + 5.7024s + 1} \qquad (1)$$

Mediante la ayuda de Matlab obtenemos el modelo digital de la planta como sigue:

$$G(z) = \frac{0.2111\,z + 0.2061}{z^2 - 1.929\,z + 0.9305} \qquad (2)$$

$$T_s = 0.1\,s$$

2.3 Control de temperatura

Debido a que la temperatura es la variable que define el proceso, el control se enfoca hacia esta variable. Posteriormente, mediante la ayuda de Matlab observamos el comportamiento de la planta con realimentación unitaria, con el fin de determinar qué tipo de control aplicar, es así, como se optó por implementar un controlador PID, debido a que el sistema realimentado presentaba inestabilidad y un error muy grande además de que queremos mejorar el tiempo de respuesta, con esto logramos mejorar el error actual, corregir proporcionalmente la integral del error, es decir asegurar que aplicando un esfuerzo de control suficiente, el error de seguimiento se reduce a cero, además de mejorar la reacción del tiempo en el que el error se produce.

En este caso se utilizó el método de Ziegler-Nichols basado en la respuesta en tiempo haciendo una estimación en lazo abierto, es decir estimando los parámetros K, T_p, T_0 que mejor aproximan las características de la respuesta, como resultado obtuvimos el siguiente modelo de controlador de la ecuación 3.

$$Gc(z) = \frac{0.5066z^2 - 0.96936z + 0.46368}{z(z-1)} \qquad (3)$$

Así mismo procedemos a evaluar la respuesta de la planta con el respectivo controlador para diferentes valores de entrada lo cual se puede observar en la Figura 9, como se observa el modelo del controlador es muy efectivo.

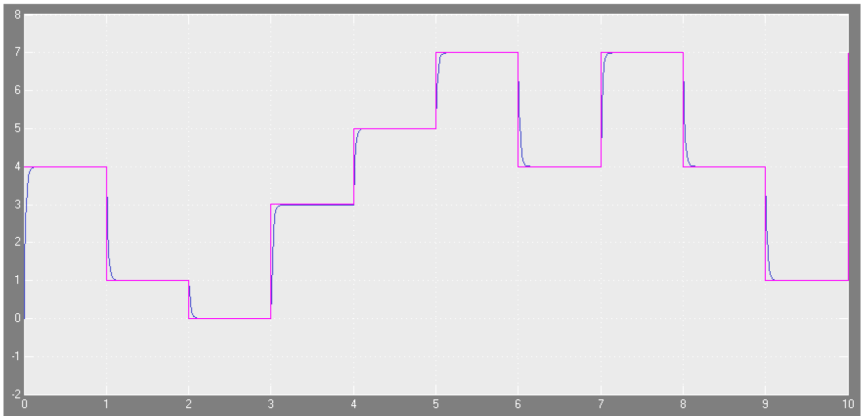

Fig. 7. Respuesta del sistema controlado

2.4 Algoritmo a implementar en el PIC

Para implementar el controlador PID en el PIC, es necesario pasar el controlador que se encuentra en el dominio Z a una ecuación en diferencia, que permite introducir una función de transferencia en un sistema digital, en este caso un PIC; para lograr este fin, aplicamos las propiedades de la transformada Z y se obtiene un modelo como es observa en la ecuación 4.

$$\boldsymbol{Y(n) = 0.5066U(n) - 0.96936U(n-1) + 0.46368U(n-2) + Y(n-1)} \qquad (4)$$

En el PIC, tenemos:

```
// TempRef: temperatura deseada (introducida por teclado)
// TempReal: temperatura sensada en el cilindro tostador
eT=TempRef-TempReal; //Cálculo del error
uT=q0*eT_1+q2*eT_2+uT_1; //ecuación en diferencia
// Guardar variables para próximo estado
eT_2=eT_1;
eT-1=eT;
uT_1=uT;
```

Luego de obtener la respectiva ecuación del controlador con sus constantes, podemos observar el diagrama completo del sistema como observamos en la **¡Error! No se encuentra el origen de la referencia.**.

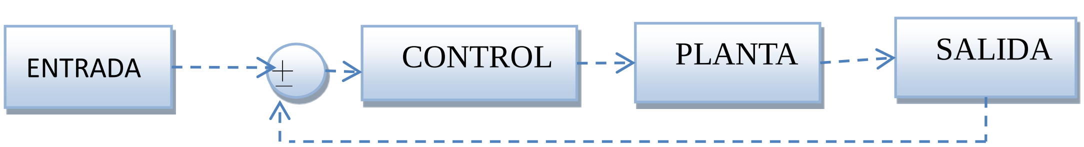

Fig. 8. Diagrama en bloque del sistema controlado

2.5 control de fase

El control de fase consistió en hacer que la resistencia calefactora alimentada con corriente alterna, es decir la señal de 60 Hz a 120 voltios, en lugar de recibir todo el ciclo senoidal de la tensión de la red, reciba solo parte. Para lograr esto se dispone la resistencia calefactora en serie con un semiconductor capaz de conducir la corriente alterna (TRIAC), como se observa en la Figura 11.

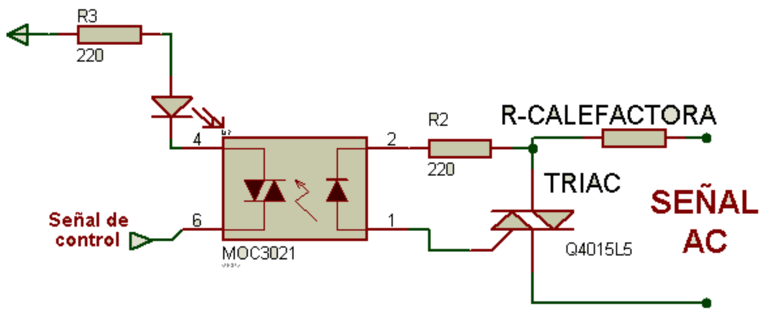

Fig. 9. Control de Fase

Es de esta forma como la resistencia calefactora no recibe toda la señal de la red, si no la correspondiente a la temperatura deseada por el usuario, como se observa en la **¡Error! No se encuentra el origen de la referencia.**.

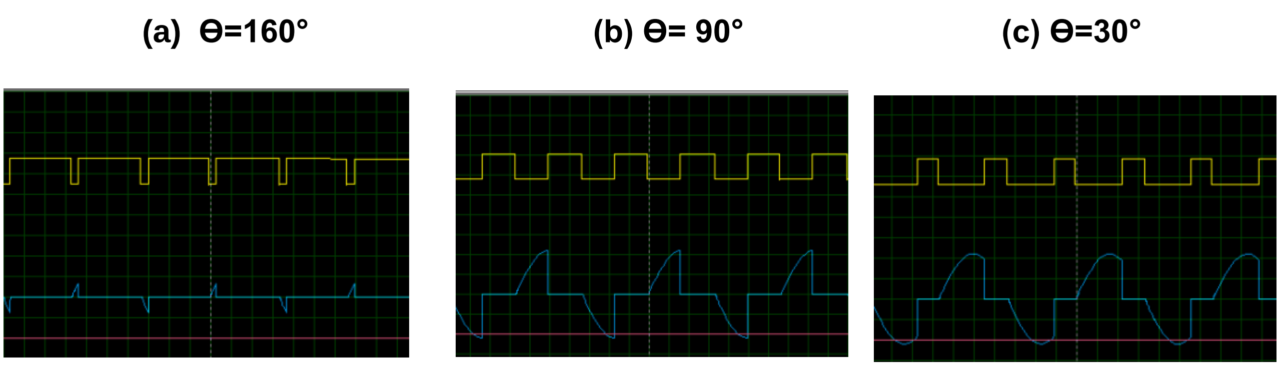

Fig. 10. Señal de control en la resistencia calefactora.

2.6. Diseño software

Se desarrolló una interfaz gráfica en el programa LabVIEW de National Instruments, debido a que el programa de Ingeniería Electrónica cuenta con la licencia para operar dicho software.

La interfaz gráfica elaborada permite al usuario visualizar el comportamiento de cada una de las variables censadas en el proceso de tostión de una forma amigable dado que está orientado hacia estudiantes que realizarán investigaciones y practicas sobre la tostión de café en el laboratorio. De este modo, la interfaz gráfica está dividida en los paneles Inicio, Temperatura, Peso y Base de datos como se observa en la Figura 12.

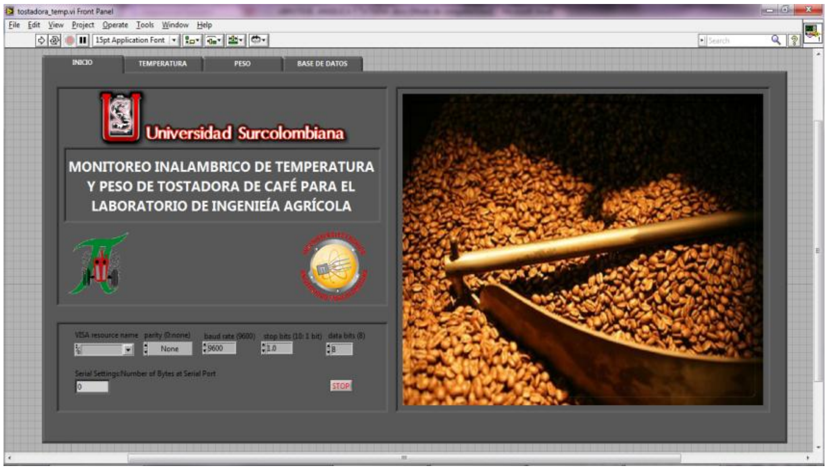

Fig. 11. Panel Inicio de la interfaz.

3. Resultados

Se realizó una serie de pruebas con café, realizando tostiones a temperaturas comunes comprendidas entre 200 y 280 grados centígrados, arrojando resultados muy efectivos puesto que se observa una diferencia de sólo 1 grado centígrado

Para probar el módulo de pesaje, se utilizaron objetos de pesos comprendidos entre 60 y 3000 gramos, con el fin de verificar el correcto funcionamiento del módulo.

El almacenamiento de la información en la base de datos por medio de Labview® se probó mientras se hacían las demás pruebas, ya que éste, por ser un módulo aparte, no afecta las mediciones y las variables se iban almacenando de la forma esperada. Se realizaron exportaciones desde la aplicación a Microsoft® Excel y se obtuvieron correctamente los archivos con la extensión correspondiente y la información completa.

Fig. 12. Vista lateral de la tostadora

Fig. 13. Vista frontal de la tostadora

4. Conclusiones

- Se diseñó e implementó la automatización de una tostadora de café del programa de Ingeniería Agrícola de la Universidad Surcolombiana, el cual consta de un sistema de pesaje, control PID de temperatura y envío inalámbrico de datos.

- La temperatura es la variable más adecuada a controlar en el proceso de torrefacción de café.

- El peso es una variable importante en el proceso de torrefacción, por lo tanto monitorearla aporta información para la investigación en este sector.

- La aplicación desarrollada en LabVIEW permite al usuario acceder de manera sencilla a los datos que están siendo monitoreados durante el proceso, mediante gráficas y tablas.

- La comunicación inalámbrica implementada por medio de tecnología Zigbee facilita al usuario el acceso a la máquina y a los datos sin necesidad de cableado.

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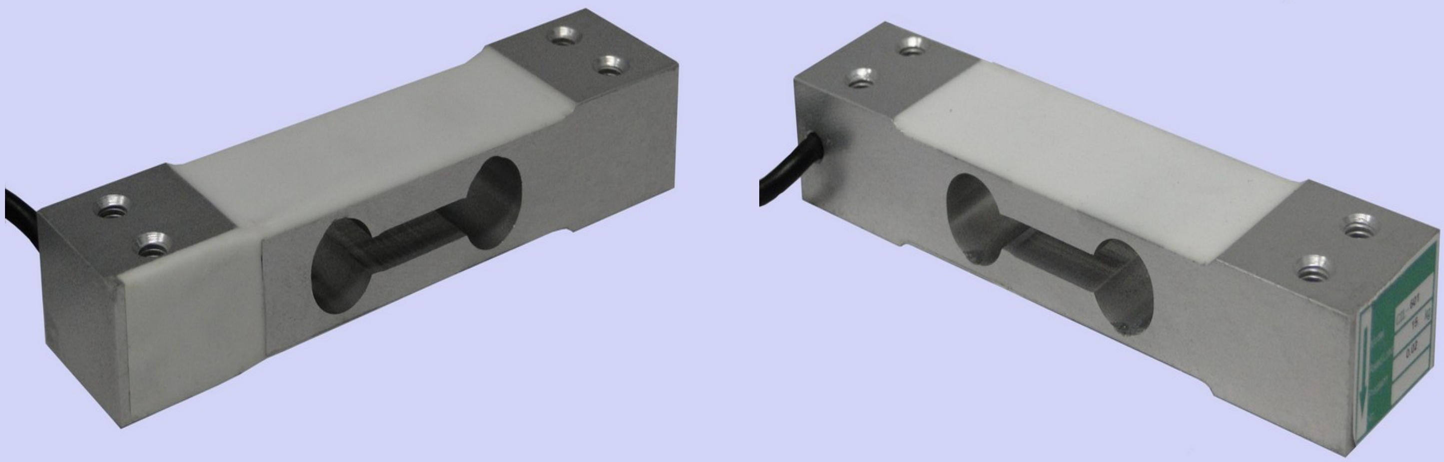
LEXUS
ELECTRONIC WEIGHING

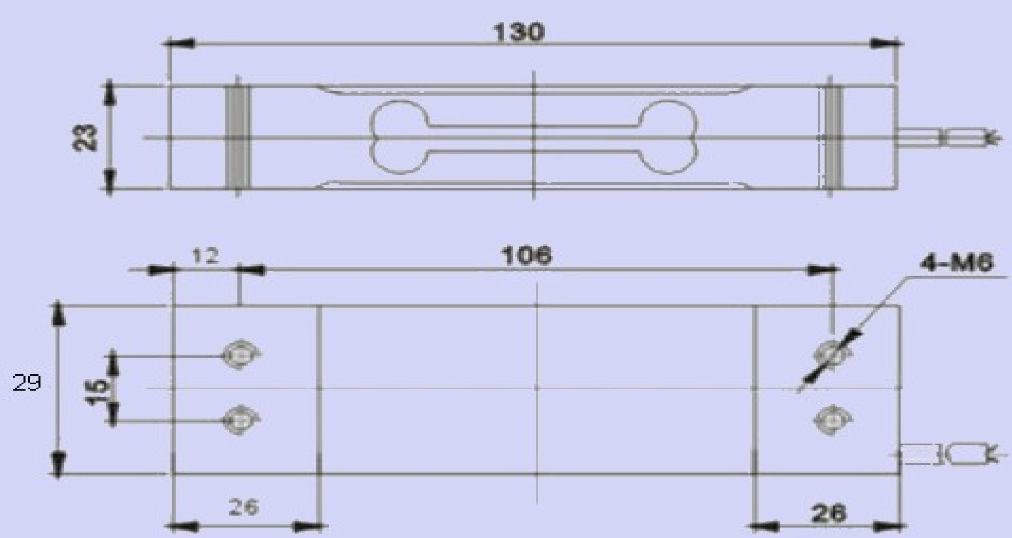
CELDA DE CARGA MONOBLOQUE
MODELO SP06

Ver. 2 (2011/10)



Celda de carga en aluminio para plataformas de 30 x 30cm especial para ambientes secos.

DIMENSIONES (mm)



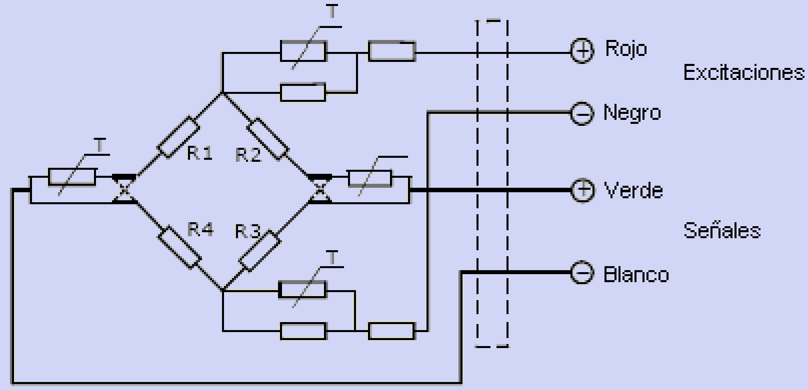
DIMENSIONES Y ESPECIFICACIONES SUJETAS A CAMBIO SIN PREVIO AVISO

LEXUS
ELECTRONIC WEIGHING

CARACTERISTICAS GENERALES

Parametros	C3	Unidades
Capacidades (Emax) :	3, 5, 15, 20, 30 y 40	Kg
Intervalos Max. de verificacion (Nlc):	3000	d
Sensibilidad (Cn) :	1.8 ± 0.002	mV/V
Repetibilidad, No linealidad, Histerisis	0.03	± % de la señal de salida
Efecto de temperatura en la sensibilidad (Tkc) :	0.02 / 10	± % de la señal de salida/ºC
Efecto de temperatura en el cero (tk0) :	0.02 / 10	± % de la señal de salida/ºC
Cero :	1.0	± % de la señal de salida
Resistencia de entrada (Rlc) :	400 ± 10	Ohms
Resistencia de salida (Ro) :	352 ± 2	Ohms
Resistencia de aislamiento :	≥ 5000	Mega-Ohms
Limite de sobrecarga :	150	% de la capacidad
Ruptura de celda :	200	% de la capacidad
Rango de temperatura en operación :	-30 a +70	ºC
Excitación Recomendada :	10 - 12	VDC
Maxima excitación permitida :	15	VDC
Peso aproximado:	200	g
Material :	Aluminio	
Clase de proteccion :	IP65	
Cable	Φ5mm x 1m	
Tamaño maximo de plataforma	30 x 30cm	

CONEXION



DIMENSIONES Y ESPECIFICACIONES SUJETAS A CAMBIO SIN PREVIO AVISO

Low Cost, Low Power Instrumentation Amplifier

AD620

FEATURES
EASY TO USE
Gain Set with One External Resistor
(Gain Range 1 to 1000)
Wide Power Supply Range (±2.3 V to ±18 V)
Higher Performance than Three Op Amp IA Designs
Available in 8-Lead DIP and SOIC Packaging
Low Power, 1.3 mA max Supply Current

EXCELLENT DC PERFORMANCE ("B GRADE")
50 μV max, Input Offset Voltage
0.6 μV/°C max, Input Offset Drift
1.0 nA max, Input Bias Current
100 dB min Common-Mode Rejection Ratio (G = 10)

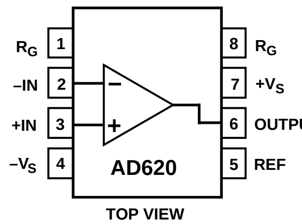
LOW NOISE
9 nV/√Hz, @ 1 kHz, Input Voltage Noise
0.28 μV p-p Noise (0.1 Hz to 10 Hz)

EXCELLENT AC SPECIFICATIONS
120 kHz Bandwidth (G = 100)
15 μs Settling Time to 0.01%

APPLICATIONS
Weigh Scales
ECG and Medical Instrumentation
Transducer Interface
Data Acquisition Systems
Industrial Process Controls
Battery Powered and Portable Equipment

CONNECTION DIAGRAM

8-Lead Plastic Mini-DIP (N), Cerdip (Q) and SOIC (R) Packages



PRODUCT DESCRIPTION

The AD620 is a low cost, high accuracy instrumentation amplifier that requires only one external resistor to set gains of 1 to 1000. Furthermore, the AD620 features 8-lead SOIC and DIP packaging that is smaller than discrete designs, and offers lower power (only 1.3 mA max supply current), making it a good fit for battery powered, portable (or remote) applications.

The AD620, with its high accuracy of 40 ppm maximum nonlinearity, low offset voltage of 50 μV max and offset drift of 0.6 μV/°C max, is ideal for use in precision data acquisition systems, such as weigh scales and transducer interfaces. Furthermore, the low noise, low input bias current, and low power of the AD620 make it well suited for medical applications such as ECG and noninvasive blood pressure monitors.

The low input bias current of 1.0 nA max is made possible with the use of Superβeta processing in the input stage. The AD620 works well as a preamplifier due to its low input voltage noise of 9 nV/√Hz at 1 kHz, 0.28 μV p-p in the 0.1 Hz to 10 Hz band, 0.1 pA/√Hz input current noise. Also, the AD620 is well suited for multiplexed applications with its settling time of 15 μs to 0.01% and its cost is low enough to enable designs with one in-amp per channel.

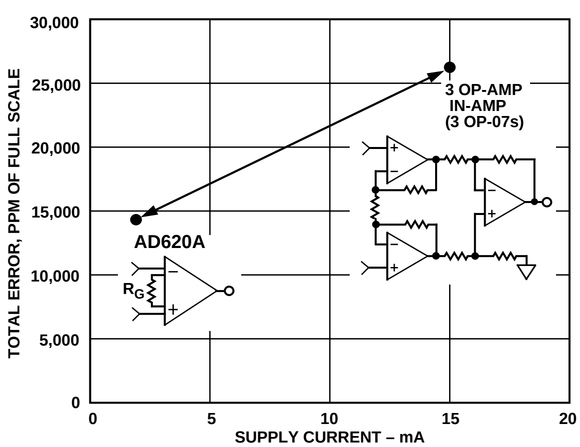


Figure 1. Three Op Amp IA Designs vs. AD620

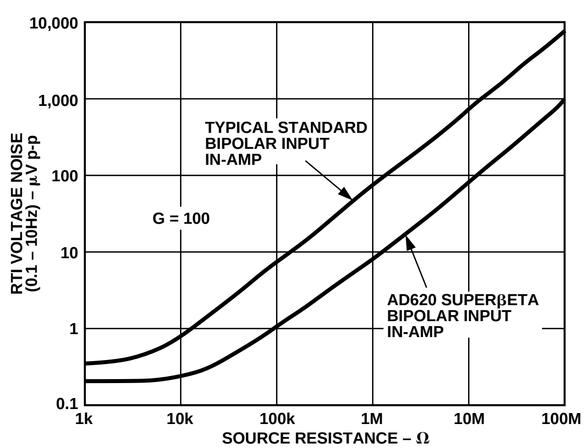


Figure 2. Total Voltage Noise vs. Source Resistance

REV. E

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
Tel: 781/329-4700 World Wide Web Site: http://www.analog.com
Fax: 781/326-8703

AD620–SPECIFICATIONS (Typical @ +25°C, V_S = ±15 V, and R_L = 2 kΩ, unless otherwise noted)

Model	Conditions	AD620A Min	AD620A Typ	AD620A Max	AD620B Min	AD620B Typ	AD620B Max	AD620S[1] Min	AD620S[1] Typ	AD620S[1] Max	Units
GAIN	G = 1 + (49.4 k/R_G)										
Gain Range		1		10,000	1		10,000	1		10,000	
Gain Error[2]	V_{OUT} = ±10 V										
G = 1			0.03	0.10		0.01	0.02		0.03	0.10	%
G = 10			0.15	0.30		0.10	0.15		0.15	0.30	%
G = 100			0.15	0.30		0.10	0.15		0.15	0.30	%
G = 1000			0.40	0.70		0.35	0.50		0.40	0.70	%
Nonlinearity,	V_{OUT} = –10 V to +10 V,										
G = 1–1000	R_L = 10 kΩ		10	40		10	40		10	40	ppm
G = 1–100	R_L = 2 kΩ		10	95		10	95		10	95	ppm
Gain vs. Temperature											
	G =1			10			10			10	ppm/°C
	Gain >1[2]			–50			–50			–50	ppm/°C
VOLTAGE OFFSET	(Total RTI Error = V_{OSI} + V_{OSO}/G)										
Input Offset, V_{OSI}	V_S = ±5 V to ±15 V		30	125		15	50		30	125	µV
Over Temperature	V_S = ±5 V to ±15 V			185			85			225	µV
Average TC	V_S = ±5 V to ±15 V		0.3	1.0		0.1	0.6		0.3	1.0	µV/°C
Output Offset, V_{OSO}	V_S = ±15 V		400	1000		200	500		400	1000	µV
	V_S = ±5 V			1500			750			1500	µV
Over Temperature	V_S = ±5 V to ±15 V			2000			1000			2000	µV
Average TC	V_S = ±5 V to ±15 V		5.0	15		2.5	7.0		5.0	15	µV/°C
Offset Referred to the Input vs. Supply (PSR)	V_S = ±2.3 V to ±18 V										
G = 1		80	100		80	100		80	100		dB
G = 10		95	120		100	120		95	120		dB
G = 100		110	140		120	140		110	140		dB
G = 1000		110	140		120	140		110	140		dB
INPUT CURRENT											
Input Bias Current			0.5	2.0		0.5	1.0		0.5	2	nA
Over Temperature				2.5			1.5			4	nA
Average TC			3.0			3.0			8.0		pA/°C
Input Offset Current			0.3	1.0		0.3	0.5		0.3	1.0	nA
Over Temperature				1.5			0.75			2.0	nA
Average TC			1.5			1.5			8.0		pA/°C
INPUT											
Input Impedance											
Differential			10‖2			10‖2			10‖2		GΩ‖pF
Common-Mode			10‖2			10‖2			10‖2		GΩ‖pF
Input Voltage Range[3]	V_S = ±2.3 V to ±5 V	$-V_S + 1.9$		$+V_S - 1.2$	$-V_S + 1.9$		$+V_S - 1.2$	$-V_S + 1.9$		$+V_S - 1.2$	V
Over Temperature		$-V_S + 2.1$		$+V_S - 1.3$	$-V_S + 2.1$		$+V_S - 1.3$	$-V_S + 2.1$		$+V_S - 1.3$	V
	V_S = ±5 V to ±18 V	$-V_S + 1.9$		$+V_S - 1.4$	$-V_S + 1.9$		$+V_S - 1.4$	$-V_S + 1.9$		$+V_S - 1.4$	V
Over Temperature		$-V_S + 2.1$		$+V_S - 1.4$	$-V_S + 2.1$		$+V_S - 1.4$	$-V_S + 2.3$		$+V_S - 1.4$	V
Common-Mode Rejection Ratio DC to 60 Hz with I kΩ Source Imbalance	V_{CM} = 0 V to ±10 V										
G = 1		73	90		80	90		73	90		dB
G = 10		93	110		100	110		93	110		dB
G = 100		110	130		120	130		110	130		dB
G = 1000		110	130		120	130		110	130		dB
OUTPUT											
Output Swing	R_L = 10 kΩ, V_S = ±2.3 V to ±5 V	$-V_S + 1.1$		$+V_S - 1.2$	$-V_S + 1.1$		$+V_S - 1.2$	$-V_S + 1.1$		$+V_S - 1.2$	V
Over Temperature		$-V_S + 1.4$		$+V_S - 1.3$	$-V_S + 1.4$		$+V_S - 1.3$	$-V_S + 1.6$		$+V_S - 1.3$	V
	V_S = ±5 V to ±18 V	$-V_S + 1.2$		$+V_S - 1.4$	$-V_S + 1.2$		$+V_S - 1.4$	$-V_S + 1.2$		$+V_S - 1.4$	V
Over Temperature		$-V_S + 1.6$		$+V_S - 1.5$	$-V_S + 1.6$		$+V_S - 1.5$	$-V_S + 2.3$		$+V_S - 1.5$	V
Short Current Circuit			±18			±18			±18		mA

Model	Conditions	AD620A Min	AD620A Typ	AD620A Max	AD620B Min	AD620B Typ	AD620B Max	AD620S[1] Min	AD620S[1] Typ	AD620S[1] Max	Units
DYNAMIC RESPONSE											
Small Signal –3 dB Bandwidth											
G = 1			1000			1000			1000		kHz
G = 10			800			800			800		kHz
G = 100			120			120			120		kHz
G = 1000			12			12			12		kHz
Slew Rate		0.75	1.2		0.75	1.2		0.75	1.2		V/µs
Settling Time to 0.01%	10 V Step										
G = 1–100			15			15			15		µs
G = 1000			150			150			150		µs
NOISE											
Voltage Noise, 1 kHz	$Total\ RTI\ Noise = \sqrt{(e^2_{ni}) + (e_{no}/G)^2}$										
Input, Voltage Noise, e_{ni}			9	13		9	13		9	13	$nV/\sqrt{Hz}$
Output, Voltage Noise, e_{no}			72	100		72	100		72	100	$nV/\sqrt{Hz}$
RTI, 0.1 Hz to 10 Hz											
G = 1			3.0			3.0	6.0		3.0	6.0	µV p-p
G = 10			0.55			0.55	0.8		0.55	0.8	µV p-p
G = 100–1000			0.28			0.28	0.4		0.28	0.4	µV p-p
Current Noise	f = 1 kHz		100			100			100		$fA/\sqrt{Hz}$
0.1 Hz to 10 Hz			10			10			10		pA p-p
REFERENCE INPUT											
R_{IN}			20			20			20		kΩ
I_{IN}	V_{IN+}, V_{REF} = 0		+50	+60		+50	+60		+50	+60	µA
Voltage Range		$-V_S + 1.6$		$+V_S - 1.6$	$-V_S + 1.6$		$+V_S - 1.6$	$-V_S + 1.6$		$+V_S - 1.6$	V
Gain to Output			1 ± 0.0001			1 ± 0.0001			1 ± 0.0001		
POWER SUPPLY											
Operating Range[4]		±2.3		±18	±2.3		±18	±2.3		±18	V
Quiescent Current	V_S = ±2.3 V to ±18 V		0.9	1.3		0.9	1.3		0.9	1.3	mA
Over Temperature			1.1	1.6		1.1	1.6		1.1	1.6	mA
TEMPERATURE RANGE											
For Specified Performance			–40 to +85			–40 to +85			–55 to +125		°C

NOTES

[1]See Analog Devices military data sheet for 883B tested specifications.

[2]Does not include effects of external resistor R_G.

[3]One input grounded. G = 1.

[4]This is defined as the same supply range which is used to specify PSR.

Specifications subject to change without notice.

ABSOLUTE MAXIMUM RATINGS[1]

Supply Voltage . . . . ±18 V
Internal Power Dissipation[2] . . . . 650 mW
Input Voltage (Common Mode) . . . . ±V_S
Differential Input Voltage . . . . ±25 V
Output Short Circuit Duration . . . . Indefinite
Storage Temperature Range (Q) . . . . –65°C to +150°C
Storage Temperature Range (N, R) . . . . –65°C to +125°C
Operating Temperature Range
  AD620 (A, B) . . . . –40°C to +85°C
  AD620 (S) . . . . –55°C to +125°C
Lead Temperature Range
  (Soldering 10 seconds) . . . . +300°C

NOTES

[1]Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other conditions above those indicated in the operational section of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

[2]Specification is for device in free air:
8-Lead Plastic Package: θ_{JA} = 95°C/W
8-Lead Cerdip Package: θ_{JA} = 110°C/W
8-Lead SOIC Package: θ_{JA} = 155°C/W

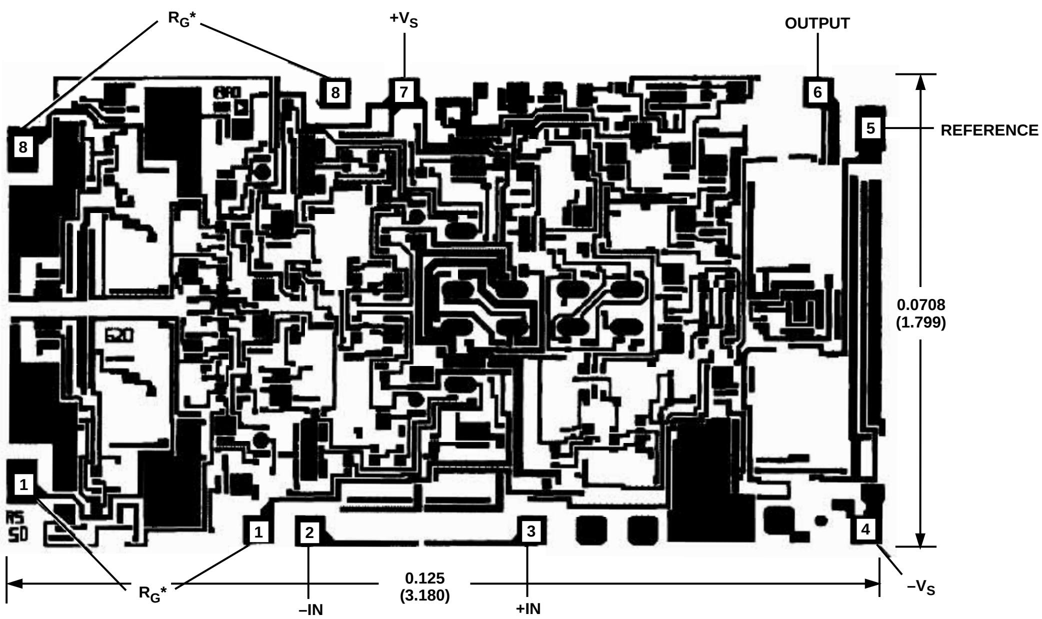
ORDERING GUIDE

Model	Temperature Ranges	Package Options*
AD620AN	–40°C to +85°C	N-8
AD620BN	–40°C to +85°C	N-8
AD620AR	–40°C to +85°C	SO-8
AD620AR-REEL	–40°C to +85°C	13" REEL
AD620AR-REEL7	–40°C to +85°C	7" REEL
AD620BR	–40°C to +85°C	SO-8
AD620BR-REEL	–40°C to +85°C	13" REEL
AD620BR-REEL7	–40°C to +85°C	7" REEL
AD620ACHIPS	–40°C to +85°C	Die Form
AD620SQ/883B	–55°C to +125°C	Q-8

*N = Plastic DIP; Q = Cerdip; SO = Small Outline.

METALIZATION PHOTOGRAPH

Dimensions shown in inches and (mm).
Contact factory for latest dimensions.



*FOR CHIP APPLICATIONS: THE PADS $1R_G$ AND $8R_G$ MUST BE CONNECTED IN PARALLEL TO THE EXTERNAL GAIN REGISTER R_G. DO NOT CONNECT THEM IN SERIES TO R_G. FOR UNITY GAIN APPLICATIONS WHERE R_G IS NOT REQUIRED, THE PADS $1R_G$ MAY SIMPLY BE BONDED TOGETHER, AS WELL AS THE PADS $8R_G$.

CAUTION

ESD (electrostatic discharge) sensitive device. Electrostatic charges as high as 4000 V readily accumulate on the human body and test equipment and can discharge without detection. Although the AD620 features proprietary ESD protection circuitry, permanent damage may occur on devices subjected to high energy electrostatic discharges. Therefore, proper ESD precautions are recommended to avoid performance degradation or loss of functionality.

Typical Characteristics (@ +25°C, V_S = ±15 V, R_L = 2 kΩ, unless otherwise noted)

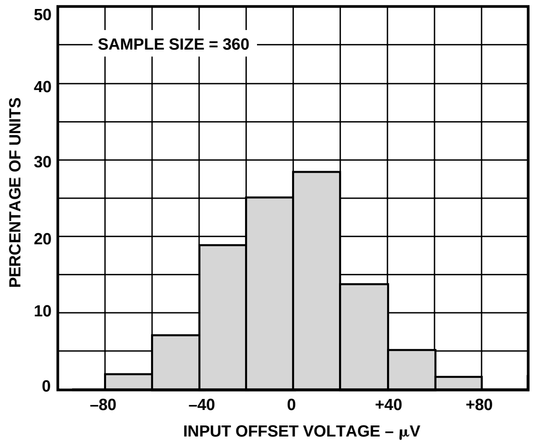


Figure 3. Typical Distribution of Input Offset Voltage

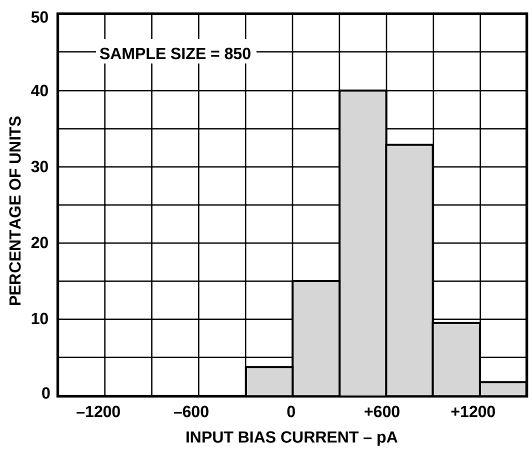


Figure 4. Typical Distribution of Input Bias Current

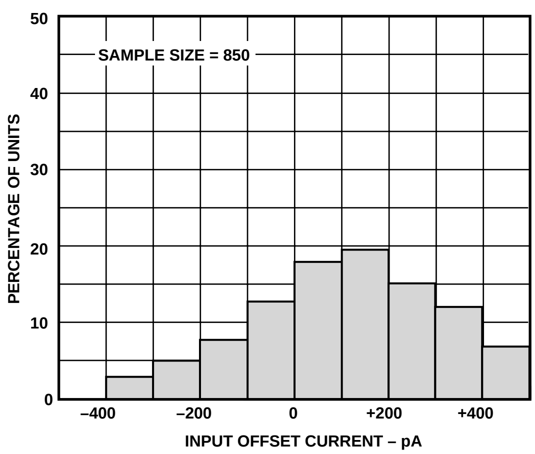


Figure 5. Typical Distribution of Input Offset Current

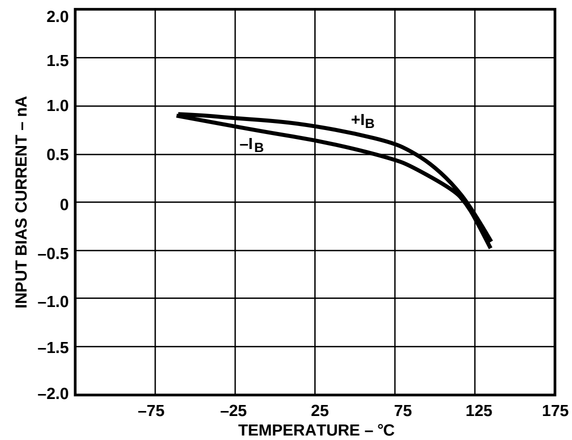


Figure 6. Input Bias Current vs. Temperature

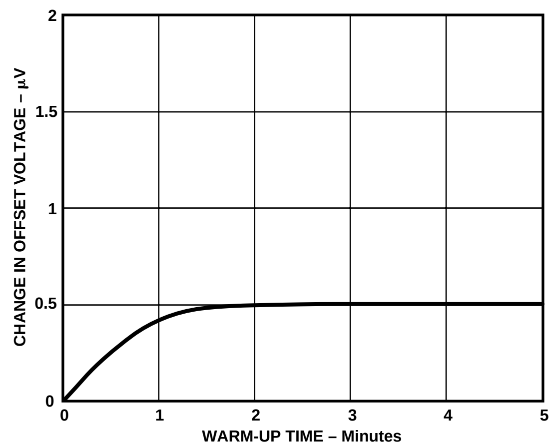


Figure 7. Change in Input Offset Voltage vs. Warm-Up Time

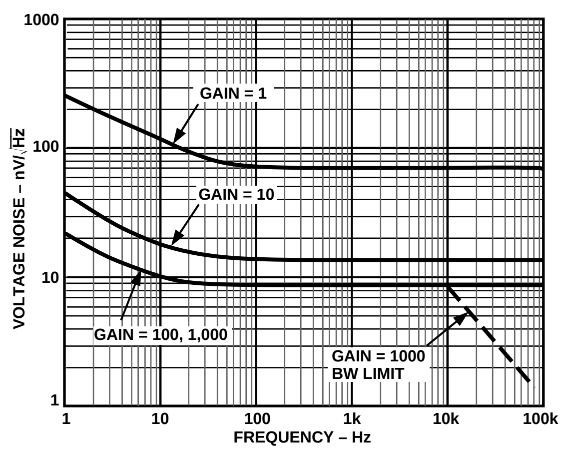


Figure 8. Voltage Noise Spectral Density vs. Frequency, (G = 1–1000)

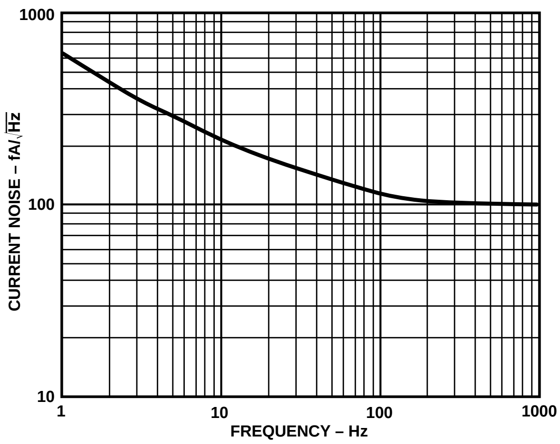


Figure 9. Current Noise Spectral Density vs. Frequency

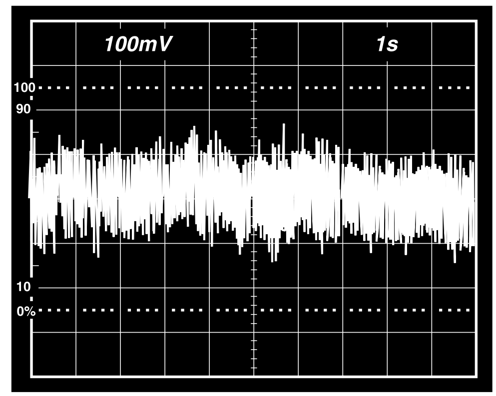


Figure 11. 0.1 Hz to 10 Hz Current Noise, 5 pA/Div

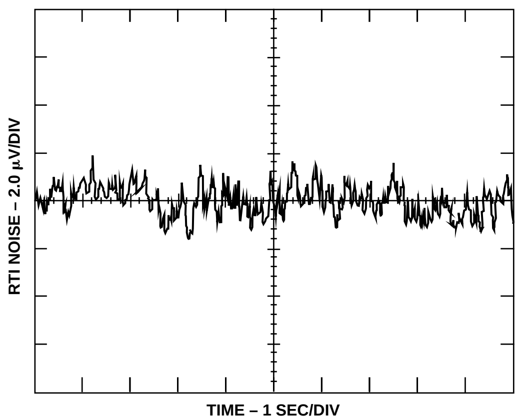


Figure 10a. 0.1 Hz to 10 Hz RTI Voltage Noise (G = 1)

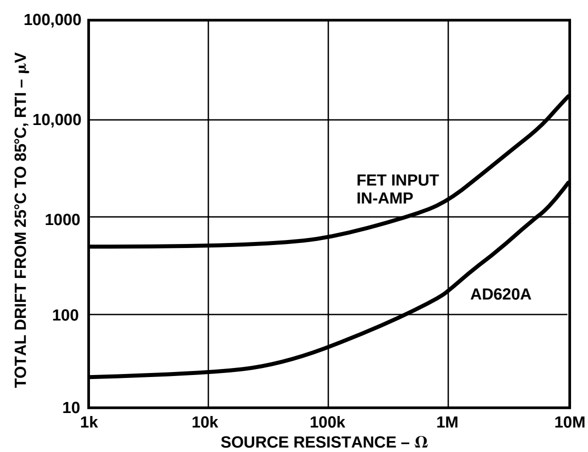


Figure 12. Total Drift vs. Source Resistance

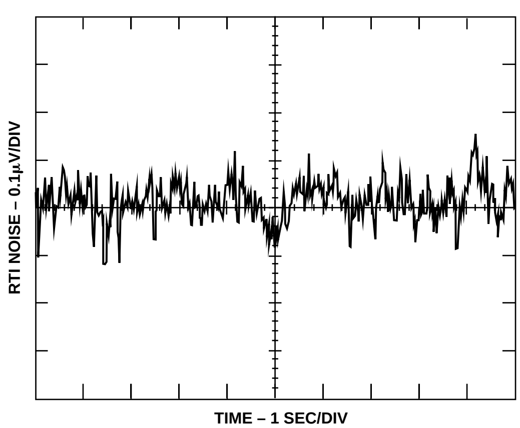


Figure 10b. 0.1 Hz to 10 Hz RTI Voltage Noise (G = 1000)

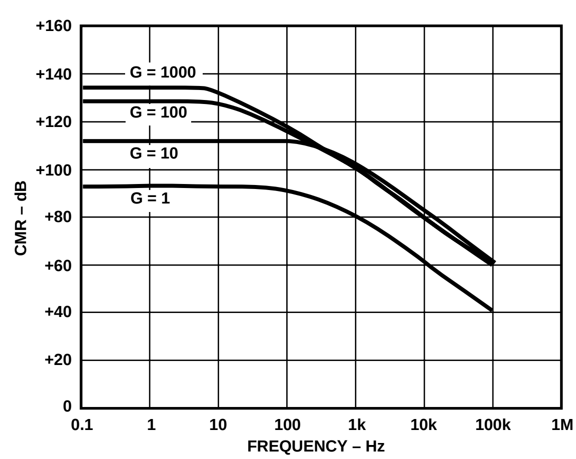


Figure 13. CMR vs. Frequency, RTI, Zero to 1 kΩ Source Imbalance

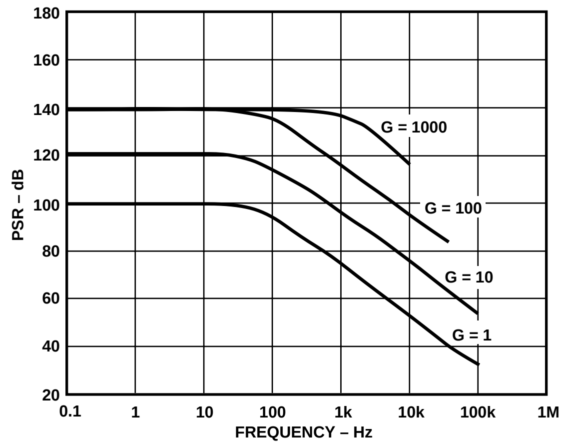


Figure 14. Positive PSR vs. Frequency, RTI (G = 1–1000)

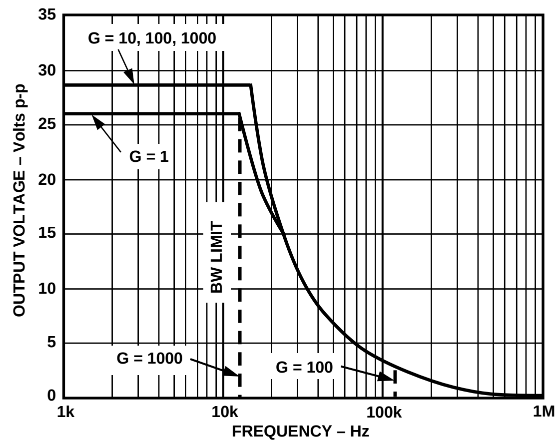


Figure 17. Large Signal Frequency Response

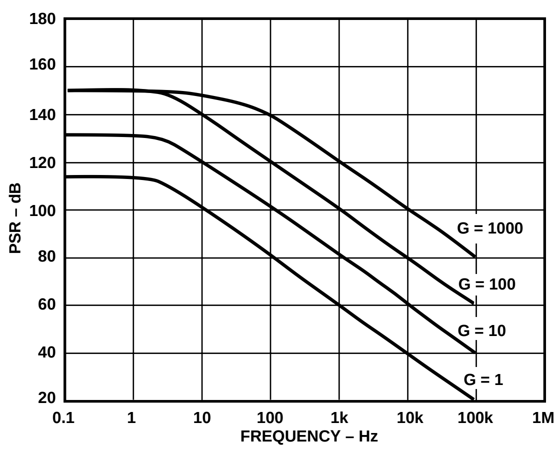


Figure 15. Negative PSR vs. Frequency, RTI (G = 1–1000)

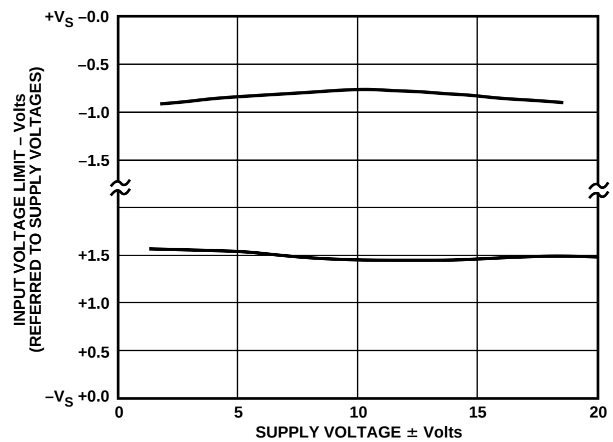


Figure 18. Input Voltage Range vs. Supply Voltage, G = 1

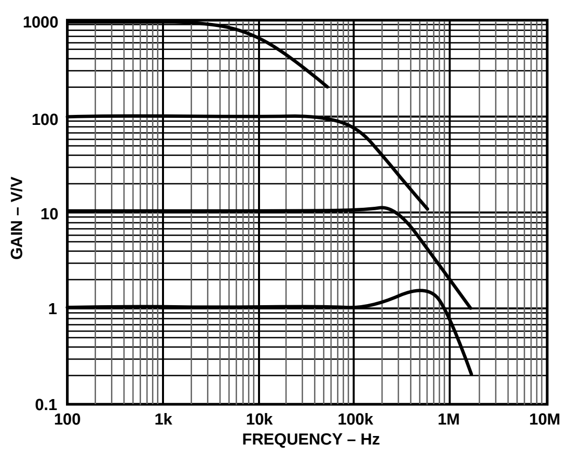


Figure 16. Gain vs. Frequency

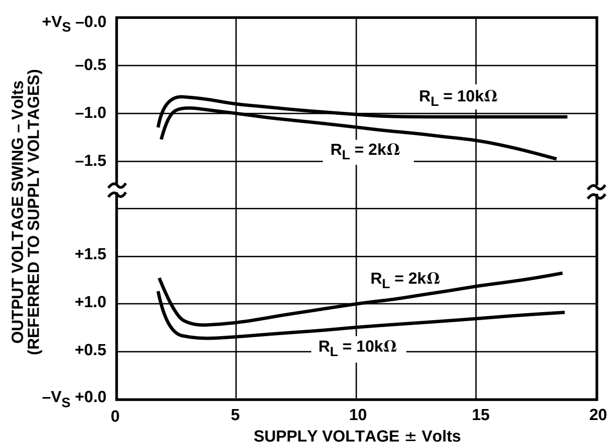


Figure 19. Output Voltage Swing vs. Supply Voltage, G = 10

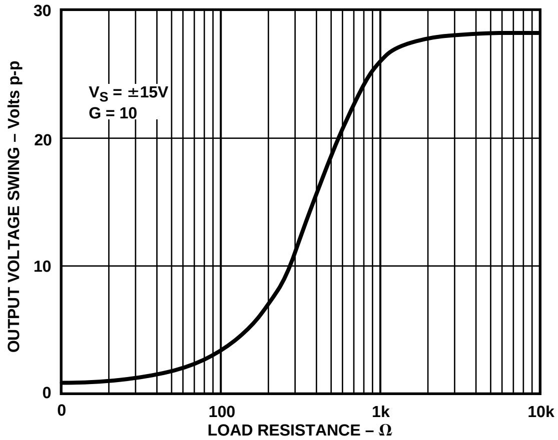


Figure 20. Output Voltage Swing vs. Load Resistance

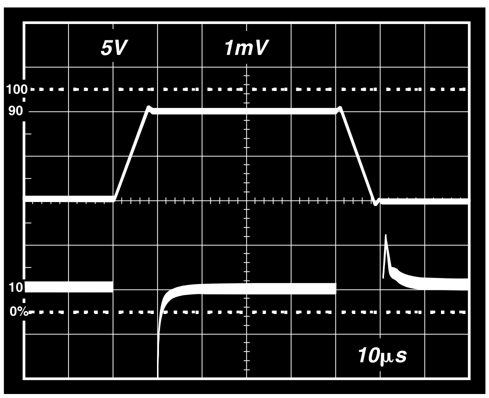


Figure 21. Large Signal Pulse Response and Settling Time G = 1 (0.5 mV = 0.01%)

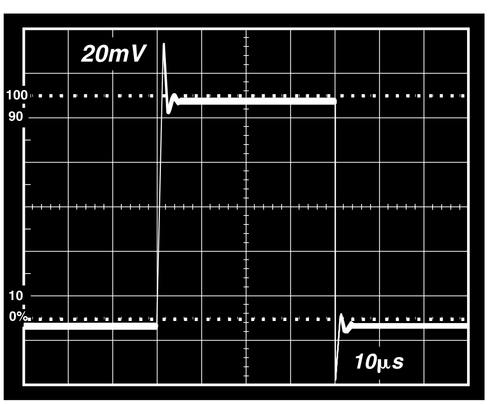


Figure 22. Small Signal Response, G = 1, R_L = 2 kΩ, C_L = 100 pF

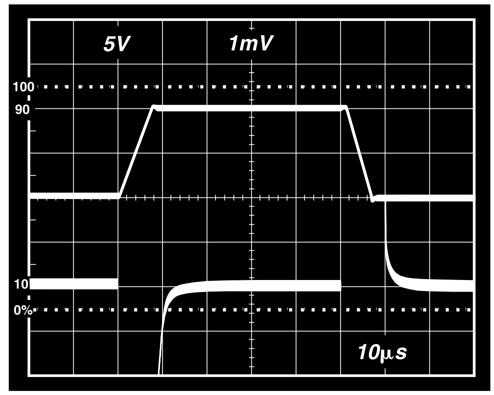


Figure 23. Large Signal Response and Settling Time, G = 10 (0.5 mV = 001%)

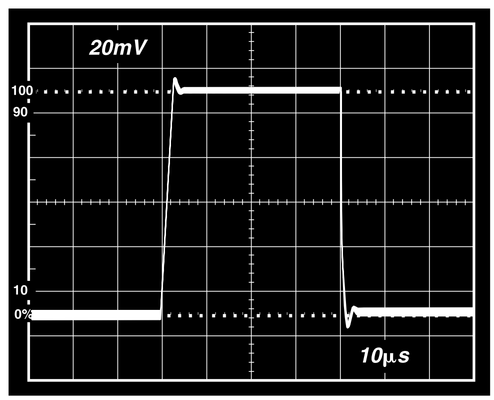


Figure 24. Small Signal Response, G = 10, R_L = 2 kΩ, C_L = 100 pF

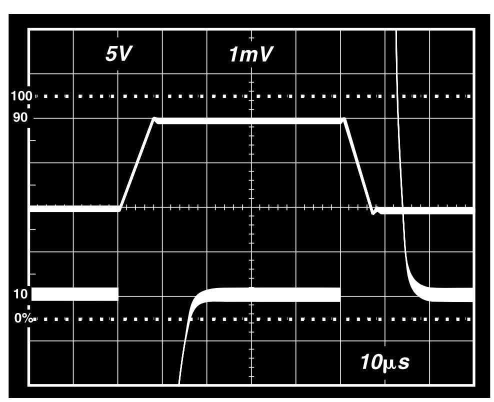


Figure 25. Large Signal Response and Settling Time, G = 100 (0.5 mV = 0.01%)

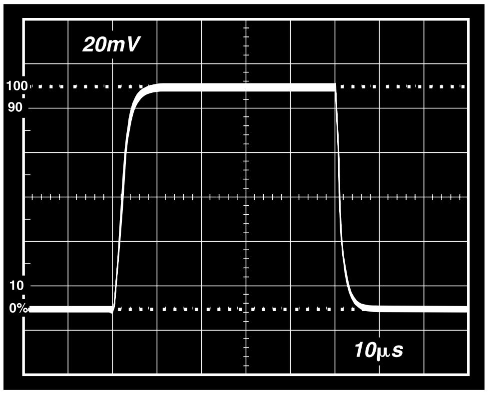


Figure 26. Small Signal Pulse Response, G = 100, R_L = 2 kΩ, C_L = 100 pF

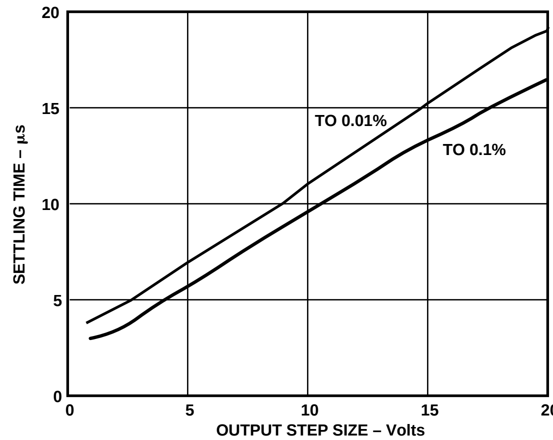


Figure 29. Settling Time vs. Step Size (G = 1)

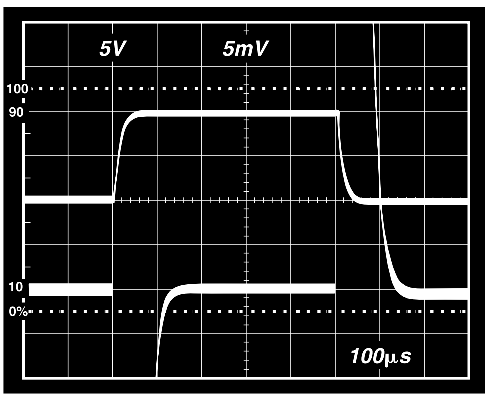


Figure 27. Large Signal Response and Settling Time, G = 1000 (0.5 mV = 0.01%)

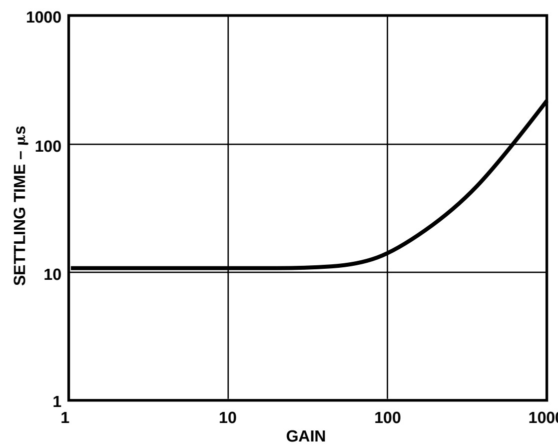


Figure 30. Settling Time to 0.01% vs. Gain, for a 10 V Step

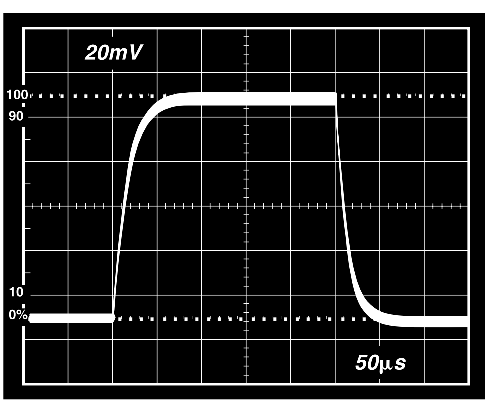


Figure 28. Small Signal Pulse Response, G = 1000, R_L = 2 kΩ, C_L = 100 pF

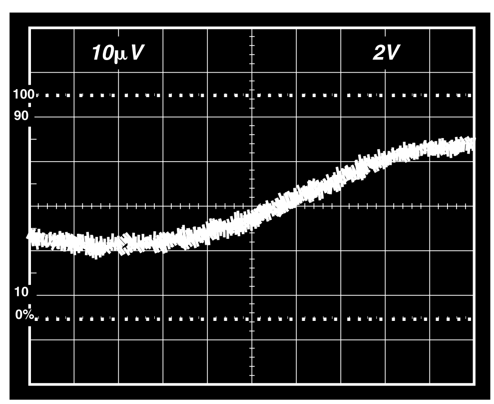


Figure 31a. Gain Nonlinearity, G = 1, R_L = 10 kΩ (10 μV = 1 ppm)

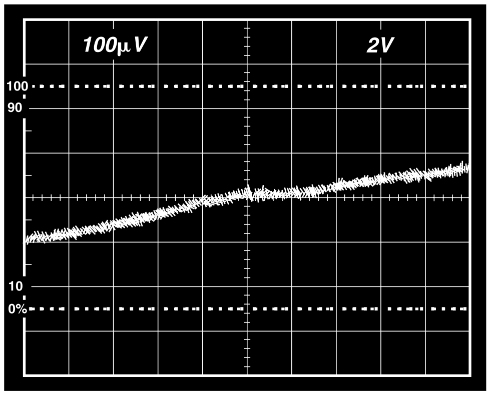


Figure 31b. Gain Nonlinearity, G = 100, R_L = 10 kΩ (100 µV = 10 ppm)

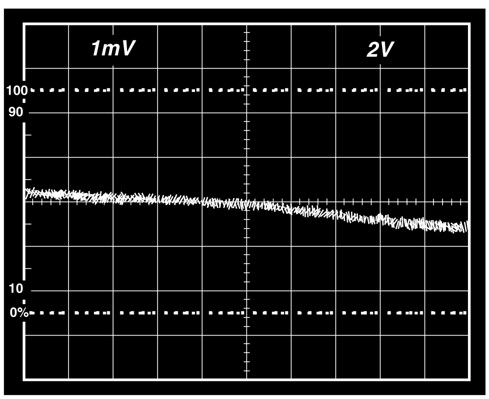


Figure 31c. Gain Nonlinearity, G = 1000, R_L = 10 kΩ (1 mV = 100 ppm)

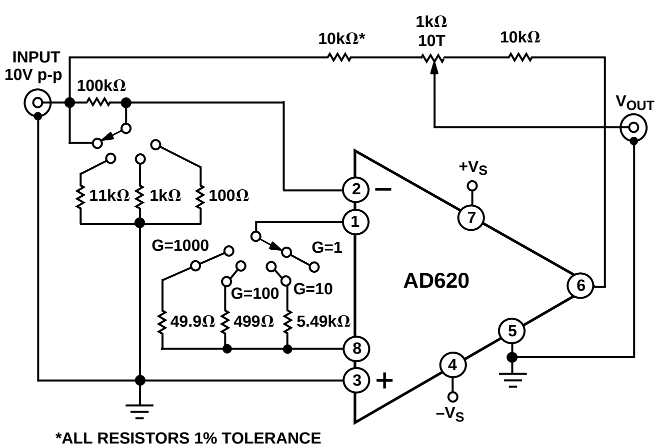


Figure 32. Settling Time Test Circuit

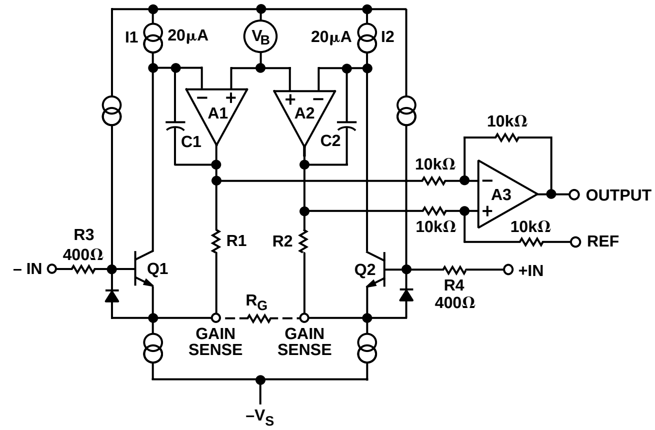


Figure 33. Simplified Schematic of AD620

THEORY OF OPERATION

The AD620 is a monolithic instrumentation amplifier based on a modification of the classic three op amp approach. Absolute value trimming allows the user to program gain *accurately* (to 0.15% at G = 100) with only one resistor. Monolithic construction and laser wafer trimming allow the tight matching and tracking of circuit components, thus ensuring the high level of performance inherent in this circuit.

The input transistors Q1 and Q2 provide a single differential-pair bipolar input for high precision (Figure 33), yet offer 10× lower Input Bias Current thanks to Superβeta processing. Feedback through the Q1-A1-R1 loop and the Q2-A2-R2 loop maintains constant collector current of the input devices Q1, Q2 thereby impressing the input voltage across the external gain setting resistor R_G. This creates a differential gain from the inputs to the A1/A2 outputs given by $G = (R1 + R2)/R_G + 1$. The unity-gain subtracter A3 removes any common-mode signal, yielding a single-ended output referred to the REF pin potential.

The value of R_G also determines the transconductance of the preamp stage. As R_G is reduced for larger gains, the transconductance increases asymptotically to that of the input transistors. This has three important advantages: (a) Open-loop gain is boosted for increasing programmed gain, thus reducing gain-related errors. (b) The gain-bandwidth product (determined by C1, C2 and the preamp transconductance) increases with programmed gain, thus optimizing frequency response. (c) The input voltage noise is reduced to a value of 9 nV/$\sqrt{Hz}$, determined mainly by the collector current and base resistance of the input devices.

The internal gain resistors, R1 and R2, are trimmed to an absolute value of 24.7 kΩ, allowing the gain to be programmed accurately with a single external resistor.

The gain equation is then

$$G = \frac{49.4\ k\Omega}{R_G} + 1$$

so that

$$R_G = \frac{49.4\ k\Omega}{G - 1}$$

Make vs. Buy: A Typical Bridge Application Error Budget

The AD620 offers improved performance over "homebrew" three op amp IA designs, along with smaller size, fewer components and 10× lower supply current. In the typical application, shown in Figure 34, a gain of 100 is required to amplify a bridge output of 20 mV full scale over the industrial temperature range of –40°C to +85°C. The error budget table below shows how to calculate the effect various error sources have on circuit accuracy.

Regardless of the system in which it is being used, the AD620 provides greater accuracy, and at low power and price. In simple systems, absolute accuracy and drift errors are by far the most significant contributors to error. In more complex systems with an intelligent processor, an autogain/autozero cycle will remove all absolute accuracy and drift errors leaving only the resolution errors of gain nonlinearity and noise, thus allowing full 14-bit accuracy.

Note that for the homebrew circuit, the OP07 specifications for input voltage offset and noise have been multiplied by $\sqrt{2}$. This is because a three op amp type in-amp has two op amps at its inputs, both contributing to the overall input error.

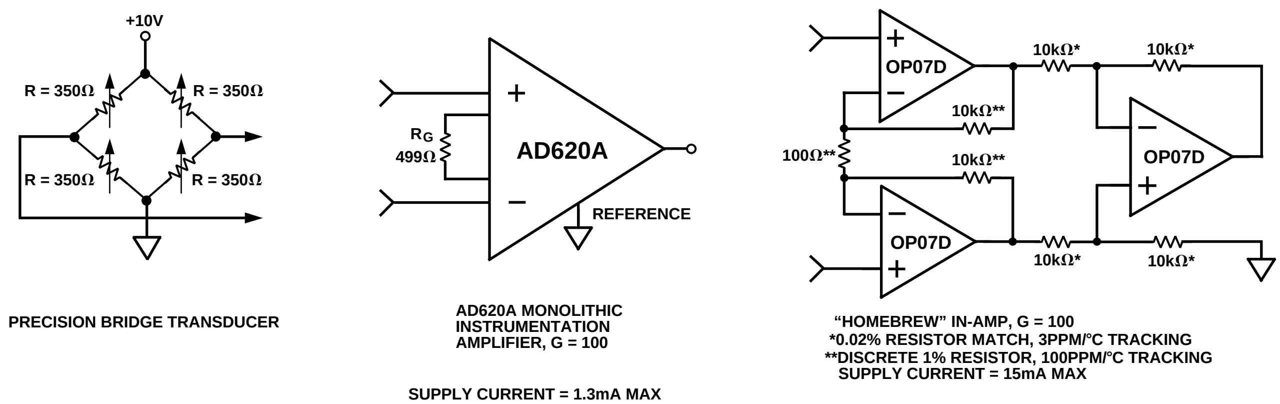


Figure 34. Make vs. Buy

Table I. Make vs. Buy Error Budget

Error Source	AD620 Circuit Calculation	"Homebrew" Circuit Calculation	Error, ppm of Full Scale AD620	Error, ppm of Full Scale Homebrew
ABSOLUTE ACCURACY at T_A = +25°C				
Input Offset Voltage, µV	125 µV/20 mV	(150 µV × $\sqrt{2}$)/20 mV	6,250	10,607
Output Offset Voltage, µV	1000 µV/100/20 mV	((150 µV × 2)/100)/20 mV	500	150
Input Offset Current, nA	2 nA × 350 Ω/20 mV	(6 nA × 350 Ω)/20 mV	18	53
CMR, dB	110 dB→3.16 ppm, × 5 V/20 mV	(0.02% Match × 5 V)/20 mV/100	791	500
		Total Absolute Error	7,558	11,310
DRIFT TO +85°C				
Gain Drift, ppm/°C	(50 ppm + 10 ppm) × 60°C	100 ppm/°C Track × 60°C	3,600	6,000
Input Offset Voltage Drift, µV/°C	1 µV/°C × 60°C/20 mV	(2.5 µV/°C × $\sqrt{2}$ × 60°C)/20 mV	3,000	10,607
Output Offset Voltage Drift, µV/°C	15 µV/°C × 60°C/100/20 mV	(2.5 µV/°C × 2 × 60°C)/100/20 mV	450	150
		Total Drift Error	7,050	16,757
RESOLUTION				
Gain Nonlinearity, ppm of Full Scale	40 ppm	40 ppm	40	40
Typ 0.1 Hz–10 Hz Voltage Noise, µV p-p	0.28 µV p-p/20 mV	(0.38 µV p-p × $\sqrt{2}$)/20 mV	14	27
		Total Resolution Error	54	67
		Grand Total Error	14,662	28,134

G = 100, V_S = ±15 V.

(All errors are min/max and referred to input.)

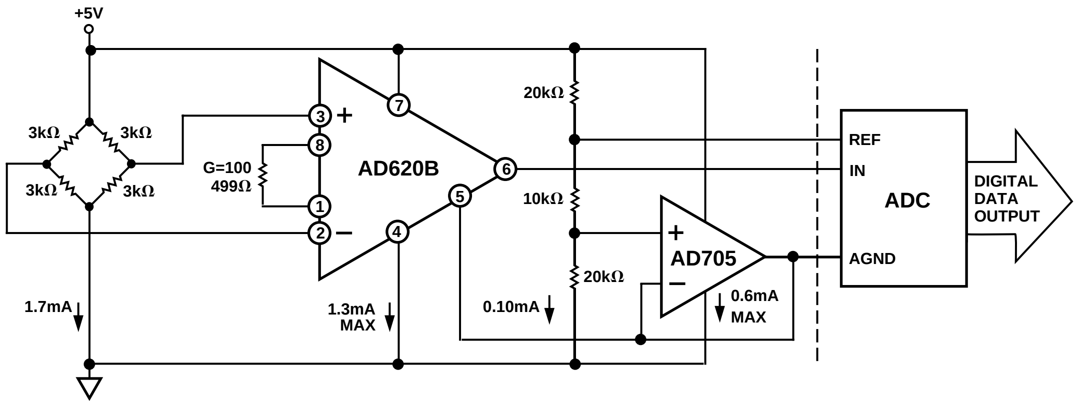


Figure 35. A Pressure Monitor Circuit which Operates on a +5 V Single Supply

Pressure Measurement

Although useful in many bridge applications such as weigh scales, the AD620 is especially suitable for higher resistance pressure sensors powered at lower voltages where small size and low power become more significant.

Figure 35 shows a 3 kΩ pressure transducer bridge powered from +5 V. In such a circuit, the bridge consumes only 1.7 mA. Adding the AD620 and a buffered voltage divider allows the signal to be conditioned for only 3.8 mA of total supply current.

Small size and low cost make the AD620 especially attractive for voltage output pressure transducers. Since it delivers low noise and drift, it will also serve applications such as diagnostic non-invasive blood pressure measurement.

Medical ECG

The low current noise of the AD620 allows its use in ECG monitors (Figure 36) where high source resistances of 1 MΩ or higher are not uncommon. The AD620's low power, low supply voltage requirements, and space-saving 8-lead mini-DIP and SOIC package offerings make it an excellent choice for battery powered data recorders.

Furthermore, the low bias currents and low current noise coupled with the low voltage noise of the AD620 improve the dynamic range for better performance.

The value of capacitor C1 is chosen to maintain stability of the right leg drive loop. Proper safeguards, such as isolation, must be added to this circuit to protect the patient from possible harm.

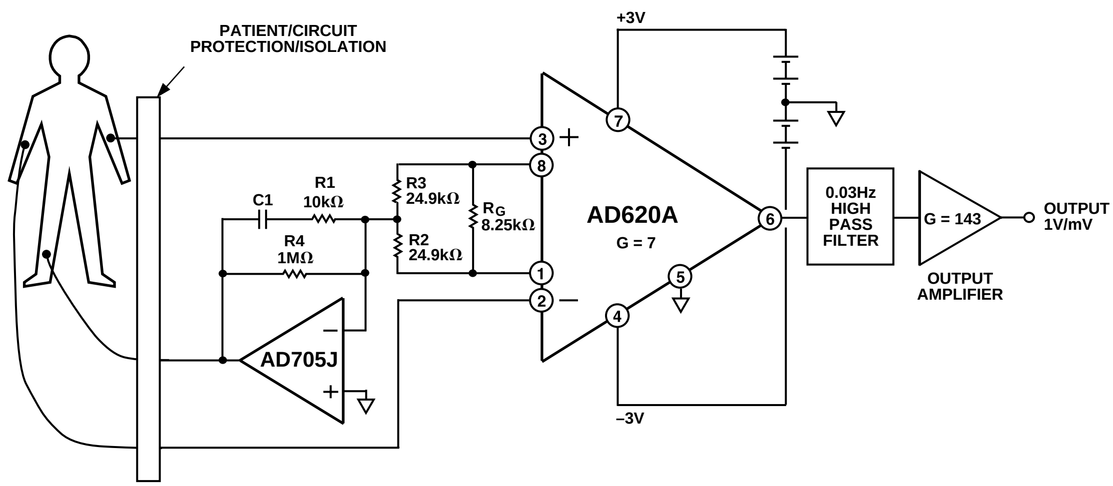


Figure 36. A Medical ECG Monitor Circuit

Precision V-I Converter

The AD620, along with another op amp and two resistors, makes a precision current source (Figure 37). The op amp buffers the reference terminal to maintain good CMR. The output voltage V_X of the AD620 appears across R1, which converts it to a current. This current less only, the input bias current of the op amp, then flows out to the load.

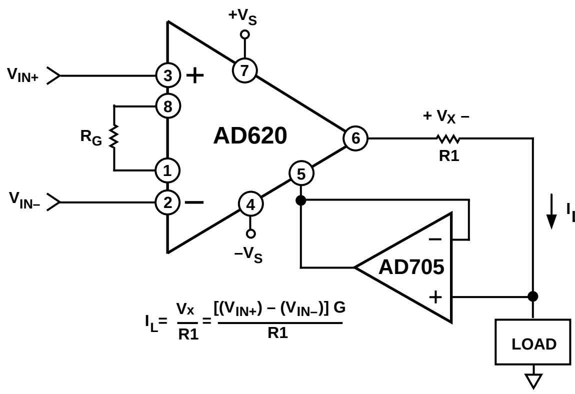


Figure 37. Precision Voltage-to-Current Converter (Operates on 1.8 mA, ±3 V)

GAIN SELECTION

The AD620's gain is resistor programmed by R_G, or more precisely, by whatever impedance appears between Pins 1 and 8. The AD620 is designed to offer accurate gains using 0.1%–1% resistors. Table II shows required values of R_G for various gains. Note that for G = 1, the R_G pins are unconnected ($R_G = \infty$). For any arbitrary gain R_G can be calculated by using the formula:

$$R_G = \frac{49.4\ k\Omega}{G-1}$$

To minimize gain error, avoid high parasitic resistance in series with R_G; to minimize gain drift, R_G should have a low TC—less than 10 ppm/°C—for the best performance.

Table II. Required Values of Gain Resistors

1% Std Table Value of R_G, Ω	Calculated Gain	0.1% Std Table Value of R_G, Ω	Calculated Gain
49.9 k	1.990	49.3 k	2.002
12.4 k	4.984	12.4 k	4.984
5.49 k	9.998	5.49 k	9.998
2.61 k	19.93	2.61 k	19.93
1.00 k	50.40	1.01 k	49.91
499	100.0	499	100.0
249	199.4	249	199.4
100	495.0	98.8	501.0
49.9	991.0	49.3	1,003

INPUT AND OUTPUT OFFSET VOLTAGE

The low errors of the AD620 are attributed to two sources, input and output errors. The output error is divided by G when referred to the input. In practice, the input errors dominate at high gains and the output errors dominate at low gains. The total V_{OS} for a given gain is calculated as:

Total Error RTI = input error + (output error/G)

Total Error RTO = (input error × G) + output error

REFERENCE TERMINAL

The reference terminal potential defines the zero output voltage, and is especially useful when the load does not share a precise ground with the rest of the system. It provides a direct means of injecting a precise offset to the output, with an allowable range of 2 V within the supply voltages. Parasitic resistance should be kept to a minimum for optimum CMR.

INPUT PROTECTION

The AD620 features 400 Ω of series thin film resistance at its inputs, and will safely withstand input overloads of up to ±15 V or ±60 mA for several hours. This is true for all gains, and power on and off, which is particularly important since the signal source and amplifier may be powered separately. For longer time periods, the current should not exceed 6 mA ($I_{IN} \leq V_{IN}/400\ \Omega$). For input overloads beyond the supplies, clamping the inputs to the supplies (using a low leakage diode such as an FD333) will reduce the required resistance, yielding lower noise.

RF INTERFERENCE

All instrumentation amplifiers can rectify out of band signals, and when amplifying small signals, these rectified voltages act as small dc offset errors. The AD620 allows direct access to the input transistor bases and emitters enabling the user to apply some first order filtering to unwanted RF signals (Figure 38), where $RC \approx 1/(2\pi f)$ and where f ≥ the bandwidth of the AD620; C ≤ 150 pF. Matching the extraneous capacitance at Pins 1 and 8 and Pins 2 and 3 helps to maintain high CMR.

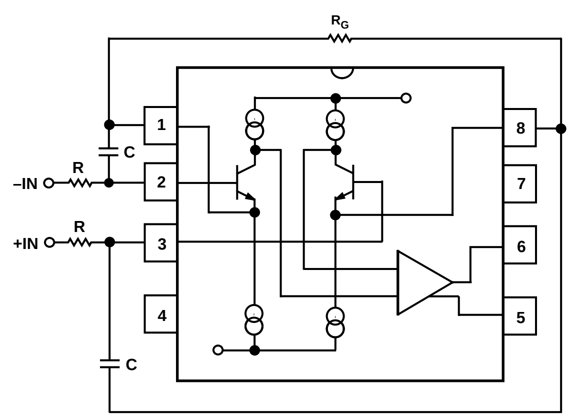


Figure 38. Circuit to Attenuate RF Interference

COMMON-MODE REJECTION

Instrumentation amplifiers like the AD620 offer high CMR, which is a measure of the change in output voltage when both inputs are changed by equal amounts. These specifications are usually given for a full-range input voltage change and a specified source imbalance.

For optimal CMR the reference terminal should be tied to a low impedance point, and differences in capacitance and resistance should be kept to a minimum between the two inputs. In many applications shielded cables are used to minimize noise, and for best CMR over frequency the shield should be properly driven. Figures 39 and 40 show active data guards that are configured to improve ac common-mode rejections by "bootstrapping" the capacitances of input cable shields, thus minimizing the capacitance mismatch between the inputs.

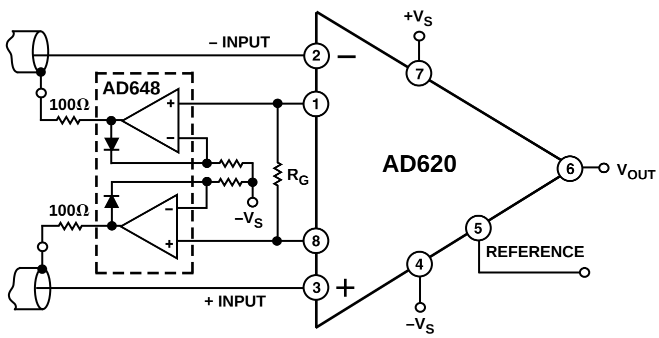


Figure 39. Differential Shield Driver

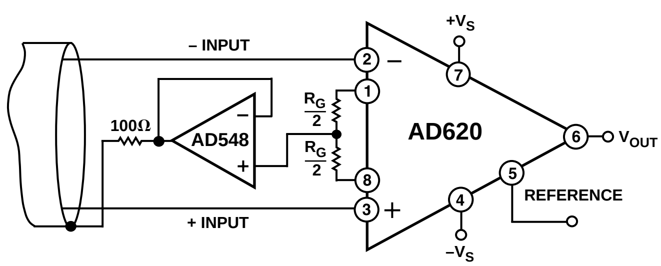


Figure 40. Common-Mode Shield Driver

GROUNDING

Since the AD620 output voltage is developed with respect to the potential on the reference terminal, it can solve many grounding problems by simply tying the REF pin to the appropriate "local ground."

In order to isolate low level analog signals from a noisy digital environment, many data-acquisition components have separate analog and digital ground pins (Figure 41). It would be convenient to use a single ground line; however, current through ground wires and PC runs of the circuit card can cause hundreds of millivolts of error. Therefore, separate ground returns should be provided to minimize the current flow from the sensitive points to the system ground. These ground returns must be tied together at some point, usually best at the ADC package as shown.

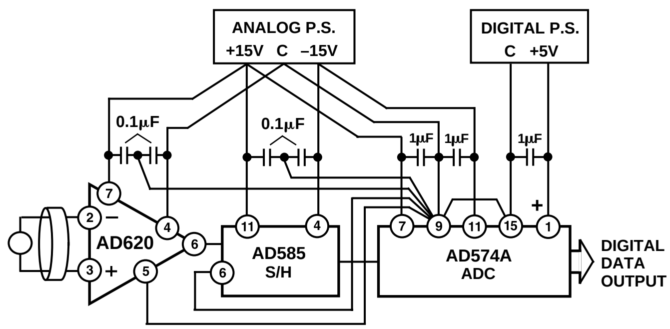


Figure 41. Basic Grounding Practice

GROUND RETURNS FOR INPUT BIAS CURRENTS

Input bias currents are those currents necessary to bias the input transistors of an amplifier. There must be a direct return path for these currents; therefore, when amplifying "floating" input sources such as transformers, or ac-coupled sources, there must be a dc path from each input to ground as shown in Figure 42. Refer to the *Instrumentation Amplifier Application Guide* (free from Analog Devices) for more information regarding in amp applications.

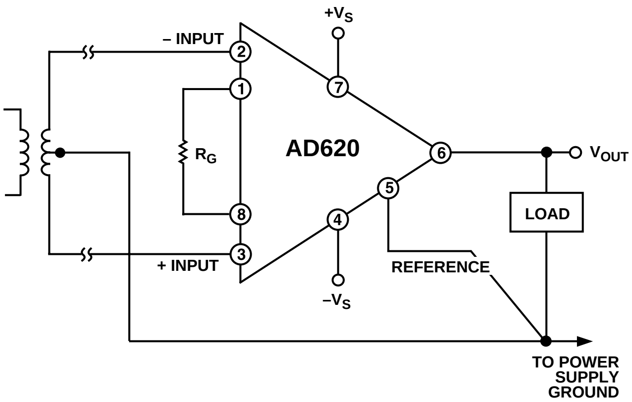


Figure 42a. Ground Returns for Bias Currents with Transformer Coupled Inputs

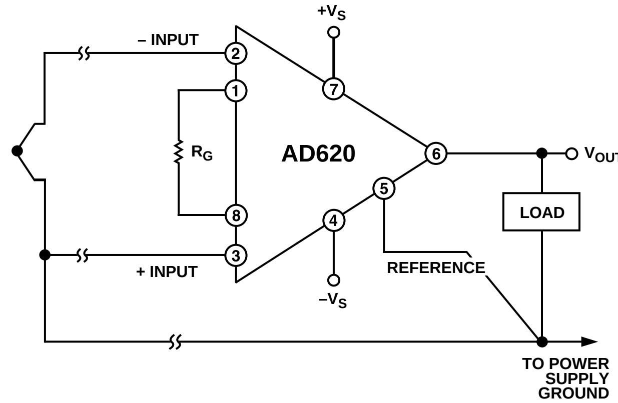


Figure 42b. Ground Returns for Bias Currents with Thermocouple Inputs

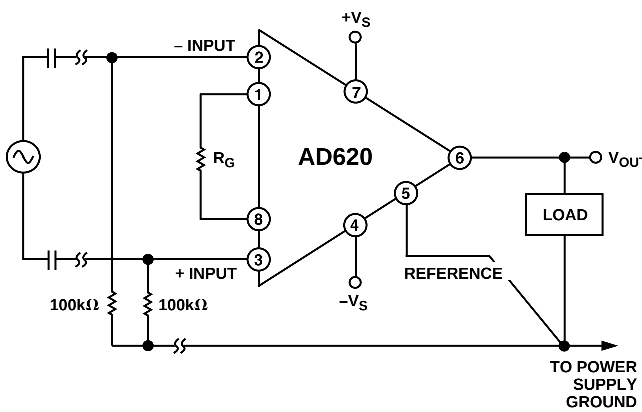
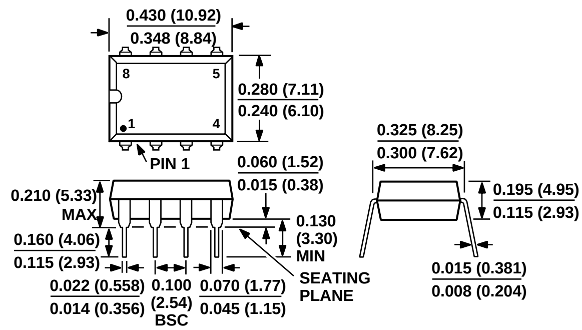


Figure 42c. Ground Returns for Bias Currents with AC Coupled Inputs

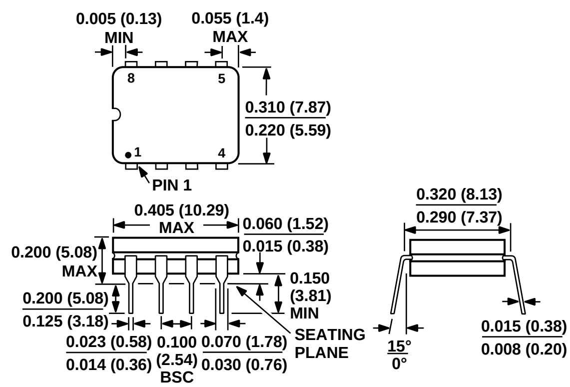
OUTLINE DIMENSIONS

Dimensions shown in inches and (mm).

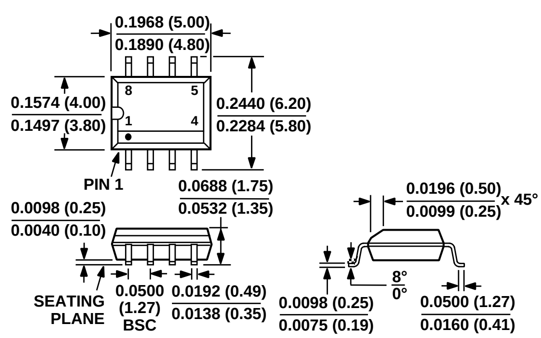
Plastic DIP (N-8) Package



Cerdip (Q-8) Package



SOIC (SO-8) Package



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XBee®/XBee-PRO® RF Modules

XBee®/XBee-PRO® RF Modules
RF Module Operation
RF Module Configuration
Appendices

Product Manual v1.xEx - 802.15.4 Protocol
For RF Module Part Numbers: XB24-A...-001, XBP24-A...-001

IEEE® 802.15.4 RF Modules by Digi International

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http://www.digi.com

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	Live Chat:	www.digi.com
	Online Support:	http://www.digi.com/support/eservice/login.jsp
	Email:	rf-experts@digi.com

Contents

1. XBee®/XBee-PRO® RF Modules

The XBee and XBee-PRO RF Modules were engineered to meet IEEE 802.15.4 standards and support the unique needs of low-cost, low-power wireless sensor networks. The modules require minimal power and provide reliable delivery of data between devices.

The modules operate within the ISM 2.4 GHz frequency band and are pin-for-pin compatible with each other.

Key Features

Long Range Data Integrity

XBee

- Indoor/Urban: up to 100’ (30 m)
- Outdoor line-of-sight: up to 300’ (90 m)
- Transmit Power: 1 mW (0 dBm)
- Receiver Sensitivity: -92 dBm

XBee-PRO

- Indoor/Urban: up to 300’ (90 m), 200' (60 m) for International variant
- Outdoor line-of-sight: up to 1 mile (1600 m), 2500' (750 m) for International variant
- Transmit Power: 63mW (18dBm), 10mW (10dBm) for International variant
- Receiver Sensitivity: -100 dBm

RF Data Rate: 250,000 bps

Advanced Networking & Security

Retries and Acknowledgements

DSSS (Direct Sequence Spread Spectrum)

Each direct sequence channels has over 65,000 unique network addresses available

Source/Destination Addressing

Unicast & Broadcast Communications

Point-to-point, point-to-multipoint and peer-to-peer topologies supported

Low Power

XBee

- TX Peak Current: 45 mA (@3.3 V)
- RX Current: 50 mA (@3.3 V)
- Power-down Current: < 10 µA

XBee-PRO

- TX Peak Current: 250mA (150mA for international variant)
- TX Peak Current (RPSMA module only): 340mA (180mA for international variant)
- RX Current: 55 mA (@3.3 V)
- Power-down Current: < 10 µA

ADC and I/O line support

Analog-to-digital conversion, Digital I/O

I/O Line Passing

Easy-to-Use

No configuration necessary for out-of box RF communications

Free X-CTU Software
(Testing and configuration software)

AT and API Command Modes for configuring module parameters

Extensive command set

Small form factor

Worldwide Acceptance

FCC Approval (USA) Refer to Appendix A [p64] for FCC Requirements.
Systems that contain XBee®/XBee-PRO® RF Modules inherit Digi Certifications.

ISM (Industrial, Scientific & Medical) **2.4 GHz frequency band**

Manufactured under **ISO 9001:2000** registered standards

XBee®/XBee-PRO® RF Modules are optimized for use in the United States, Canada, Australia, Japan, and Europe. Contact Digi for complete list of government agency approvals.

Specifications

Table 1-01. Specifications of the XBee®/XBee-PRO® RF Modules

Specification	XBee	XBee-PRO
Performance		
Indoor/Urban Range	Up to 100 ft (30 m)	Up to 300 ft. (90 m), up to 200 ft (60 m) International variant
Outdoor RF line-of-sight Range	Up to 300 ft (90 m)	Up to 1 mile (1600 m), up to 2500 ft (750 m) international variant
Transmit Power Output (software selectable)	1mW (0 dBm)	63mW (18dBm)* 10mW (10 dBm) for International variant
RF Data Rate	250,000 bps	250,000 bps
Serial Interface Data Rate (software selectable)	1200 bps - 250 kbps (non-standard baud rates also supported)	1200 bps - 250 kbps (non-standard baud rates also supported)
Receiver Sensitivity	-92 dBm (1% packet error rate)	-100 dBm (1% packet error rate)
Power Requirements		
Supply Voltage	2.8 – 3.4 V	2.8 – 3.4 V
Transmit Current (typical)	45mA (@ 3.3 V)	250mA (@3.3 V) (150mA for international variant) RPSMA module only: 340mA (@3.3 V) (180mA for international variant)
Idle / Receive Current (typical)	50mA (@ 3.3 V)	55mA (@ 3.3 V)
Power-down Current	< 10 µA	< 10 µA
General		
Operating Frequency	ISM 2.4 GHz	ISM 2.4 GHz
Dimensions	0.960" x 1.087" (2.438cm x 2.761cm)	0.960" x 1.297" (2.438cm x 3.294cm)
Operating Temperature	-40 to 85º C (industrial)	-40 to 85º C (industrial)
Antenna Options	Integrated Whip, Chip or U.FL Connector, RPSMA Connector	Integrated Whip, Chip or U.FL Connector, RPSMA Connector
Networking & Security		
Supported Network Topologies	Point-to-point, Point-to-multipoint & Peer-to-peer	
Number of Channels (software selectable)	16 Direct Sequence Channels	12 Direct Sequence Channels
Addressing Options	PAN ID, Channel and Addresses	PAN ID, Channel and Addresses
Agency Approvals		
United States (FCC Part 15.247)	OUR-XBEE	OUR-XBEEPRO
Industry Canada (IC)	4214A XBEE	4214A XBEEPRO
Europe (CE)	ETSI	ETSI (Max. 10 dBm transmit power output)*
Japan	R201WW07215214	R201WW08215111 (Max. 10 dBm transmit power output)*
Austraila	C-Tick	C-Tick

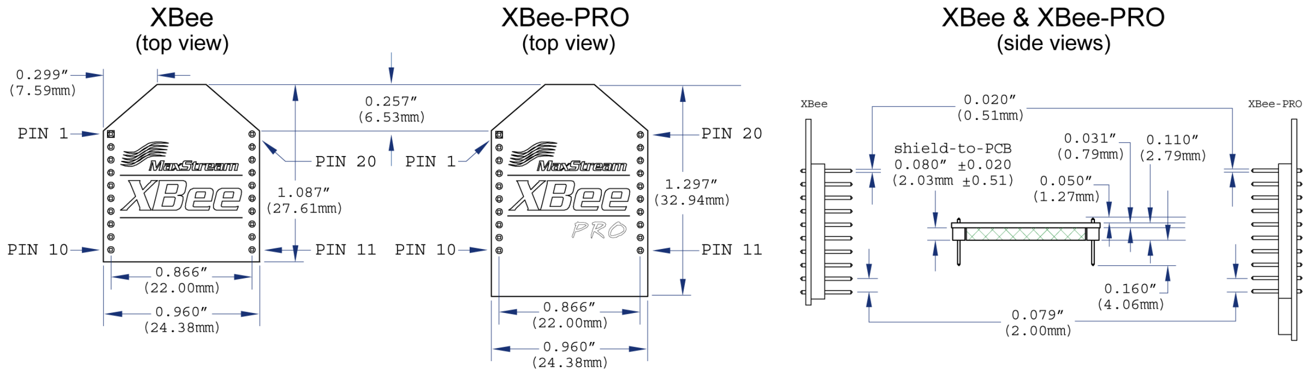
* See Appendix A for region-specific certification requirements.

Antenna Options: The ranges specified are typical when using the integrated Whip (1.5 dBi) and Dipole (2.1 dBi) antennas. The Chip antenna option provides advantages in its form factor; however, it typically yields shorter range than the Whip and Dipole antenna options when transmitting outdoors.For more information, refer to the "XBee Antennas" Knowledgebase Article located on Digi's Support Web site

Mechanical Drawings

Figure 1-01. Mechanical drawings of the XBee®/XBee-PRO® RF Modules (antenna options not shown)

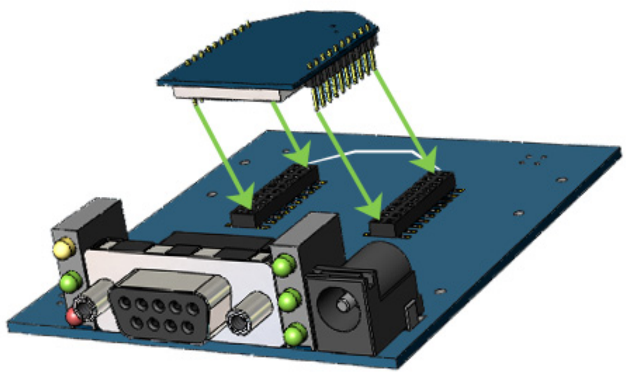
The XBee and XBee-PRO RF Modules are pin-for-pin compatible.



Mounting Considerations

The XBee®/XBee-PRO® RF Module was designed to mount into a receptacle (socket) and therefore does not require any soldering when mounting it to a board. The XBee Development Kits contain RS-232 and USB interface boards which use two 20-pin receptacles to receive modules.

Figure 1-02. XBee Module Mounting to an RS-232 Interface Board.



The receptacles used on Digi development boards are manufactured by Century Interconnect. Several other manufacturers provide comparable mounting solutions; however, Digi currently uses the following receptacles:

- Through-hole single-row receptacles -
  Samtec P/N: MMS-110-01-L-SV (or equivalent)
- Surface-mount double-row receptacles -
  Century Interconnect P/N: CPRMSL20-D-0-1 (or equivalent)
- Surface-mount single-row receptacles -
  Samtec P/N: SMM-110-02-SM-S

Digi also recommends printing an outline of the module on the board to indicate the orientation the module should be mounted.

Pin Signals

Figure 1-03. XBee®/XBee-PRO® RF Module Pin Numbers

(top sides shown - shields on bottom)

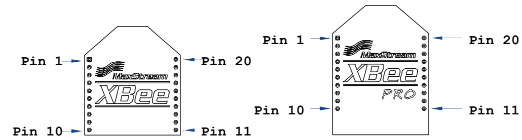


Table 1-02. Pin Assignments for the XBee and XBee-PRO Modules
(Low-asserted signals are distinguished with a horizontal line above signal name.)

Pin #	Name	Direction	Description
1	VCC	-	Power supply
2	DOUT	Output	UART Data Out
3	DIN / **CONFIG**	Input	UART Data In
4	DO8*	Output	Digital Output 8
5	**RESET**	Input	Module Reset (reset pulse must be at least 200 ns)
6	PWM0 / RSSI	Output	PWM Output 0 / RX Signal Strength Indicator
7	PWM1	Output	PWM Output 1
8	[reserved]	-	Do not connect
9	DTR / SLEEP_RQ / DI8	Input	Pin Sleep Control Line or Digital Input 8
10	GND	-	Ground
11	AD4 / DIO4	Either	Analog Input 4 or Digital I/O 4
12	**CTS** / DIO7	Either	Clear-to-Send Flow Control or Digital I/O 7
13	ON / **SLEEP**	Output	Module Status Indicator
14	VREF	Input	Voltage Reference for A/D Inputs
15	Associate / AD5 / DIO5	Either	Associated Indicator, Analog Input 5 or Digital I/O 5
16	**RTS** / AD6 / DIO6	Either	Request-to-Send Flow Control, Analog Input 6 or Digital I/O 6
17	AD3 / DIO3	Either	Analog Input 3 or Digital I/O 3
18	AD2 / DIO2	Either	Analog Input 2 or Digital I/O 2
19	AD1 / DIO1	Either	Analog Input 1 or Digital I/O 1
20	AD0 / DIO0	Either	Analog Input 0 or Digital I/O 0

* Function is not supported at the time of this release

Design Notes:

- Minimum connections: VCC, GND, DOUT & DIN
- Minimum connections for updating firmware: VCC, GND, DIN, DOUT, RTS & DTR
- Signal Direction is specified with respect to the module
- Module includes a 50k Ω pull-up resistor attached to **RESET**
- Several of the input pull-ups can be configured using the PR command
- Unused pins should be left disconnected

Electrical Characteristics

Table 1-03. DC Characteristics (VCC = 2.8 - 3.4 VDC)

Symbol	Characteristic	Condition	Min	Typical		Max	Unit
V_{IL}	Input Low Voltage	All Digital Inputs	-	-		0.35 * VCC	V
V_{IH}	Input High Voltage	All Digital Inputs	0.7 * VCC	-		-	V
V_{OL}	Output Low Voltage	I_{OL} = 2 mA, VCC >= 2.7 V	-	-		0.5	V
V_{OH}	Output High Voltage	I_{OH} = -2 mA, VCC >= 2.7 V	VCC - 0.5	-		-	V
II_{IN}	Input Leakage Current	V_{IN} = VCC or GND, all inputs, per pin	-	0.025		1	µA
II_{OZ}	High Impedance Leakage Current	V_{IN} = VCC or GND, all I/O High-Z, per pin	-	0.025		1	µA
TX	Transmit Current	VCC = 3.3 V	-	45 (XBee)	215, 140 (PRO, Int)	-	mA
RX	Receive Current	VCC = 3.3 V	-	50 (XBee)	55 (PRO)	-	mA
PWR-DWN	Power-down Current	SM parameter = 1	-	< 10		-	µA

Table 1-04. ADC Characteristics (Operating)

Symbol	Characteristic	Condition	Min	Typical	Max	Unit
V_{REFH}	VREF - Analog-to-Digital converter reference range		2.08	-	V_{DDAD}*	V
I_{REF}	VREF - Reference Supply Current	Enabled	-	200	-	µA
		Disabled or Sleep Mode	-	< 0.01	0.02	µA
V_{INDC}	Analog Input Voltage[1]		V_{SSAD} - 0.3	-	V_{DDAD} + 0.3	V

1. Maximum electrical operating range, not valid conversion range.
* V_{DDAD} is connected to VCC.

Table 1-05. ADC Timing/Performance Characteristics[1]

Symbol	Characteristic	Condition	Min	Typical	Max	Unit
R_{AS}	Source Impedance at Input[2]		-	-	10	kΩ
V_{AIN}	Analog Input Voltage[3]		V_{REFL}		V_{REFH}	V
RES	Ideal Resolution (1 LSB)[4]	$2.08V \le V_{DDAD} \le 3.6V$	2.031	-	3.516	mV
DNL	Differential Non-linearity[5]		-	±0.5	±1.0	LSB
INL	Integral Non-linearity[6]		-	±0.5	±1.0	LSB
E_{ZS}	Zero-scale Error[7]		-	±0.4	±1.0	LSB
F_{FS}	Full-scale Error[8]		-	±0.4	±1.0	LSB
E_{IL}	Input Leakage Error[9]		-	±0.05	±5.0	LSB
E_{TU}	Total Unadjusted Error[10]		-	±1.1	±2.5	LSB

1. All ACCURACY numbers are based on processor and system being in WAIT state (very little activity and no IO switching) and that adequate low-pass filtering is present on analog input pins (filter with 0.01 µF to 0.1 µF capacitor between analog input and VREFL). Failure to observe these guidelines may result in system or microcontroller noise causing accuracy errors which will vary based on board layout and the type and magnitude of the activity.
Data transmission and reception during data conversion may cause some degradation of these specifications, depending on the number and timing of packets. It is advisable to test the ADCs in your installation if best accuracy is required.
2. R_{AS} is the real portion of the impedance of the network driving the analog input pin. Values greater than this amount may not fully charge the input circuitry of the ATD resulting in accuracy error.
3. Analog input must be between V_{REFL} and V_{REFH} for valid conversion. Values greater than V_{REFH} will convert to $3FF.
4. The resolution is the ideal step size or $1LSB = (V_{REFH}–V_{REFL})/1024$
5. Differential non-linearity is the difference between the current code width and the ideal code width (1LSB). The current code width is the difference in the transition voltages to and from the current code.
6. Integral non-linearity is the difference between the transition voltage to the current code and the adjusted ideal transition voltage for the current code. The adjusted ideal transition voltage is $(Current Code–1/2)*(1/((V_{REFH}+E_{FS})–(V_{REFL}+E_{ZS})))$.
7. Zero-scale error is the difference between the transition to the first valid code and the ideal transition to that code. The Ideal transition voltage to a given code is $(Code–1/2)*(1/(V_{REFH}–V_{REFL}))$.
8. Full-scale error is the difference between the transition to the last valid code and the ideal transition to that code. The ideal transition voltage to a given code is $(Code–1/2)*(1/(V_{REFH}–V_{REFL}))$.
9. Input leakage error is error due to input leakage across the real portion of the impedance of the network driving the analog pin. Reducing the impedance of the network reduces this error.

10. Total unadjusted error is the difference between the transition voltage to the current code and the ideal straight-line transfer function. This measure of error includes inherent quantization error (1/2LSB) and circuit error (differential, integral, zero-scale, and full-scale) error. The specified value of E_{TU} assumes zero E_{IL} (no leakage or zero real source impedance).

2. RF Module Operation

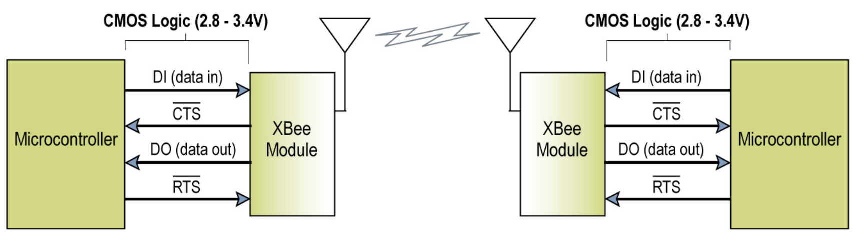
Serial Communications

The XBee®/XBee-PRO® RF Modules interface to a host device through a logic-level asynchronous serial port. Through its serial port, the module can communicate with any logic and voltage compatible UART; or through a level translator to any serial device (For example: Through a Digi proprietary RS-232 or USB interface board).

UART Data Flow

Devices that have a UART interface can connect directly to the pins of the RF module as shown in the figure below.

Figure 2-01. System Data Flow Diagram in a UART-interfaced environment
(Low-asserted signals distinguished with horizontal line over signal name.)

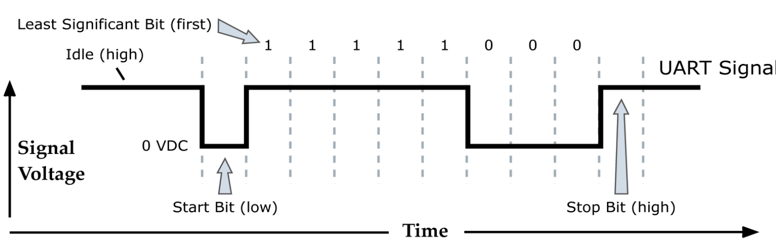


Serial Data

Data enters the module UART through the DI pin (pin 3) as an asynchronous serial signal. The signal should idle high when no data is being transmitted.

Each data byte consists of a start bit (low), 8 data bits (least significant bit first) and a stop bit (high). The following figure illustrates the serial bit pattern of data passing through the module.

Figure 2-02. UART data packet 0x1F (decimal number "31") as transmitted through the RF module
Example Data Format is 8-N-1 (bits - parity - # of stop bits)



Serial communications depend on the two UARTs (the microcontroller's and the RF module's) to be configured with compatible settings (baud rate, parity, start bits, stop bits, data bits).

The UART baud rate and parity settings on the XBee module can be configured with the BD and SB commands, respectively. See the command table in Chapter 3 for details.

Transparent Operation

By default, XBee®/XBee-PRO® RF Modules operate in Transparent Mode. When operating in this mode, the modules act as a serial line replacement - all UART data received through the DI pin is queued up for RF transmission. When RF data is received, the data is sent out the DO pin.

Serial-to-RF Packetization

Data is buffered in the DI buffer until one of the following causes the data to be packetized and transmitted:

1. No serial characters are received for the amount of time determined by the RO (Packetization Timeout) parameter. If RO = 0, packetization begins when a character is received.
2. The maximum number of characters that will fit in an RF packet (100) is received.
3. The Command Mode Sequence (GT + CC + GT) is received. Any character buffered in the DI buffer before the sequence is transmitted.

If the module cannot immediately transmit (for instance, if it is already receiving RF data), the serial data is stored in the DI Buffer. The data is packetized and sent at any RO timeout or when 100 bytes (maximum packet size) are received.

If the DI buffer becomes full, hardware or software flow control must be implemented in order to prevent overflow (loss of data between the host and module).

API Operation

API (Application Programming Interface) Operation is an alternative to the default Transparent Operation. The frame-based API extends the level to which a host application can interact with the networking capabilities of the module.

When in API mode, all data entering and leaving the module is contained in frames that define operations or events within the module.

Transmit Data Frames (received through the DI pin (pin 3)) include:

- RF Transmit Data Frame
- Command Frame (equivalent to AT commands)

Receive Data Frames (sent out the DO pin (pin 2)) include:

- RF-received data frame
- Command response
- Event notifications such as reset, associate, disassociate, etc.

The API provides alternative means of configuring modules and routing data at the host application layer. A host application can send data frames to the module that contain address and payload information instead of using command mode to modify addresses. The module will send data frames to the application containing status packets; as well as source, RSSI and payload information from received data packets.

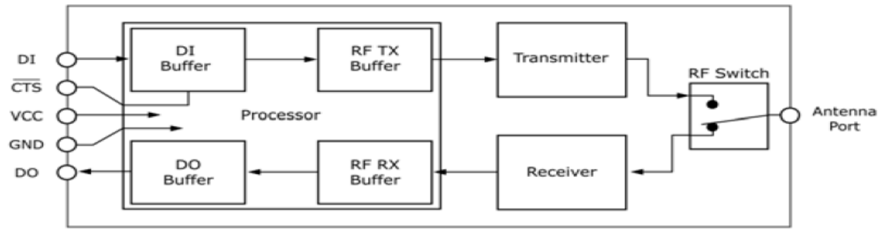
The API operation option facilitates many operations such as the examples cited below:

-> Transmitting data to multiple destinations without entering Command Mode
-> Receive success/failure status of each transmitted RF packet
-> Identify the source address of each received packet

To implement API operations, refer to API sections [p57].

Flow Control

Figure 2-03. Internal Data Flow Diagram



DI (Data In) Buffer

When serial data enters the RF module through the DI pin (pin 3), the data is stored in the DI Buffer until it can be processed.

Hardware Flow Control (CTS). When the DI buffer is 17 bytes away from being full; by default, the module de-asserts CTS (high) to signal to the host device to stop sending data [refer to D7 (DIO7 Configuration) parameter]. CTS is re-asserted after the DI Buffer has 34 bytes of memory available.

How to eliminate the need for flow control:

1. Send messages that are smaller than the DI buffer size (202 bytes).
2. Interface at a lower baud rate [BD (Interface Data Rate) parameter] than the throughput data rate.

Case in which the DI Buffer may become full and possibly overflow:

If the module is receiving a continuous stream of RF data, any serial data that arrives on the DI pin is placed in the DI Buffer. The data in the DI buffer will be transmitted over-the-air when the module is no longer receiving RF data in the network.

Refer to the RO (Packetization Timeout), BD (Interface Data Rate) and D7 (DIO7 Configuration) command descriptions for more information.

DO (Data Out) Buffer

When RF data is received, the data enters the DO buffer and is sent out the serial port to a host device. Once the DO Buffer reaches capacity, any additional incoming RF data is lost.

Hardware Flow Control (RTS). If RTS is enabled for flow control (D6 (DIO6 Configuration) Parameter = 1), data will not be sent out the DO Buffer as long as RTS (pin 16) is de-asserted.

Two cases in which the DO Buffer may become full and possibly overflow:

1. If the RF data rate is set higher than the interface data rate of the module, the module will receive data from the transmitting module faster than it can send the data to the host.
2. If the host does not allow the module to transmit data out from the DO buffer because of being held off by hardware or software flow control.

Refer to the D6 (DIO6 Configuration) command description for more information.

ADC and Digital I/O Line Support

The XBee®/XBee-PRO® RF Modules support ADC (Analog-to-digital conversion) and digital I/O line passing. The following pins support multiple functions:

Table 2-01. Pin functions and their associated pin numbers and commands
AD = Analog-to-Digital Converter, DIO = Digital Input/Output
Pin functions not applicable to this section are denoted within (parenthesis).

Pin Function	Pin#	AT Command
AD0 / DIO0	20	D0
AD1 / DIO1	19	D1
AD2 / DIO2	18	D2
AD3 / DIO3 / (COORD_SEL)	17	D3
AD4 / DIO4	11	D4
AD5 / DIO5 / (ASSOCIATE)	15	D5
DIO6 / (RTS)	16	D6
DIO7 / (CTS)	12	D7
DI8 / (DTR) / (Sleep_RQ)	9	D8

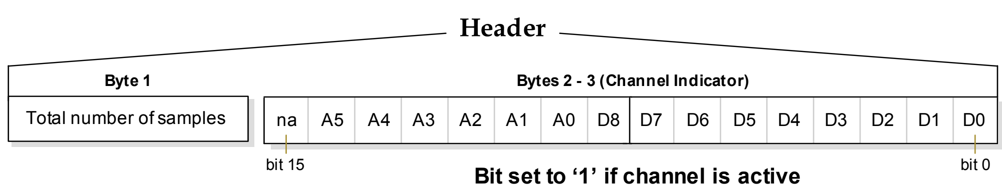
To enable ADC and DIO pin functions:

For ADC Support:	Set ATDn = 2
For Digital Input support:	Set ATDn = 3
For Digital Output Low support:	Set ATDn = 4
For Digital Output High support:	Set ATDn = 5

I/O Data Format

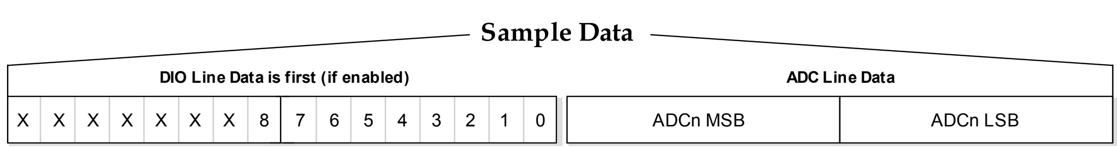
I/O data begins with a header. The first byte of the header defines the number of samples forthcoming. The last 2 bytes of the header (Channel Indicator) define which inputs are active. Each bit represents either a DIO line or ADC channel.

Figure 2-04. Header



Sample data follows the header and the channel indicator frame is used to determine how to read the sample data. If any of the DIO lines are enabled, the first 2 bytes are the DIO sample. The ADC data follows. ADC channel data is represented as an unsigned 10-bit value right-justified on a 16- bit boundary.

Figure 2-05. Sample Data



API Support

I/O data is sent out the UART using an API frame. All other data can be sent and received using Transparent Operation [refer to p11] or API framing if API mode is enabled (AP > 0).

API Operations support two RX (Receive) frame identifiers for I/O data (set 16-bit address to 0xFFFE and the module will do 64-bit addressing):

- 0x82 for RX (Receive) Packet: 64-bit address I/O
- 0x83 for RX (Receive) Packet: 16-bit address I/O

The API command header is the same as shown in the "RX (Receive) Packet: 64-bit Address" and "RX (Receive) Packet: 64-bit Address" API types [refer to p63]. RX data follows the format described in the I/O Data Format section [p13].

Applicable Commands: AP (API Enable)

Sleep Support

Automatic wakeup sampling can be suppressed by setting SO bit 1.When an RF module wakes, it will always do a sample based on any active ADC or DIO lines. This allows sampling based on the sleep cycle whether it be Cyclic Sleep (SM parameter = 4 or 5) or Pin Sleep (SM = 1 or 2). To gather more samples when awake, set the IR (Sample Rate) parameter.

For Cyclic Sleep modes: If the IR parameter is set, the module will stay awake until the IT (Samples before TX) parameter is met. The module will stay awake for ST (Time before Sleep) time.

Applicable Commands: IR (Sample Rate), IT (Samples before TX), SM (Sleep Mode), IC (DIO Change Detect), SO (Sleep Options)

DIO Pin Change Detect

When "DIO Change Detect" is enabled (using the IC command), DIO lines 0-7 are monitored. When a change is detected on a DIO line, the following will occur:

1. An RF packet is sent with the updated DIO pin levels. This packet will not contain any ADC samples.
2. Any queued samples are transmitted before the change detect data. This may result in receiving a packet with less than IT (Samples before TX) samples.

Note: Change detect will not affect Pin Sleep wake-up. The D8 pin (DTR/Sleep_RQ/DI8) is the only line that will wake a module from Pin Sleep. If not all samples are collected, the module will still enter Sleep Mode after a change detect packet is sent.

Applicable Commands: IC (DIO Change Detect), IT (Samples before TX)

NOTE: Change detect is only supported when the Dx (DIOx Configuration) parameter equals 3,4 or 5.

Sample Rate (Interval)

The Sample Rate (Interval) feature allows enabled ADC and DIO pins to be read periodically on modules that are not configured to operate in Sleep Mode. When one of the Sleep Modes is enabled and the IR (Sample Rate) parameter is set, the module will stay awake until IT (Samples before TX) samples have been collected.

Once a particular pin is enabled, the appropriate sample rate must be chosen. The maximum sample rate that can be achieved while using one A/D line is 1 sample/ms or 1 KHz (Note that the modem will not be able to keep up with transmission when IR & IT are equal to "1" and that configuring the modem to sample at rates greater than once every 20ms is not recommended).

Applicable Commands: IR (Sample Rate), IT (Samples before TX), SM (Sleep Mode)

I/O Line Passing

Virtual wires can be set up between XBee®/XBee-PRO® Modules. When an RF data packet is received that contains I/O data, the receiving module can be setup to update any enabled outputs (PWM and DIO) based on the data it receives.

Note that I/O lines are mapped in pairs. For example: AD0 can only update PWM0 and DI5 can only update DO5. The default setup is for outputs not to be updated, which results in the I/O data being sent out the UART (refer to the IU (Enable I/O Output) command). To enable the outputs to be updated, the IA (I/O Input Address) parameter must be setup with the address of the module that has the appropriate inputs enabled. This effectively binds the outputs to a particular module's input. This does not affect the ability of the module to receive I/O line data from other modules - only its ability to update enabled outputs. The IA parameter can also be setup to accept I/O data for output changes from any module by setting the IA parameter to 0xFFFF.

When outputs are changed from their non-active state, the module can be setup to return the output level to it non-active state. The timers are set using the Tn (Dn Output Timer) and PT (PWM Output Timeout) commands. The timers are reset every time a valid I/O packet (passed IA check) is received. The IC (Change Detect) and IR (Sample Rate) parameters can be setup to keep the output set to their active output if the system needs more time than the timers can handle.

Note: DI8 cannot be used for I/O line passing.

Applicable Commands: IA (I/O Input Address), Tn (Dn Output Timeout), P0 (PWM0 Configuration), P1 (PWM1 Configuration), M0 (PWM0 Output Level), M1 (PWM1 Output Level), PT (PWM Output Timeout), RP (RSSSI PWM Timer)

Configuration Example

As an example for a simple A/D link, a pair of RF modules could be set as follows:

Remote Configuration	Base Configuration
DL = 0x1234	DL = 0x5678
MY = 0x5678	MY = 0x1234
D0 = 2	P0 = 2
D1 = 2	P1 = 2
IR = 0x14	IU = 1
IT = 5	IA = 0x5678 (or 0xFFFF)

These settings configure the remote module to sample AD0 and AD1 once each every 20 ms. It then buffers 5 samples each before sending them back to the base module. The base should then receive a 32-Byte transmission (20 Bytes data and 12 Bytes framing) every 100 ms.

XBee®/XBee-PRO® Networks

The following terms will be used to explicate the network operations:

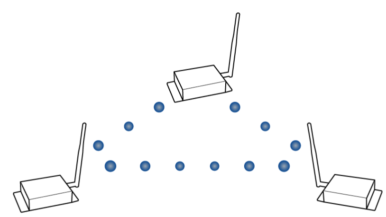
Table 2-02. Terms and definitions

Term	Definition
PAN	Personal Area Network - A data communication network that includes one or more End Devices and optionally a Coordinator.
Coordinator	A Full-function device (FFD) that provides network synchronization by polling nodes [NonBeacon (w/ Coordinator) networks only]
End Device	*When in the same network as a Coordinator* - RF modules that rely on a Coordinator for synchronization and can be put into states of sleep for low-power applications.
Association	The establishment of membership between End Devices and a Coordinator. Association is only applicable in NonBeacon (w/Coordinator) networks.

Peer-to-Peer

By default, XBee®/XBee-PRO RF Modules are configured to operate within a Peer-to-Peer network topology and therefore are not dependent upon Master/Slave relationships. NonBeacon systems operate within a Peer-to-Peer network topology and therefore are not dependent upon Master/Slave relationships. This means that modules remain synchronized without use of master/server configurations and each module in the network shares both roles of master and slave. Digi's peer-to-peer architecture features fast synchronization times and fast cold start times. This default configuration accommodates a wide range of RF data applications.

Figure 2-06. Peer-to-Peer Architecture



A peer-to-peer network can be established by configuring each module to operate as an End Device (CE = 0), disabling End Device Association on all modules (A1 = 0) and setting ID and CH parameters to be identical across the network.

NonBeacon (w/ Coordinator)

A device is configured as a Coordinator by setting the CE (Coordinator Enable) parameter to “1”. Coordinator power-up is governed by the A2 (Coordinator Association) parameter.

In a Coordinator system, the Coordinator can be configured to use direct or indirect transmissions. If the SP (Cyclic Sleep Period) parameter is set to “0”, the Coordinator will send data immediately. Otherwise, the SP parameter determines the length of time the Coordinator will retain the data before discarding it. Generally, SP (Cyclic Sleep Period) and ST (Time before Sleep) parameters should be set to match the SP and ST settings of the End Devices.

Association

Association is the establishment of membership between End Devices and a Coordinator. The establishment of membership is useful in scenarios that require a central unit (Coordinator) to relay messages to or gather data from several remote units (End Devices), assign channels or assign PAN IDs.

An RF data network that consists of one Coordinator and one or more End Devices forms a PAN (Personal Area Network). Each device in a PAN has a PAN Identifier [ID (PAN ID) parameter]. PAN IDs must be unique to prevent miscommunication between PANs. The Coordinator PAN ID is set using the ID (PAN ID) and A2 (Coordinator Association) commands.

An End Device can associate to a Coordinator without knowing the address, PAN ID or channel of the Coordinator. The A1 (End Device Association) parameter bit fields determine the flexibility of an End Device during association. The A1 parameter can be used for an End Device to dynamically set its destination address, PAN ID and/or channel.

For example: If the PAN ID of a Coordinator is known, but the operating channel is not; the A1 command on the End Device should be set to enable the 'Auto_Associate' and 'Reassign_Channel' bits. Additionally, the ID parameter should be set to match the PAN ID of the associated Coordinator.

Coordinator / End Device Setup and Operation

To configure a module to operate as a Coordinator, set the CE (Coordinator Enable) parameter to '1'. Set the CE parameter of End Devices to '0' (default). Coordinator and End Devices should contain matching firmware versions.

NonBeacon (w/ Coordinator) Systems

The Coordinator can be configured to use direct or indirect transmissions. If the SP (Cyclic Sleep Period) parameter is set to '0', the Coordinator will send data immediately. Otherwise, the SP parameter determines the length of time the Coordinator will retain the data before discarding it. Generally, SP (Cyclic Sleep Period) and ST (Time before Sleep) parameters should be set to match the SP and ST settings of the End Devices.

Coordinator Start-up

Coordinator power-up is governed by the A2 (Coordinator Association) command. On power-up, the Coordinator undergoes the following sequence of events:

1. Check A2 parameter- Reassign_PANID Flag

Set (bit 0 = 1) - The Coordinator issues an Active Scan. The Active Scan selects one channel and transmits a request to the broadcast address (0xFFFF) and broadcast PAN ID (0xFFFF). It then listens on that channel for beacons from any Coordinator operating on that channel. The listen time on each channel is determined by the SD (Scan Duration) parameter value.

Once the time expires on that channel, the Active Scan selects another channel and again transmits the BeaconRequest as before. This process continues until all channels have been scanned, or until 5 PANs have been discovered. When the Active Scan is complete, the results include a list of PAN IDs and Channels that are being used by other PANs. This list is used to assign an unique PAN ID to the new Coordinator. The ID parameter will be retained if it is not found in the Active Scan results. Otherwise, the ID (PAN ID) parameter setting will be updated to a PAN ID that was not detected.

Not Set (bit 0 = 0) - The Coordinator retains its ID setting. No Active Scan is performed.

2. Check A2 parameter - Reassign_Channel Flag (bit 1)

Set (bit 1 = 1) - The Coordinator issues an Energy Scan. The Energy Scan selects one channel and scans for energy on that channel. The duration of the scan is specified by the SD (Scan Duration) parameter. Once the scan is completed on a channel, the Energy Scan selects the next channel and begins a new scan on that channel. This process continues until all channels have been scanned.

When the Energy Scan is complete, the results include the maximal energy values detected on each channel. This list is used to determine a channel where the least energy was detected. If an Active Scan was performed (Reassign_PANID Flag set), the channels used by the detected PANs are eliminated as possible channels. Thus, the results of the Energy Scan and the Active Scan (if performed) are used to find the best channel (channel with the least energy that is not used by any detected PAN). Once the best channel has been selected, the CH (Channel) parameter value is updated to that channel.

Not Set (bit 1 = 0) - The Coordinator retains its CH setting. An Energy Scan is not performed.

3. Start Coordinator

The Coordinator starts on the specified channel (CH parameter) and PAN ID (ID parameter). Note, these may be selected in steps 1 and/or 2 above. The Coordinator will only allow End Devices to associate to it if the A2 parameter "AllowAssociation" flag is set. Once the Coordinator has successfully started, the Associate LED will blink 1 time per second. (The LED is solid if the Coordinator has not started.)

4. Coordinator Modifications

Once a Coordinator has started:
Modifying the A2 (Reassign_Channel or Reassign_PANID bits), ID, CH or MY parameters will cause the Coordinator's MAC to reset (The Coordinator RF module (including volatile RAM) is not reset). Changing the A2 AllowAssociation bit will not reset the Coordinator's MAC. In a non-beaconing system, End Devices that associated to the Coordinator prior to a MAC reset will have knowledge of the new settings on the Coordinator. Thus, if the Coordinator were to change its ID, CH or MY settings, the End Devices would no longer be able to communicate with the non-beacon Coordinator. Once a Coordinator has started, the ID, CH, MY or A2 (Reassign_Channel or Reassign_PANID bits) should not be changed.

End Device Start-up

End Device power-up is governed by the A1 (End Device Association) command. On power-up, the End Device undergoes the following sequence of events:

1. Check A1 parameter - AutoAssociate Bit

Set (bit 2 = 1) - End Device will attempt to associate to a Coordinator. (refer to steps 2-3).

Not Set (bit 2 = 0) - End Device will not attempt to associate to a Coordinator. The End Device will operate as specified by its ID, CH and MY parameters. Association is considered complete and the Associate LED will blink quickly (5 times per second). When the AutoAssociate bit is not set, the remaining steps (2-3) do not apply.

2. Discover Coordinator (if Auto-Associate Bit Set)

The End Device issues an Active Scan. The Active Scan selects one channel and transmits a BeaconRequest command to the broadcast address (0xFFFF) and broadcast PAN ID (0xFFFF). It then listens on that channel for beacons from any Coordinator operating on that channel. The listen time on each channel is determined by the SD parameter.

Once the time expires on that channel, the Active Scan selects another channel and again transmits the BeaconRequest command as before. This process continues until all channels have been scanned, or until 5 PANs have been discovered. When the Active Scan is complete, the results include a list of PAN IDs and Channels that are being used by detected PANs.

The End Device selects a Coordinator to associate with according to the A1 parameter "Reassign_PANID" and "Reassign_Channel" flags:

Reassign_PANID Bit Set (bit 0 = 1)- End Device can associate with a PAN with any ID value.

Reassign_PANID Bit Not Set (bit 0 = 0) - End Device will only associate with a PAN whose ID setting matches the ID setting of the End Device.

Reassign_Channel Bit Set (bit 1 = 1) - End Device can associate with a PAN with any CH value.

Reassign_Channel Bit Not Set (bit 1 = 0)- End Device will only associate with a PAN whose CH setting matches the CH setting of the End Device.

After applying these filters to the discovered Coordinators, if multiple candidate PANs exist, the End Device will select the PAN whose transmission link quality is the strongest. If no valid Coordinator is found, the End Device will either go to sleep (as dictated by its SM (Sleep Mode) parameter) or retry Association.

Note - An End Device will also disqualify Coordinators if they are not allowing association (A2 - AllowAssociation bit); or, if the Coordinator is not using the same NonBeacon scheme as the End Device. (They must both be programmed with NonBeacon code.)

3. Associate to Valid Coordinator

Once a valid Coordinator is found (step 2), the End Device sends an AssociationRequest message to the Coordinator. It then waits for an AssociationConfirmation to be sent from the Coordinator. Once the Confirmation is received, the End Device is Associated and the Associate LED will blink rapidly (2 times per second). The LED is solid if the End Device has not associated.

4. End Device Changes once an End Device has associated

Changing A1, ID or CH parameters will cause the End Device to disassociate and restart the Association procedure.

If the End Device fails to associate, the AI command can give some indication of the failure.

XBee®/XBee-PRO® Addressing

Every RF data packet sent over-the-air contains a Source Address and Destination Address field in its header. The RF module conforms to the 802.15.4 specification and supports both short 16-bit addresses and long 64-bit addresses. A unique 64-bit IEEE source address is assigned at the factory and can be read with the SL (Serial Number Low) and SH (Serial Number High) commands. Short addressing must be configured manually. A module will use its unique 64-bit address as its Source Address if its MY (16-bit Source Address) value is “0xFFFF” or “0xFFFE”.

To send a packet to a specific module using 64-bit addressing: Set the Destination Address (DL + DH) of the sender to match the Source Address (SL + SH) of the intended destination module.

To send a packet to a specific module using 16-bit addressing: Set DL (Destination Address Low) parameter to equal the MY parameter of the intended destination module and set the DH (Destination Address High) parameter to '0'.

Unicast Mode

By default, the RF module operates in Unicast Mode. Unicast Mode is the only mode that supports retries. While in this mode, receiving modules send an ACK (acknowledgement) of RF packet reception to the transmitter. If the transmitting module does not receive the ACK, it will re-send the packet up to three times or until the ACK is received.

Short 16-bit addresses. The module can be configured to use short 16-bit addresses as the Source Address by setting (MY < 0xFFFE). Setting the DH parameter (DH = 0) will configure the Destination Address to be a short 16-bit address (if DL < 0xFFFE). For two modules to communicate using short addressing, the Destination Address of the transmitter module must match the MY parameter of the receiver.

The following table shows a sample network configuration that would enable Unicast Mode communications using short 16-bit addresses.

Table 2-03. Sample Unicast Network Configuration (using 16-bit addressing)

Parameter	RF Module 1	RF Module 2
MY (Source Address)	0x01	0x02
DH (Destination Address High)	0	0
DL (Destination Address Low)	0x02	0x01

Long 64-bit addresses. The RF module’s serial number (SL parameter concatenated to the SH parameter) can be used as a 64-bit source address when the MY (16-bit Source Address) parameter is disabled. When the MY parameter is disabled (MY = 0xFFFF or 0xFFFE), the module’s source address is set to the 64-bit IEEE address stored in the SH and SL parameters.

When an End Device associates to a Coordinator, its MY parameter is set to 0xFFFE to enable 64-bit addressing. The 64-bit address of the module is stored as SH and SL parameters. To send a packet to a specific module, the Destination Address (DL + DH) on the sender must match the Source Address (SL + SH) of the desired receiver.

Broadcast Mode

Any RF module within range will accept a packet that contains a broadcast address. When configured to operate in Broadcast Mode, receiving modules do not send ACKs (Acknowledgements) and transmitting modules do not automatically re-send packets as is the case in Unicast Mode.

To send a broadcast packet to all modules regardless of 16-bit or 64-bit addressing, set the destination addresses of all the modules as shown below.

Sample Network Configuration (All modules in the network):

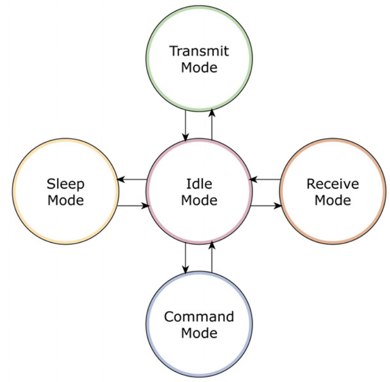
- DL (Destination Low Address) = 0x0000FFFF
- DH (Destination High Address) = 0x00000000 (default value)

NOTE: When programming the module, parameters are entered in hexadecimal notation (without the “0x” prefix). Leading zeros may be omitted.

Modes of Operation

XBee®/XBee-PRO® RF Modules operate in five modes.

Figure 2-07. Modes of Operation



Idle Mode

When not receiving or transmitting data, the RF module is in Idle Mode. The module shifts into the other modes of operation under the following conditions:

- Transmit Mode (Serial data is received in the DI Buffer)
- Receive Mode (Valid RF data is received through the antenna)
- Sleep Mode (Sleep Mode condition is met)
- Command Mode (Command Mode Sequence is issued)

Transmit/Receive Modes

RF Data Packets

Each transmitted data packet contains a Source Address and Destination Address field. The Source Address matches the address of the transmitting module as specified by the MY (Source Address) parameter (if MY >= 0xFFFE), the SH (Serial Number High) parameter or the SL (Serial Number Low) parameter. The <Destination Address> field is created from the DH (Destination Address High) and DL (Destination Address Low) parameter values. The Source Address and/or Destination Address fields will either contain a 16-bit short or long 64-bit long address.

The RF data packet structure follows the 802.15.4 specification.

[Refer to the XBee/XBee-PRO Addressing section for more information]

Direct and Indirect Transmission

There are two methods to transmit data:

- Direct Transmission - data is transmitted immediately to the Destination Address
- Indirect Transmission - A packet is retained for a period of time and is only transmitted after the destination module (Source Address = Destination Address) requests the data.

Indirect Transmissions can only occur on a Coordinator. Thus, if all nodes in a network are End Devices, only Direct Transmissions will occur. Indirect Transmissions are useful to ensure packet delivery to a sleeping node. The Coordinator currently is able to retain up to 2 indirect messages.

Direct Transmission

A Coordinator can be configured to use only Direct Transmission by setting the SP (Cyclic Sleep Period) parameter to "0". Also, a Coordinator using indirect transmissions will revert to direct transmission if it knows the destination module is awake.

To enable this behavior, the ST (Time before Sleep) value of the Coordinator must be set to match the ST value of the End Device. Once the End Device either transmits data to the Coordinator or polls the Coordinator for data, the Coordinator will use direct transmission for all subsequent data transmissions to that module address until ST time occurs with no activity (at which point it will revert to using indirect transmissions for that module address). "No activity" means no transmission or reception of messages with a specific address. Global messages will not reset the ST timer.

Indirect Transmission

To configure Indirect Transmissions in a PAN (Personal Area Network), the SP (Cyclic Sleep Period) parameter value on the Coordinator must be set to match the longest sleep value of any End Device. The sleep period value on the Coordinator determines how long (time or number of beacons) the Coordinator will retain an indirect message before discarding it.

An End Device must poll the Coordinator once it wakes from Sleep to determine if the Coordinator has an indirect message for it. For Cyclic Sleep Modes, this is done automatically every time the module wakes (after SP time). For Pin Sleep Modes, the A1 (End Device Association) parameter value must be set to enable Coordinator polling on pin wake-up. Alternatively, an End Device can use the FP (Force Poll) command to poll the Coordinator as needed.

CCA (Clear Channel Assessment)

Prior to transmitting a packet, a CCA (Clear Channel Assessment) is performed on the channel to determine if the channel is available for transmission. The detected energy on the channel is compared with the CA (Clear Channel Assessment) parameter value. If the detected energy exceeds the CA parameter value, the packet is not transmitted.

Also, a delay is inserted before a transmission takes place. This delay is settable using the RN (Backoff Exponent) parameter. If RN is set to "0", then there is no delay before the first CCA is performed. The RN parameter value is the equivalent of the "minBE" parameter in the 802.15.4 specification. The transmit sequence follows the 802.15.4 specification.

By default, the MM (MAC Mode) parameter = 0. On a CCA failure, the module will attempt to re-send the packet up to two additional times.

When in Unicast packets with RR (Retries) = 0, the module will execute two CCA retries. Broadcast packets always get two CCA retries.

Acknowledgement

If the transmission is not a broadcast message, the module will expect to receive an acknowledgement from the destination node. If an acknowledgement is not received, the packet will be resent up to 3 more times. If the acknowledgement is not received after all transmissions, an ACK failure is recorded.

Sleep Mode

Sleep Modes enable the RF module to enter states of low-power consumption when not in use. In order to enter Sleep Mode, one of the following conditions must be met (in addition to the module having a non-zero SM parameter value):

- Sleep_RQ (pin 9) is asserted and the module is in a pin sleep mode (SM = 1, 2, or 5)
- The module is idle (no data transmission or reception) for the amount of time defined by the ST (Time before Sleep) parameter. [NOTE: ST is only active when SM = 4-5.]

Table 2-04. Sleep Mode Configurations

Sleep Mode Setting	Transition into Sleep Mode	Transition out of Sleep Mode (wake)	Characteristics	Related Commands	Power Consumption
Pin Hibernate (SM = 1)	Assert (high) Sleep_RQ (pin 9)	De-assert (low) Sleep_RQ	Pin/Host-controlled / NonBeacon systems only / Lowest Power	(SM)	< 10 µA (@3.0 VCC)
Pin Doze (SM = 2)	Assert (high) Sleep_RQ (pin 9)	De-assert (low) Sleep_RQ	Pin/Host-controlled / NonBeacon systems only / Fastest wake-up	(SM)	< 50 µA
Cyclic Sleep (SM = 4)	Automatic transition to Sleep Mode as defined by the SM (Sleep Mode) and ST (Time before Sleep) parameters.	Transition occurs after the cyclic sleep time interval elapses. The time interval is defined by the SP (Cyclic Sleep Period) parameter.	RF module wakes in pre-determined time intervals to detect if RF data is present / When SM = 5	(SM), SP, ST	< 50 µA when sleeping
Cyclic Sleep (SM = 5)	Automatic transition to Sleep Mode as defined by the SM (Sleep Mode) and ST (Time before Sleep) parameters or or on a falling edge transition of the SLEEP_RQ pin.	Transition occurs after the cyclic sleep time interval elapses. The time interval is defined by the SP (Cyclic Sleep Period) parameter.	RF module wakes in pre-determined time intervals to detect if RF data is present. Module also wakes on a falling edge of SLEEP_RQ	(SM), SP, ST	< 50 µA when sleeping

The SM command is central to setting Sleep Mode configurations. By default, Sleep Modes are disabled (SM = 0) and the module remains in Idle/Receive Mode. When in this state, the module is constantly ready to respond to serial or RF activity.

Pin/Host-controlled Sleep Modes

The transient current when waking from pin sleep (SM = 1 or 2) does not exceed the idle current of the module. The current ramps up exponentially to its idle current.

Pin Hibernate (SM = 1)

- Pin/Host-controlled
- Typical power-down current: < 10 µA (@3.0 VCC)
- Wake-up time: 13.2 msec

Pin Hibernate Mode minimizes quiescent power (power consumed when in a state of rest or inactivity). This mode is voltage level-activated; when Sleep_RQ (pin 9) is asserted, the module will finish any transmit, receive or association activities, enter Idle Mode, and then enter a state of sleep. The module will not respond to either serial or RF activity while in pin sleep.

To wake a sleeping module operating in Pin Hibernate Mode, de-assert Sleep_RQ (pin 9). The module will wake when Sleep_RQ is de-asserted and is ready to transmit or receive when the CTS line is low. When waking the module, the pin must be de-asserted at least two 'byte times' after CTS goes low. This assures that there is time for the data to enter the DI buffer.

Pin Doze (SM = 2)

- Pin/Host-controlled
- Typical power-down current: < 50 µA
- Wake-up time: 2 msec

Pin Doze Mode functions as does Pin Hibernate Mode; however, Pin Doze features faster wake-up time and higher power consumption.

To wake a sleeping module operating in Pin Doze Mode, de-assert Sleep_RQ (pin 9). The module will wake when Sleep_RQ is de-asserted and is ready to transmit or receive when the CTS line is low. When waking the module, the pin must be de-asserted at least two 'byte times' after CTS goes low. This assures that there is time for the data to enter the DI buffer.

Cyclic Sleep Modes

Cyclic Sleep Remote (SM = 4)

- Typical Power-down Current: < 50 μA (when asleep)
- Wake-up time: 2 msec

The Cyclic Sleep Modes allow modules to periodically check for RF data. When the SM parameter is set to ‘4’, the module is configured to sleep, then wakes once a cycle to check for data from a module configured as a Cyclic Sleep Coordinator (SM = 0, CE = 1). The Cyclic Sleep Remote sends a poll request to the coordinator at a specific interval set by the SP (Cyclic Sleep Period) parameter. The coordinator will transmit any queued data addressed to that specific remote upon receiving the poll request.

If no data is queued for the remote, the coordinator will not transmit and the remote will return to sleep for another cycle. If queued data is transmitted back to the remote, it will stay awake to allow for back and forth communication until the ST (Time before Sleep) timer expires.

Also note that $\overline{\text{CTS}}$ will go low each time the remote wakes, allowing for communication initiated by the remote host if desired.

Cyclic Sleep Remote with Pin Wake-up (SM = 5)

Use this mode to wake a sleeping remote module through either the RF interface or by the de-assertion of Sleep_RQ for event-driven communications. The cyclic sleep mode works as described above (Cyclic Sleep Remote) with the addition of a pin-controlled wake-up at the remote module. The Sleep_RQ pin is edge-triggered, not level-triggered. The module will wake when a low is detected then set $\overline{\text{CTS}}$ low as soon as it is ready to transmit or receive.

Any activity will reset the ST (Time before Sleep) timer so the module will go back to sleep only after there is no activity for the duration of the timer. Once the module wakes (pin-controlled), further pin activity is ignored. The module transitions back into sleep according to the ST time regardless of the state of the pin.

[Cyclic Sleep Coordinator (SM = 6)]

- Typical current = Receive current
- Always awake

NOTE: The SM=6 parameter value exists solely for backwards compatibility with firmware version 1.x60. If backwards compatibility with the older firmware version is not required, always use the CE (Coordinator Enable) command to configure a module as a Coordinator.

This mode configures a module to wake cyclic sleeping remotes through RF interfacing. The Coordinator will accept a message addressed to a specific remote 16 or 64-bit address and hold it in a buffer until the remote wakes and sends a poll request. Messages not sent directly (buffered and requested) are called "Indirect messages". The Coordinator only queues one indirect message at a time. The Coordinator will hold the indirect message for a period 2.5 times the sleeping period indicated by the SP (Cyclic Sleep Period) parameter. The Coordinator's SP parameter should be set to match the value used by the remotes.

Command Mode

To modify or read RF Module parameters, the module must first enter into Command Mode - a state in which incoming characters are interpreted as commands. Two Command Mode options are supported: AT Command Mode [refer to section below] and API Command Mode [p57].

AT Command Mode

To Enter AT Command Mode:

Send the 3-character command sequence "+++" and observe guard times before and after the command characters. [Refer to the "Default AT Command Mode Sequence" below.]

Default AT Command Mode Sequence (for transition to Command Mode):

- No characters sent for one second [GT (Guard Times) parameter = 0x3E8]
- Input three plus characters ("+++") within one second [CC (Command Sequence Character) parameter = 0x2B.]
- No characters sent for one second [GT (Guard Times) parameter = 0x3E8]

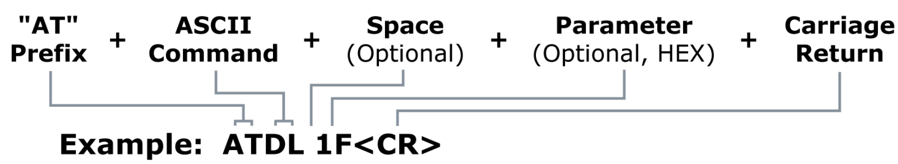
All of the parameter values in the sequence can be modified to reflect user preferences.

NOTE: Failure to enter AT Command Mode is most commonly due to baud rate mismatch. Ensure the 'Baud' setting on the "PC Settings" tab matches the interface data rate of the RF module. By default, the BD parameter = 3 (9600 bps).

To Send AT Commands:

Send AT commands and parameters using the syntax shown below.

Figure 2-08. Syntax for sending AT Commands



To read a parameter value stored in the RF module's register, omit the parameter field.

The preceding example would change the RF module Destination Address (Low) to "0x1F". To store the new value to non-volatile (long term) memory, subsequently send the WR (Write) command.

For modified parameter values to persist in the module's registry after a reset, changes must be saved to non-volatile memory using the WR (Write) Command. Otherwise, parameters are restored to previously saved values after the module is reset.

System Response. When a command is sent to the module, the module will parse and execute the command. Upon successful execution of a command, the module returns an "OK" message. If execution of a command results in an error, the module returns an "ERROR" message.

To Exit AT Command Mode:

1. Send the ATCN (Exit Command Mode) command (followed by a carriage return).

   [OR]

2. If no valid AT Commands are received within the time specified by CT (Command Mode Timeout) Command, the RF module automatically returns to Idle Mode.

For an example of programming the RF module using AT Commands and descriptions of each configurable parameter, refer to the RF Module Configuration chapter [p26].

3. RF Module Configuration

Programming the RF Module

Refer to the Command Mode section [p25] for more information about entering Command Mode, sending AT commands and exiting Command Mode. For information regarding module programming using API Mode, refer to the API Operation sections [p57].

Programming Examples

Setup

The programming examples in this section require the installation of Digi's X-CTU Software and a serial connection to a PC. (Digi stocks RS-232 and USB boards to facilitate interfacing with a PC.)

1. Install Digi's X-CTU Software to a PC by double-clicking the "setup_X-CTU.exe" file. (The file is located on the Digi CD and www.digi.com/xctu.)
2. Mount the RF module to an interface board, then connect the module assembly to a PC.
3. Launch the X-CTU Software and select the 'PC Settings' tab. Verify the baud and parity settings of the Com Port match those of the RF module.

NOTE: Failure to enter AT Command Mode is most commonly due to baud rate mismatch. Ensure the 'Baud' setting on the 'PC Settings' tab matches the interface data rate of the RF module. By default, the BD parameter = 3 (which corresponds to 9600 bps).

Sample Configuration: Modify RF Module Destination Address

Example: Utilize the X-CTU "Terminal" tab to change the RF module's DL (Destination Address Low) parameter and save the new address to non-volatile memory.

After establishing a serial connection between the RF module and a PC [refer to the 'Setup' section above], select the "Terminal" tab of the X-CTU Software and enter the following command lines ('CR' stands for carriage return):

Method 1 (One line per command)

Send AT Command	**System Response**
+++	OK <CR> (Enter into Command Mode)
ATDL <Enter>	{current value} <CR> (Read Destination Address Low)
ATDL1A0D <Enter>	OK <CR> (Modify Destination Address Low)
ATWR <Enter>	OK <CR> (Write to non-volatile memory)
ATCN <Enter>	OK <CR> (Exit Command Mode)

Method 2 (Multiple commands on one line)

Send AT Command	**System Response**
+++	OK <CR> (Enter into Command Mode)
ATDL <Enter>	{current value} <CR> (Read Destination Address Low)
ATDL1A0D,WR,CN <Enter>	OK<CR> OK<CR> OK<CR>

Sample Configuration: Restore RF Module Defaults

Example: Utilize the X-CTU "Modem Configuration" tab to restore default parameter values.

After establishing a connection between the module and a PC [refer to the 'Setup' section above], select the "Modem Configuration" tab of the X-CTU Software.

1. Select the 'Read' button.
2. Select the 'Restore' button.

Remote Configuration Commands

The API firmware has provisions to send configuration commands to remote devices using the Remote Command Request API frame (see API Operation). This API frame can be used to send commands to a remote module to read or set command parameters.

The API firmware has provisions to send configuration commands (set or read) to a remote module using the Remote Command Request API frame (see API Operations). Remote commands can be issued to read or set command parameters on a remote device.

Sending a Remote Command

To send a remote command, the Remote Command Request frame should be populated with values for the 64 bit and 16 bit addresses. If 64 bit addressing is desired then the 16 bit address field should be filled with 0xFFFE. If any value other than 0xFFFE is used in the 16 bit address field then the 64 bit address field will be ignored and 16 bit addressing will be used. If a command response is desired, the Frame ID should be set to a non-zero value.

Applying Changes on Remote

When remote commands are used to change command parameter settings on a remote device, parameter changes do not take effect until the changes are applied. For example, changing the BD parameter will not change the actual serial interface rate on the remote until the changes are applied. Changes can be applied using remote commands in one of three ways:

Set the apply changes option bit in the API frame

Issue an AC command to the remote device

Issue a WR + FR command to the remote device to save changes and reset the device.

Remote Command Responses

If the remote device receives a remote command request transmission, and the API frame ID is non-zero, the remote will send a remote command response transmission back to the device that sent the remote command. When a remote command response transmission is received, a device sends a remote command response API frame out its UART. The remote command response indicates the status of the command (success, or reason for failure), and in the case of a command query, it will include the register value.

The device that sends a remote command will not receive a remote command response frame if:

The destination device could not be reached

The frame ID in the remote command request is set to 0.

Command Reference Tables

XBee®/XBee-PRO® RF Modules expect numerical values in hexadecimal. Hexadecimal values are designated by a “0x” prefix. Decimal equivalents are designated by a “d” suffix. Commands are contained within the following command categories (listed in the order that their tables appear):

- Special
- Networking & Security
- RF Interfacing
- Sleep (Low Power)
- Serial Interfacing
- I/O Settings
- Diagnostics
- AT Command Options

All modules within a PAN should operate using the same firmware version.

Special

Table 3-01. XBee-PRO Commands - Special

AT Command	Command Category	Name and Description	Parameter Range	Default
WR	Special	**Write**. Write parameter values to non-volatile memory so that parameter modifications persist through subsequent power-up or reset. Note: Once WR is issued, no additional characters should be sent to the module until after the response "OK\r" is received.	-	-
RE	Special	**Restore Defaults**. Restore module parameters to factory defaults.	-	-
FR (v1.x80*)	Special	**Software Reset**. Responds immediately with an OK then performs a hard reset ~100ms later.	-	-

* Firmware version in which the command was first introduced (firmware versions are numbered in hexadecimal notation.)

Networking & Security

Table 3-02. XBee®/XBee-PRO® Commands - Networking & Security (Sub-categories designated within {brackets})

AT Command	Command Category	Name and Description	Parameter Range	Default
CH	Networking {Addressing}	**Channel**. Set/Read the channel number used for transmitting and receiving data between RF modules (uses 802.15.4 protocol channel numbers).	0x0B - 0x1A (XBee) 0x0C - 0x17 (XBee-PRO)	0x0C (12d)
ID	Networking {Addressing}	**PAN ID**. Set/Read the PAN (Personal Area Network) ID. Use 0xFFFF to broadcast messages to all PANs.	0 - 0xFFFF	0x3332 (13106d)
DH	Networking {Addressing}	**Destination Address High**. Set/Read the upper 32 bits of the 64-bit destination address. When combined with DL, it defines the destination address used for transmission. To transmit using a 16-bit address, set DH parameter to zero and DL less than 0xFFFF. 0x000000000000FFFF is the broadcast address for the PAN.	0 - 0xFFFFFFFF	0
DL	Networking {Addressing}	**Destination Address Low**. Set/Read the lower 32 bits of the 64-bit destination address. When combined with DH, DL defines the destination address used for transmission. To transmit using a 16-bit address, set DH parameter to zero and DL less than 0xFFFF. 0x000000000000FFFF is the broadcast address for the PAN.	0 - 0xFFFFFFFF	0
MY	Networking {Addressing}	**16-bit Source Address.** Set/Read the RF module 16-bit source address. Set MY = 0xFFFF to disable reception of packets with 16-bit addresses. 64-bit source address (serial number) and broadcast address (0x000000000000FFFF) is always enabled.	0 - 0xFFFF	0
SH	Networking {Addressing}	**Serial Number High**. Read high 32 bits of the RF module's unique IEEE 64-bit address. 64-bit source address is always enabled.	0 - 0xFFFFFFFF [read-only]	Factory-set
SL	Networking {Addressing}	**Serial Number Low**. Read low 32 bits of the RF module's unique IEEE 64-bit address. 64-bit source address is always enabled.	0 - 0xFFFFFFFF [read-only]	Factory-set
RR (v1.xA0*)	Networking {Addressing}	**XBee Retries**. Set/Read the maximum number of retries the module will execute in addition to the 3 retries provided by the 802.15.4 MAC. For each XBee retry, the 802.15.4 MAC can execute up to 3 retries.	0 - 6	0
RN	Networking {Addressing}	**Random Delay Slots.** Set/Read the minimum value of the back-off exponent in the CSMA-CA algorithm that is used for collision avoidance. If RN = 0, collision avoidance is disabled during the first iteration of the algorithm (802.15.4 - macMinBE).	0 - 3 [exponent]	0
MM (v1.x80*)	Networking {Addressing}	**MAC Mode.** MAC Mode. Set/Read MAC Mode value. MAC Mode enables/disables the use of a Digi header in the 802.15.4 RF packet. When Modes 0 or 3 are enabled (MM=0,3), duplicate packet detection is enabled as well as certain AT commands. Please see the detailed MM description on page 47 for additional information.	0 - 3 0 = Digi Mode 1 = 802.15.4 (no ACKs) 2 = 802.15.4 (with ACKs) 3 = Digi Mode (no ACKs)	0
NI (v1.x80*)	Networking {Identification}	**Node Identifier.** Stores a string identifier. The register only accepts printable ASCII data. A string can not start with a space. Carriage return ends command. Command will automatically end when maximum bytes for the string have been entered. This string is returned as part of the ND (Node Discover) command. This identifier is also used with the DN (Destination Node) command.	20-character ASCII string	-
ND (v1.x80*)	Networking {Identification}	**Node Discover.** Discovers and reports all RF modules found. The following information is reported for each module discovered (the example cites use of Transparent operation (AT command format) - refer to the long ND command description regarding differences between Transparent and API operation). MY<CR> SH<CR> SL<CR> DB<CR> NI<CR><CR> The amount of time the module allows for responses is determined by the NT parameter. In Transparent operation, command completion is designated by a <CR> (carriage return). ND also accepts a Node Identifier as a parameter. In this case, only a module matching the supplied identifier will respond. If ND self-response is enabled (NO=1) the module initiating the node discover will also output a response for itself.	optional 20-character NI value	
NT (v1.xA0*)	Networking {Identification}	**Node Discover Time.** Set/Read the amount of time a node will wait for responses from other nodes when using the ND (Node Discover) command.	0x01 - 0xFC [x 100 ms]	0x19

Table 3-02. XBee®/XBee-PRO® Commands - Networking & Security (Sub-categories designated within {brackets})

AT Command	Command Category	Name and Description	Parameter Range	Default
NO (v1xC5)	Networking {Identification}	**Node Discover Options**. Enables node discover self-response on the module.	0-1	0
DN (v1.x80*)	Networking {Identification}	**Destination Node.** Resolves an NI (Node Identifier) string to a physical address. The following events occur upon successful command execution: 1. DL and DH are set to the address of the module with the matching Node Identifier. 2. "OK" is returned. 3. RF module automatically exits AT Command Mode If there is no response from a module within 200 msec or a parameter is not specified (left blank), the command is terminated and an "ERROR" message is returned.	20-character ASCII string	-
CE (v1.x80*)	Networking {Association}	**Coordinator Enable**. Set/Read the coordinator setting.	0 - 1 0 = End Device 1 = Coordinator	0
SC (v1.x80*)	Networking {Association}	**Scan Channels**. Set/Read list of channels to scan for all Active and Energy Scans as a bitfield. This affects scans initiated in command mode (AS, ED) and during End Device Association and Coordinator startup: bit 0 - 0x0B bit 4 - 0x0F bit 8 - 0x13 bit12 - 0x17 bit 1 - 0x0C bit 5 - 0x10 bit 9 - 0x14 bit13 - 0x18 bit 2 - 0x0D bit 6 - 0x11 bit 10 - 0x15 bit14 - 0x19 bit 3 - 0x0E bit 7 - 0x12 bit 11 - 0x16 bit 15 - 0x1A	0 - 0xFFFF [bitfield] (bits 0, 14, 15 not allowed on the XBee-PRO)	0x1FFE (all XBee-PRO Channels)
SD (v1.x80*)	Networking {Association}	**Scan Duration**. Set/Read the scan duration exponent. ***End Device*** - Duration of Active Scan during Association. ***Coordinator*** - If 'ReassignPANID' option is set on Coordinator [refer to A2 parameter], SD determines the length of time the Coordinator will scan channels to locate existing PANs. If 'ReassignChannel' option is set, SD determines how long the Coordinator will perform an Energy Scan to determine which channel it will operate on. 'Scan Time' is measured as (# of channels to scan] * (2 ^ SD) * 15.36ms). The number of channels to scan is set by the SC command. The XBee can scan up to 16 channels (SC = 0xFFFF). The XBee PRO can scan up to 13 channels (SC = 0x3FFE). Example: The values below show results for a 13 channel scan: If SD = 0, time = 0.18 sec SD = 8, time = 47.19 sec SD = 2, time = 0.74 sec SD = 10, time = 3.15 min SD = 4, time = 2.95 sec SD = 12, time = 12.58 min SD = 6, time = 11.80 sec SD = 14, time = 50.33 min	0-0x0F [exponent]	4
A1 (v1.x80*)	Networking {Association}	**End Device Association**. Set/Read End Device association options. bit 0 - ReassignPanID 0 - Will only associate with Coordinator operating on PAN ID that matches module ID 1 - May associate with Coordinator operating on any PAN ID bit 1 - ReassignChannel 0 - Will only associate with Coordinator operating on matching CH Channel setting 1 - May associate with Coordinator operating on any Channel bit 2 - AutoAssociate 0 - Device will not attempt Association 1 - Device attempts Association until success Note: This bit is used only for Non-Beacon systems. End Devices in Beacon-enabled system must always associate to a Coordinator bit 3 - PollCoordOnPinWake 0 - Pin Wake will not poll the Coordinator for indirect (pending) data 1 - Pin Wake will send Poll Request to Coordinator to extract any pending data bits 4 - 7 are reserved	0 - 0x0F [bitfield]	0
A2 (v1.x80*)	Networking {Association}	**Coordinator Association**. Set/Read Coordinator association options. bit 0 - ReassignPanID 0 - Coordinator will not perform Active Scan to locate available PAN ID. It will operate on ID (PAN ID). 1 - Coordinator will perform Active Scan to determine an available ID (PAN ID). If a PAN ID conflict is found, the ID parameter will change. bit 1 - ReassignChannel - 0 - Coordinator will not perform Energy Scan to determine free channel. It will operate on the channel determined by the CH parameter. 1 - Coordinator will perform Energy Scan to find a free channel, then operate on that channel. bit 2 - AllowAssociation - 0 - Coordinator will not allow any devices to associate to it. 1 - Coordinator will allow devices to associate to it. bits 3 - 7 are reserved	0 - 7 [bitfield]	0

Table 3-02. XBee®/XBee-PRO® Commands - Networking & Security (Sub-categories designated within {brackets})

AT Command	Command Category	Name and Description	Parameter Range	Default
AI (v1.x80*)	Networking {Association}	**Association Indication**. Read errors with the last association request: 0x00 - Successful Completion - Coordinator successfully started or End Device association complete 0x01 - Active Scan Timeout 0x02 - Active Scan found no PANs 0x03 - Active Scan found PAN, but the CoordinatorAllowAssociation bit is not set 0x04 - Active Scan found PAN, but Coordinator and End Device are not configured to support beacons 0x05 - Active Scan found PAN, but the Coordinator ID parameter does not match the ID parameter of the End Device 0x06 - Active Scan found PAN, but the Coordinator CH parameter does not match the CH parameter of the End Device 0x07 - Energy Scan Timeout 0x08 - Coordinator start request failed 0x09 - Coordinator could not start due to invalid parameter 0x0A - Coordinator Realignment is in progress 0x0B - Association Request not sent 0x0C - Association Request timed out - no reply was received 0x0D - Association Request had an Invalid Parameter 0x0E - Association Request Channel Access Failure. Request was not transmitted - CCA failure 0x0F - Remote Coordinator did not send an ACK after Association Request was sent 0x10 - Remote Coordinator did not reply to the Association Request, but an ACK was received after sending the request 0x11 - [reserved] 0x12 - Sync-Loss - Lost synchronization with a Beaconing Coordinator 0x13 - Disassociated - No longer associated to Coordinator 0xFF - RF Module is attempting to associate	0 - 0x13 [read-only]	-
DA (v1.x80*)	Networking {Association}	**Force Disassociation**. End Device will immediately disassociate from a Coordinator (if associated) and reattempt to associate.	-	-
FP (v1.x80*)	Networking {Association}	**Force Poll**. Request indirect messages being held by a coordinator.	-	-
AS (v1.x80*)	Networking {Association}	**Active Scan**. Send Beacon Request to Broadcast Address (0xFFFF) and Broadcast PAN (0xFFFF) on every channel. The parameter determines the time the radio will listen for Beacons on each channel. A PanDescriptor is created and returned for every Beacon received from the scan. Each PanDescriptor contains the following information: CoordAddress (SH, SL)<CR> CoordPanID (ID)<CR> CoordAddrMode <CR> 0x02 = 16-bit Short Address 0x03 = 64-bit Long Address Channel (CH parameter) <CR> SecurityUse<CR> ACLEntry<CR> SecurityFailure<CR> SuperFrameSpec<CR> (2 bytes): bit 15 - Association Permitted (MSB) bit 14 - PAN Coordinator bit 13 - Reserved bit 12 - Battery Life Extension bits 8-11 - Final CAP Slot bits 4-7 - Superframe Order bits 0-3 - Beacon Order GtsPermit<CR> RSSI<CR> (RSSI is returned as -dBm) TimeStamp<CR> (3 bytes) <CR> A carriage return <CR> is sent at the end of the AS command. The Active Scan is capable of returning up to 5 PanDescriptors in a scan. The actual scan time on each channel is measured as Time = [(2 ^SD PARAM) * 15.36] ms. Note the total scan time is this time multiplied by the number of channels to be scanned (16 for the XBee and 13 for the XBee-PRO). Also refer to SD command description.	0 - 6	-
ED (v1.x80*)	Networking {Association}	**Energy Scan**. Send an Energy Detect Scan. This parameter determines the length of scan on each channel. The maximal energy on each channel is returned & each value is followed by a carriage return. An additional carriage return is sent at the end of the command. The values returned represent the detected energy level in units of -dBm. The actual scan time on each channel is measured as Time = [(2 ^ED) * 15.36] ms. Note the total scan time is this time multiplied by the number of channels to be scanned (refer to SD parameter).	0 - 6	-
EE (v1.xA0*)	Networking {Security}	**AES Encryption Enable**. Disable/Enable 128-bit AES encryption support. Use in conjunction with the KY command.	0 - 1	0 (disabled)
KY (v1.xA0*)	Networking {Security}	**AES Encryption Key**. Set the 128-bit AES (Advanced Encryption Standard) key for encrypting/decrypting data. The KY register cannot be read.	0 - (any 16-Byte value)	-

* Firmware version in which the command was first introduced (firmware versions are numbered in hexadecimal notation.)

RF Interfacing

Table 3-03. XBee/XBee-PRO Commands - RF Interfacing

AT Command	Command Category	Name and Description	Parameter Range	Default
PL	RF Interfacing	**Power Level**. Select/Read the power level at which the RF module transmits conducted power.	0 - 4 (XBee / XBee-PRO) 0 = -10 / 10 dBm 1 = -6 / 12 dBm 2 = -4 / 14 dBm 3 = -2 / 16 dBm 4 = 0 / 18 dBm XBee-PRO International variant: PL=4: 10 dBm PL=3: 8 dBm PL=2: 2 dBm PL=1: -3 dBm PL=0: -3 dBm	4
CA (v1.x80*)	RF Interfacing	**CCA Threshold**. Set/read the CCA (Clear Channel Assessment) threshold. Prior to transmitting a packet, a CCA is performed to detect energy on the channel. If the detected energy is above the CCA Threshold, the module will not transmit the packet.	0x24 - 0x50 [-dBm]	0x2C (-44d dBm)

* Firmware version in which the command was first introduced (firmware versions are numbered in hexadecimal notation.)

Sleep (Low Power)

Table 3-04. XBee®/XBee-PRO® Commands - Sleep (Low Power)

AT Command	Command Category	Name and Description	Parameter Range	Default
SM	Sleep (Low Power)	**Sleep Mode**. Set/Read Sleep Mode configurations.	0 - 5 0 = No Sleep 1 = Pin Hibernate 2 = Pin Doze 3 = Reserved 4 = Cyclic sleep remote 5 = Cyclic sleep remote w/ pin wake-up 6 = [Sleep Coordinator] for backwards compatibility w/ v1.x6 only; otherwise, use CE command.	0
SO	Sleep (Low Power)	Sleep Options Set/Read the sleep mode options. Bit 0 - Poll wakeup disable 0 - Normal operations. A module configured for cyclic sleep will poll for data on waking. 1 - Disable wakeup poll. A module configured for cyclic sleep will not poll for data on waking. Bit 1 - ADC/DIO wakeup sampling disable. 0 - Normal operations. A module configured in a sleep mode with ADC/DIO sampling enabled will automatically perform a sampling on wakeup. 1 - Suppress sample on wakeup. A module configured in a sleep mode with ADC/DIO sampling enabled will not automatically sample on wakeup.	0-4	0
ST	Sleep (Low Power)	**Time before Sleep.** <NonBeacon firmware> Set/Read time period of inactivity (no serial or RF data is sent or received) before activating Sleep Mode. ST parameter is only valid with Cyclic Sleep settings (SM = 4 - 5). Coordinator and End Device ST values must be equal. Also note, the GT parameter value must always be less than the ST value. (If GT > ST, the configuration will render the module unable to enter into command mode.) If the ST parameter is modified, also modify the GT parameter accordingly.	1 - 0xFFFF [x 1 ms]	0x1388 (5000d)
SP	Sleep (Low Power)	**Cyclic Sleep Period.** <NonBeacon firmware> Set/Read sleep period for cyclic sleeping remotes. Coordinator and End Device SP values should always be equal. To send Direct Messages, set SP = 0. *End Device* - SP determines the sleep period for cyclic sleeping remotes. Maximum sleep period is 268 seconds (0x68B0). *Coordinator* - If non-zero, SP determines the time to hold an indirect message before discarding it. A Coordinator will discard indirect messages after a period of (2.5 * SP).	0 - 0x68B0 [x 10 ms]	0
DP (1.x80*)	Sleep (Low Power)	**Disassociated Cyclic Sleep Period.** <NonBeacon firmware> *End Device* - Set/Read time period of sleep for cyclic sleeping remotes that are configured for Association but are not associated to a Coordinator. (i.e. If a device is configured to associate, configured as a Cyclic Sleep remote, but does not find a Coordinator, it will sleep for DP time before reattempting association.) Maximum sleep period is 268 seconds (0x68B0). DP should be > 0 for NonBeacon systems.	1 - 0x68B0 [x 10 ms]	0x3E8 (1000d)

* Firmware version in which the command was first introduced (firmware versions are numbered in hexadecimal notation.)

Serial Interfacing

Table 3-05. XBee-PRO Commands - Serial Interfacing

AT Command	Command Category	Name and Description	Parameter Range	Default
BD	Serial Interfacing	**Interface Data Rate**. Set/Read the serial interface data rate for communications between the RF module serial port and host. Request non-standard baud rates with values above 0x80 using a terminal window. Read the BD register to find actual baud rate achieved.	0 - 7 (standard baud rates) 0 = 1200 bps 1 = 2400 2 = 4800 3 = 9600 4 = 19200 5 = 38400 6 = 57600 7 = 115200 0x80 - 0x3D090 (non-standard baud rates up to 250 Kbps)	3
RO	Serial Interfacing	**Packetization Timeout**. Set/Read number of character times of inter-character delay required before transmission. Set to zero to transmit characters as they arrive instead of buffering them into one RF packet.	0 - 0xFF [x character times]	3
AP (v1.x80*)	Serial Interfacing	**API Enable**. Disable/Enable API Mode.	0 - 2 0 =Disabled 1 = API enabled 2 = API enabled (w/escaped control characters)	0
NB	Serial Interfacing	**Parity.** Set/Read parity settings.	0 - 4 0 = 8-bit no parity 1 = 8-bit even 2 = 8-bit odd 3 = 8-bit mark 4 = 8-bit space	0
PR (v1.x80*)	Serial Interfacing	**Pull-up Resistor Enable**. Set/Read bitfield to configure internal pull-up resistor status for I/O lines Bitfield Map: bit 0 - AD4/DIO4 (pin11) bit 1 - AD3 / DIO3 (pin17) bit 2 - AD2/DIO2 (pin18) bit 3 - AD1/DIO1 (pin19) bit 4 - AD0 / DIO0 (pin20) bit 5 - RTS / AD6 / DIO6 (pin16) bit 6 - DTR / SLEEP_RQ / DI8 (pin9) bit 7 - DIN/CONFIG (pin3) Bit set to “1” specifies pull-up enabled; “0” specifies no pull-up	0 - 0xFF	0xFF

* Firmware version in which the command was first introduced (firmware versions are numbered in hexadecimal notation.)

I/O Settings

Table 3-06. XBee-PRO Commands - I/O Settings (sub-category designated within {brackets})

AT Command	Command Category	Name and Description	Parameter Range	Default
D8	I/O Settings	**DI8 Configuration**. Select/Read options for the DI8 line (pin 9) of the RF module.	0 - 1 0 = Disabled 3 = DI (1,2,4 & 5 n/a)	0
D7 (v1.x80*)	I/O Settings	**DIO7 Configuration**. Select/Read settings for the DIO7 line (pin 12) of the RF module. Options include CTS flow control and I/O line settings.	0 - 1 0 = Disabled 1 = CTS Flow Control 2 = (n/a) 3 = DI 4 = DO low 5 = DO high 6 = RS485 Tx Enable Low 7 = RS485 Tx Enable High	1
D6 (v1.x80*)	I/O Settings	**DIO6 Configuration**. Select/Read settings for the DIO6 line (pin 16) of the RF module. Options include RTS flow control and I/O line settings.	0 - 1 0 = Disabled 1 = RTS flow control 2 = (n/a) 3 = DI 4 = DO low 5 = DO high	0

Table 3-06. **XBee-PRO Commands - I/O Settings** (sub-category designated within {brackets})

AT Command	Command Category	Name and Description	Parameter Range	Default
D5 (v1.x80*)	I/O Settings	**DIO5 Configuration**. Configure settings for the DIO5 line (pin 15) of the RF module. Options include Associated LED indicator (blinks when associated) and I/O line settings.	0 - 1 0 = Disabled 1 = Associated indicator 2 = ADC 3 = DI 4 = DO low 5 = DO high	1
D0 - D4 (v1.xA0*)	I/O Settings	**(DIO4 -DIO4) Configuration**. Select/Read settings for the following lines: AD0/DIO0 (pin 20), AD1/DIO1 (pin 19), AD2/DIO2 (pin 18), AD3/DIO3 (pin 17), AD4/DIO4 (pin 11). Options include: Analog-to-digital converter, Digital Input and Digital Output.	0 - 1 0 = Disabled 1 = (n/a) 2 = ADC 3 = DI 4 = DO low 5 = DO high	0
IU (v1.xA0*)	I/O Settings	**I/O Output Enable.** Disables/Enables I/O data received to be sent out UART. The data is sent using an API frame regardless of the current AP parameter value.	0 - 1 0 = Disabled 1 = Enabled	1
IT (v1.xA0*)	I/O Settings	**Samples before TX.** Set/Read the number of samples to collect before transmitting data. Maximum number of samples is dependent upon the number of enabled inputs.	1 - 0xFF	1
IS (v1.xA0*)	I/O Settings	**Force Sample.** Force a read of all enabled inputs (DI or ADC). Data is returned through the UART. If no inputs are defined (DI or ADC), this command will return error.	8-bit bitmap (each bit represents the level of an I/O line setup as an output)	-
IO (v1.xA0*)	I/O Settings	**Digital Output Level.** Set digital output level to allow DIO lines that are setup as outputs to be changed through Command Mode.	-	-
IC (v1.xA0*)	I/O Settings	**DIO Change Detect.** Set/Read bitfield values for change detect monitoring. Each bit enables monitoring of DIO0 - DIO7 for changes. If detected, data is transmitted with DIO data only. Any samples queued waiting for transmission will be sent first.	0 - 0xFF [bitfield]	0 (disabled)
IR (v1.xA0*)	I/O Settings	**Sample Rate.** Set/Read sample rate. When set, this parameter causes the module to sample all enabled inputs at a specified interval.	0 - 0xFFFF [x 1 msec]	0
IA (v1.xA0*)	I/O Settings {I/O Line Passing}	**I/O Input Address**. Set/Read addresses of module to which outputs are bound. Setting all bytes to 0xFF will not allow any received I/O packet to change outputs. Setting address to 0xFFFF will allow any received I/O packet to change outputs.	0 - 0xFFFFFFFFFFFFFFFF	0xFFFFFFFF FFFFFFFF
T0 - T7 (v1.xA0*)	I/O Settings {I/O Line Passing}	**(D0 - D7) Output Timeout.** Set/Read Output timeout values for lines that correspond with the D0 - D7 parameters. When output is set (due to I/O line passing) to a non-default level, a timer is started which when expired will set the output to it default level. The timer is reset when a valid I/O packet is received.	0 - 0xFF [x 100 ms]	0xFF
P0	I/O Settings {I/O Line Passing}	**PWM0 Configuration**. Select/Read function for PWM0 pin.	0 - 2 0 = Disabled 1 = RSSI 2 = PWM Output	1
P1 (v1.xA0*)	I/O Settings {I/O Line Passing}	**PWM1 Configuration**. Select/Read function for PWM1 pin.	0 - 2 0 = Disabled 1 = RSSI 2 = PWM Output	0
M0 (v1.xA0*)	I/O Settings {I/O Line Passing}	**PWM0 Output Level**. Set/Read the PWM0 output level.	0 - 0x03FF	-
M1 (v1.xA0*)	I/O Settings {I/O Line Passing}	**PWM1 Output Level**. Set/Read the PWM1 output level.	0 - 0x03FF	-
PT (v1.xA0*)	I/O Settings {I/O Line Passing}	**PWM Output Timeout.** Set/Read output timeout value for both PWM outputs. When PWM is set to a non-zero value: Due to I/O line passing, a time is started which when expired will set the PWM output to zero. The timer is reset when a valid I/O packet is received.]	0 - 0xFF [x 100 ms]	0xFF
RP	I/O Settings {I/O Line Passing}	**RSSI PWM Timer.** Set/Read PWM timer register. Set the duration of PWM (pulse width modulation) signal output on the RSSI pin. The signal duty cycle is updated with each received packet and is shut off when the timer expires.]	0 - 0xFF [x 100 ms]	0x28 (40d)

* Firmware version in which the command was first introduced (firmware versions are numbered in hexadecimal notation.)

Diagnostics

Table 3-07. **XBee®/XBee-PRO® Commands - Diagnostics**

AT Command	Command Category	Name and Description	Parameter Range	Default
VR	Diagnostics	**Firmware Version**. Read firmware version of the RF module.	0 - 0xFFFF [read-only]	Factory-set
VL (v1.x80*)	Diagnostics	**Firmware Version - Verbose**. Read detailed version information (including application build date, MAC, PHY and bootloader versions). The VL command has been deprecated in version 10C9. It is not supported in firmware versions after 10C8	-	-

Table 3-07. XBee®/XBee-PRO® Commands - Diagnostics

AT Command	Command Category	Name and Description	Parameter Range	Default
HV (v1.x80*)	Diagnostics	**Hardware Version**. Read hardware version of the RF module.	0 - 0xFFFF [read-only]	Factory-set
DB	Diagnostics	**Received Signal Strength**. Read signal level [in dB] of last good packet received (RSSI). Absolute value is reported. (For example: 0x58 = -88 dBm) Reported value is accurate between -40 dBm and RX sensitivity.	0x17-0x5C (XBee) 0x24-0x64 (XBee-PRO) [read-only]	-
EC (v1.x80*)	Diagnostics	**CCA Failures.** Reset/Read count of CCA (Clear Channel Assessment) failures. This parameter value increments when the module does not transmit a packet because it detected energy above the CCA threshold level set with CA command. This count saturates at its maximum value. Set count to “0” to reset count.	0 - 0xFFFF	-
EA (v1.x80*)	Diagnostics	**ACK Failures**. Reset/Read count of acknowledgment failures. This parameter value increments when the module expires its transmission retries without receiving an ACK on a packet transmission. This count saturates at its maximum value. Set the parameter to “0” to reset count.	0 - 0xFFFF	-
ED (v1.x80*)	Diagnostics	**Energy Scan**. Send ‘Energy Detect Scan’. ED parameter determines the length of scan on each channel. The maximal energy on each channel is returned and each value is followed by a carriage return. Values returned represent detected energy levels in units of -dBm. Actual scan time on each channel is measured as Time = [(2 ^ SD) * 15.36] ms. Total scan time is this time multiplied by the number of channels to be scanned.	0 - 6	-

* Firmware version in which the command was first introduced (firmware versions are numbered in hexadecimal notation.)

AT Command Options

Table 3-08. XBee®/XBee-PRO® Commands - AT Command Options

AT Command	Command Category	Name and Description	Parameter Range	Default
CT	AT Command Mode Options	**Command Mode Timeout.** Set/Read the period of inactivity (no valid commands received) after which the RF module automatically exits AT Command Mode and returns to Idle Mode.	2 - 0xFFFF [x 100 ms]	0x64 (100d)
CN	AT Command Mode Options	**Exit Command Mode**. Explicitly exit the module from AT Command Mode.	--	--
AC (v1.xA0*)	AT Command Mode Options	**Apply Changes**. Explicitly apply changes to queued parameter value(s) and re-initialize module.	--	--
GT	AT Command Mode Options	**Guard Times**. Set required period of silence before and after the Command Sequence Characters of the AT Command Mode Sequence (GT+ CC + GT). The period of silence is used to prevent inadvertent entrance into AT Command Mode.	2 - 0x0CE4 [x 1 ms]	0x3E8 (1000d)
CC	AT Command Mode Options	**Command Sequence Character**. Set/Read the ASCII character value to be used between Guard Times of the AT Command Mode Sequence (GT+CC+GT). The AT Command Mode Sequence enters the RF module into AT Command Mode.	0 - 0xFF	0x2B ('+' ASCII)

* Firmware version in which the command was first introduced (firmware versions are numbered in hexadecimal notation.)

Command Descriptions

Command descriptions in this section are listed alphabetically. Command categories are designated within "< >" symbols that follow each command title. XBee®/XBee-PRO® RF Modules expect parameter values in hexadecimal (designated by the "0x" prefix).

All modules operating within the same network should contain the same firmware version.

A1 (End Device Association) Command

<Networking {Association}> The A1 command is used to set and read association options for an End Device.

Use the table below to determine End Device behavior in relation to the A1 parameter.

AT Command: ATA1

Parameter Range: 0 – 0x0F [bitfield]

Default Parameter Value: 0

Related Commands: ID (PAN ID), NI (Node Identifier), CH (Channel), CE (Coordinator Enable), A2 (Coordinator Association)

Minimum Firmware Version Required: v1.x80

Bit number	End Device Association Option
0 - ReassignPanID	0 - Will only associate with Coordinator operating on PAN ID that matches Node Identifier
	1 - May associate with Coordinator operating on any PAN ID
1 - ReassignChannel	0 - Will only associate with Coordinator operating on Channel that matches CH setting
	1 - May associate with Coordinator operating on any Channel
2 - AutoAssociate	0 - Device will not attempt Association
	1 - Device attempts Association until success Note: This bit is used only for Non-Beacon systems. End Devices in a Beaconing system must always associate to a Coordinator
3 - PollCoordOnPinWake	0 - Pin Wake will not poll the Coordinator for pending (indirect) Data
	1 - Pin Wake will send Poll Request to Coordinator to extract any pending data
4 - 7	[reserved]

A2 (Coordinator Association) Command

<Networking {Association}> The A2 command is used to set and read association options of the Coordinator.

Use the table below to determine Coordinator behavior in relation to the A2 parameter.

AT Command: ATA2

Parameter Range: 0 – 7 [bitfield]

Default Parameter Value: 0

Related Commands: ID (PAN ID), NI (Node Identifier), CH (Channel), CE (Coordinator Enable), A1 (End Device Association), AS Active Scan), ED (Energy Scan)

Minimum Firmware Version Required: v1.x80

Bit number	End Device Association Option
0 - ReassignPanID	0 - Coordinator will not perform Active Scan to locate available PAN ID. It will operate on ID (PAN ID).
	1 - Coordinator will perform Active Scan to determine an available ID (PAN ID). If a PAN ID conflict is found, the ID parameter will change.
1 - ReassignChannel	0 - Coordinator will not perform Energy Scan to determine free channel. It will operate on the channel determined by the CH parameter.
	1 - Coordinator will perform Energy Scan to find a free channel, then operate on that channel.
2 - AllowAssociate	0 - Coordinator will not allow any devices to associate to it.
	1 - Coordinator will allow devices to associate to it.
3 - 7	[reserved]

The binary equivalent of the default value (0x06) is 00000110. ‘Bit 0’ is the last digit of the sequence.

AC (Apply Changes) Command

AT Command: ATAC
Minimum Firmware Version Required: v1.xA0

<AT Command Mode Options> The AC command is used to explicitly apply changes to module parameter values. 'Applying changes' means that the module is re-initialized based on changes made to its parameter values. Once changes are applied, the module immediately operates according to the new parameter values.

This behavior is in contrast to issuing the WR (Write) command. The WR command saves parameter values to non-volatile memory, but the module still operates according to previously saved values until the module is re-booted or the CN (Exit AT Command Mode) command is issued.

Refer to the "AT Command - Queue Parameter Value" API type for more information.

AI (Association Indication) Command

AT Command: ATAI
Parameter Range: 0 - 0x13 [read-only]
Related Commands: AS (Active Scan), ID (PAN ID), CH (Channel), ED (Energy Scan), A1 (End Device Association), A2 (Coordinator Association), CE (Coordinator Enable)
Minimum Firmware Version Required: v1.x80

<Networking {Association}> The AI command is used to indicate occurrences of errors during the last association request.

Use the table below to determine meaning of the returned values.

Returned Value (Hex)	Association Indication
0x00	Successful Completion - Coordinator successfully started or End Device association complete
0x01	Active Scan Timeout
0x02	Active Scan found no PANs
0x03	Active Scan found PAN, but the Coordinator Allow Association bit is not set
0x04	Active Scan found PAN, but Coordinator and End Device are not configured to support beacons
0x05	Active Scan found PAN, but Coordinator ID (PAN ID) value does not match the ID of the End Device
0x06	Active Scan found PAN, but Coordinator CH (Channel) value does not match the CH of the End Device
0x07	Energy Scan Timeout
0x08	Coordinator start request failed
0x09	Coordinator could not start due to Invalid Parameter
0x0A	Coordinator Realignment is in progress
0x0B	Association Request not sent
0x0C	Association Request timed out - no reply was received
0x0D	Association Request had an Invalid Parameter
0x0E	Association Request Channel Access Failure - Request was not transmitted - CCA failure
0x0F	Remote Coordinator did not send an ACK after Association Request was sent
0x10	Remote Coordinator did not reply to the Association Request, but an ACK was received after sending the request
0x11	[reserved]
0x12	Sync-Loss - Lost synchronization with a Beaconing Coordinator
0x13	Disassociated - No longer associated to Coordinator
0xFF	RF Module is attempting to associate

AP (API Enable) Command

<Serial Interfacing> The AP command is used to enable the RF module to operate using a frame-based API instead of using the default Transparent (UART) mode.

AT Command: ATAP	
Parameter Range:0 – 2	
Parameter	Configuration
0	Disabled (Transparent operation)
1	API enabled
2	API enabled (with escaped characters)
Default Parameter Value:0	
Minimum Firmware Version Required: v1.x80	

Refer to the API Operation section when API operation is enabled (AP = 1 or 2).

AS (Active Scan) Command

<Network {Association}> The AS command is used to send a Beacon Request to a Broadcast (0xFFFF) and Broadcast PAN (0xFFFF) on every channel. The parameter determines the amount of time the RF module will listen for Beacons on each channel. A 'PanDescriptor' is created and returned for every Beacon received from the scan. Each PanDescriptor contains the following information:

AT Command: ATAS
Parameter Range: 0 – 6
Related Command: SD (Scan Duration), DL (Destination Low Address), DH (Destination High Address), ID (PAN ID), CH (Channel)
Minimum Firmware Version Required: v1.x80

CoordAddress (SH + SL parameters)<CR> (NOTE: If MY on the coordinator is set less than 0xFFFF, the MY value is displayed)
CoordPanID (ID parameter)<CR>
CoordAddrMode <CR>
  0x02 = 16-bit Short Address
  0x03 = 64-bit Long Address
Channel (CH parameter) <CR>
SecurityUse<CR>
ACLEntry<CR>
SecurityFailure<CR>
SuperFrameSpec<CR> (2 bytes):
  bit 15 - Association Permitted (MSB)
  bit 14 - PAN Coordinator
  bit 13 - Reserved
  bit 12 - Battery Life Extension
  bits 8-11 - Final CAP Slot
  bits 4-7 - Superframe Order
  bits 0-3 - Beacon Order
GtsPermit<CR>
RSSI<CR> (- RSSI is returned as -dBm)
TimeStamp<CR> (3 bytes)
<CR> (A carriage return <CR> is sent at the end of the AS command.

The Active Scan is capable of returning up to 5 PanDescriptors in a scan. The actual scan time on each channel is measured as Time = [(2 ^ (SD Parameter)) * 15.36] ms. Total scan time is this time multiplied by the number of channels to be scanned (16 for the XBee, 12 for the XBee-PRO).

NOTE: Refer the scan table in the SD description to determine scan times. If using API Mode, no <CR>'s are returned in the response. Refer to the API Mode Operation section.

BD (Interface Data Rate) Command

<Serial Interfacing> The BD command is used to set and read the serial interface data rate used between the RF module and host. This parameter determines the rate at which serial data is sent to the module from the host. Modified interface data rates do not take effect until the CN (Exit AT Command Mode) command is issued and the system returns the 'OK' response.

When parameters 0-7 are sent to the module, the respective interface data rates are used (as shown in the table on the right).

The RF data rate is not affected by the BD parameter. If the interface data rate is set higher than the RF data rate, a flow control configuration may need to be implemented.

AT Command: ATBD

Parameter Range:0 – 7 (standard rates)
0x80-0x3D090 (non-standard rates up to 250 Kbps)

Parameter	Configuration (bps)
0	1200
1	2400
2	4800
3	9600
4	19200
5	38400
6	57600
7	115200

Default Parameter Value:3

Non-standard Interface Data Rates:
Any value above 0x07 will be interpreted as an actual baud rate. When a value above 0x07 is sent, the closest interface data rate represented by the number is stored in the BD register. For example, a rate of 19200 bps can be set by sending the following command line "ATBD4B00". NOTE: When using Digi's X-CTU Software, non-standard interface data rates can only be set and read using the X-CTU 'Terminal' tab. Non-standard rates are not accessible through the 'Modem Configuration' tab.

When the BD command is sent with a non-standard interface data rate, the UART will adjust to accommodate the requested interface rate. In most cases, the clock resolution will cause the stored BD parameter to vary from the parameter that was sent (refer to the table below). Reading the BD command (send "ATBD" command without an associated parameter value) will return the value actually stored in the module's BD register.

Parameters Sent Versus Parameters Stored

BD Parameter Sent (HEX)	Interface Data Rate (bps)	BD Parameter Stored (HEX)
0	1200	0
4	19,200	4
7	115,200*	7
12C	300	12B
1C200	115,200	1B207

* The 115,200 baud rate setting is actually at 111,111 baud (-3.5% target UART speed).

CA (CCA Threshold) Command

<RF Interfacing> CA command is used to set and read CCA (Clear Channel Assessment) thresholds.

Prior to transmitting a packet, a CCA is performed to detect energy on the transmit channel. If the detected energy is above the CCA Threshold, the RF module will not transmit the packet.

AT Command: ATCA

Parameter Range: 0 – 0x50 [-dBm]

Default Parameter Value: 0x2C (-44 decimal dBm)

Minimum Firmware Version Required: v1.x80

CC (Command Sequence Character) Command

<AT Command Mode Options> The CC command is used to set and read the ASCII character used between guard times of the AT Command Mode Sequence (GT + CC + GT). This sequence enters the RF module into AT Command Mode so that data entering the module from the host is recognized as commands instead of payload.

AT Command: ATCC
Parameter Range: 0 – 0xFF
Default Parameter Value: 0x2B (ASCII "+")
Related Command: GT (Guard Times)

The AT Command Sequence is explained further in the AT Command Mode section.

CE (Coordinator Enable) Command

<Networking {Association} The CE command is used to set and read the behavior (End Device vs. Coordinator) of the RF module.

AT Command: ATCE

Parameter Range:0 – 1

Parameter	Configuration
0	End Device
1	Coordinator

Default Parameter Value:0

Minimum Firmware Version Required: v1.x80

CH (Channel) Command

<Networking {Addressing}> The CH command is used to set/read the operating channel on which RF connections are made between RF modules. The channel is one of three addressing options available to the module. The other options are the PAN ID (ID command) and destination addresses (DL & DH commands).

AT Command: ATCH
Parameter Range: 0x0B – 0x1A (XBee) 0x0C – 0x17 (XBee-PRO)
Default Parameter Value: 0x0C (12 decimal)
Related Commands: ID (PAN ID), DL (Destination Address Low, DH (Destination Address High)

In order for modules to communicate with each other, the modules must share the same channel number. Different channels can be used to prevent modules in one network from listening to transmissions of another. Adjacent channel rejection is 23 dB.

The module uses channel numbers of the 802.15.4 standard.

Center Frequency = 2.405 + (CH - 11d) * 5 MHz (d = decimal)

Refer to the XBee/XBee-PRO Addressing section for more information.

CN (Exit Command Mode) Command

<AT Command Mode Options> The CN command is used to explicitly exit the RF module from AT Command Mode.

AT Command: ATCN

CT (Command Mode Timeout) Command

<AT Command Mode Options> The CT command is used to set and read the amount of inactive time that elapses before the RF module automatically exits from AT Command Mode and returns to Idle Mode.

Use the CN (Exit Command Mode) command to exit AT Command Mode manually.

AT Command: ATCT
Parameter Range:2 – 0xFFFF [x 100 milliseconds]
Default Parameter Value: 0x64 (100 decimal (which equals 10 decimal seconds))
Number of bytes returned: 2
Related Command: CN (Exit Command Mode)

D0 - D4 (DIOn Configuration) Commands

<I/O Settings> The D0, D1, D2, D3 and D4 commands are used to select/read the behavior of their respective AD/DIO lines (pins 20, 19, 18, 17 and 11 respectively).

Options include:

- Analog-to-digital converter
- Digital input
- Digital output

AT Commands: ATD0, ATD1, ATD2, ATD3, ATD4

Parameter Range:0 – 5

Parameter	Configuration
0	Disabled
1	n/a
2	ADC
3	DI
4	DO low
5	DO high

Default Parameter Value:0

Minimum Firmware Version Required: 1.x.A0

D5 (DIO5 Configuration) Command

<I/O Settings> The D5 command is used to select/read the behavior of the DIO5 line (pin 15).

Options include:

- Associated Indicator (LED blinks when the module is associated)
- Analog-to-digital converter
- Digital input
- Digital output

AT Command: ATD5

Parameter Range:0 – 5

Parameter	Configuration
0	Disabled
1	Associated Indicator
2	ADC
3	DI
4	DO low
5	DO high

Default Parameter Value:1

Parameters 2–5 supported as of firmware version 1.xA0

D6 (DIO6 Configuration) Command

<I/O Settings> The D6 command is used to select/read the behavior of the DIO6 line (pin 16). Options include:

- RTS flow control
- Analog-to-digital converter
- Digital input
- Digital output

AT Command: ATD6

Parameter Range:0 – 5

Parameter	Configuration
0	Disabled
1	RTS Flow Control
2	n/a
3	DI
4	DO low
5	DO high

Default Parameter Value:0

Parameters 3–5 supported as of firmware version 1.xA0

D7 (DIO7 Configuration) Command

<I/O Settings> The D7 command is used to select/read the behavior of the DIO7 line (pin 12). Options include:

- CTS flow control
- Analog-to-digital converter
- Digital input
- Digital output
- RS485 TX Enable (this output is 3V CMOS level, and is useful in a 3V CMOS to RS485 conversion circuit)

AT Command: ATD7

Parameter Range:0 – 5

Parameter	Configuration
0	Disabled
1	CTS Flow Control
2	n/a
3	DI
4	DO low
5	DO high
6	RS485 TX Enable Low
7	RS485 TX Enable High

Default Parameter Value:1

Parameters 3-7 supported as of firmware version 1.x.A0

D8 (DI8 Configuration) Command

<I/O Settings> The D8 command is used to select/read the behavior of the DI8 line (pin 9). This command enables configuring the pin to function as a digital input. This line is also used with Pin Sleep.

AT Command: ATD8

Parameter Range:0 – 5
(1, 2, 4 & 5 n/a)

Parameter	Configuration
0	Disabled
3	DI

Default Parameter Value:0

Minimum Firmware Version Required: 1.xA0

DA (Force Disassociation) Command

<(Special)> The DA command is used to immediately disassociate an End Device from a Coordinator and reattempt to associate.

AT Command: ATDA

Minimum Firmware Version Required: v1.x80

DB (Received Signal Strength) Command

<Diagnostics> DB parameter is used to read the received signal strength (in dBm) of the last RF packet received. Reported values are accurate between -40 dBm and the RF module's receiver sensitivity.

AT Command: ATDB

Parameter Range [read-only]:
0x17-0x5C (XBee), 0x24-0x64 (XBee-PRO)

Absolute values are reported. For example: 0x58 = -88 dBm (decimal). If no packets have been received (since last reset, power cycle or sleep event), "0" will be reported.

DH (Destination Address High) Command

<Networking {Addressing}> The DH command is used to set and read the upper 32 bits of the RF module's 64-bit destination address. When combined with the DL (Destination Address Low) parameter, it defines the destination address used for transmission.

An module will only communicate with other modules having the same channel (CH parameter), PAN ID (ID parameter) and destination address (DH + DL parameters).

AT Command: ATDH

Parameter Range: 0 – 0xFFFFFFFF

Default Parameter Value: 0

Related Commands: DL (Destination Address Low), CH (Channel), ID (PAN VID), MY (Source Address)

To transmit using a 16-bit address, set the DH parameter to zero and the DL parameter less than 0xFFFF. 0x000000000000FFFF (DL concatenated to DH) is the broadcast address for the PAN.

Refer to the XBee/XBee-PRO Addressing section for more information.

DL (Destination Address Low) Command

<Networking {Addressing}> The DL command is used to set and read the lower 32 bits of the RF module's 64-bit destination address. When combined with the DH (Destination Address High) parameter, it defines the destination address used for transmission.

AT Command: ATDL
Parameter Range: 0 - 0xFFFFFFFF
Default Parameter Value: 0
Related Commands: DH (Destination Address High), CH (Channel), ID (PAN VID), MY (Source Address)

A module will only communicate with other modules having the same channel (CH parameter), PAN ID (ID parameter) and destination address (DH + DL parameters).

To transmit using a 16-bit address, set the DH parameter to zero and the DL parameter less than 0xFFFF. 0x000000000000FFFF (DL concatenated to DH) is the broadcast address for the PAN.

Refer to the XBee/XBee-PRO Addressing section for more information.

DN (Destination Node) Command

<Networking {Identification}> The DN command is used to resolve a NI (Node Identifier) string to a physical address. The following events occur upon successful command execution:

AT Command: ATDN
Parameter Range: 20-character ASCII String
Minimum Firmware Version Required: v1.x80

1. DL and DH are set to the address of the module with the matching NI (Node Identifier).
2. 'OK' is returned.
3. RF module automatically exits AT Command Mode.

If there is no response from a modem within 200 msec or a parameter is not specified (left blank), the command is terminated and an 'ERROR' message is returned.

DP (Disassociation Cyclic Sleep Period) Command

<Sleep Mode (Low Power)>

AT Command: ATDP
Parameter Range: 1 – 0x68B0 [x 10 milliseconds]
Default Parameter Value:0x3E8 (1000 decimal)
Related Commands: SM (Sleep Mode), SP (Cyclic Sleep Period), ST (Time before Sleep)
Minimum Firmware Version Required: v1.x80

NonBeacon Firmware

End Device - The DP command is used to set and read the time period of sleep for cyclic sleeping remotes that are configured for Association but are not associated to a Coordinator. (i.e. If a device is configured to associate, configured as a Cyclic Sleep remote, but does not find a Coordinator; it will sleep for DP time before reattempting association.) Maximum sleep period is 268 seconds (0x68B0). DP should be > 0 for NonBeacon systems.

EA (ACK Failures) Command

<Diagnostics> The EA command is used to reset and read the count of ACK (acknowledgement) failures. This parameter value increments when the module expires its transmission retries without receiving an ACK on a packet transmission. This count saturates at its maximum value.

AT Command: ATEA
Parameter Range:0 – 0xFFFF
Minimum Firmware Version Required: v1.x80

Set the parameter to "0" to reset count.

EC (CCA Failures) Command

<Diagnostics> The EC command is used to read and reset the count of CCA (Clear Channel Assessment) failures. This parameter value increments when the RF module does not transmit a packet due to the detection of energy that is above the CCA threshold level (set with CA command). This count saturates at its maximum value.

Set the EC parameter to "0" to reset count.

AT Command: ATEC
Parameter Range:0 – 0xFFFF
Related Command: CA (CCA Threshold)
Minimum Firmware Version Required: v1.x80

ED (Energy Scan) Command

<Networking {Association}> The ED command is used to send an "Energy Detect Scan". This parameter determines the length of scan on each channel. The maximal energy on each channel is returned and each value is followed by a carriage return. An additional carriage return is sent at the end of the command.

AT Command: ATED
Parameter Range:0 – 6
Related Command: SD (Scan Duration), SC (Scan Channel)
Minimum Firmware Version Required: v1.x80

The values returned represent the detected energy level in units of -dBm. The actual scan time on each channel is measured as Time = [(2 ^ ED PARAM) * 15.36] ms.

Note: Total scan time is this time multiplied by the number of channels to be scanned. Also refer to the SD (Scan Duration) table. Use the SC (Scan Channel) command to choose which channels to scan.

EE (AES Encryption Enable) Command

<Networking {Security}> The EE command is used to set/read the parameter that disables/enables 128-bit AES encryption.

The XBee®/XBee-PRO® firmware uses the 802.15.4 Default Security protocol and uses AES encryption with a 128-bit key. AES encryption dictates that all modules in the network use the same key and the maximum RF packet size is 95 Bytes.

AT Command: ATEE		
Parameter Range:0 – 1		
	Parameter	Configuration
	0	Disabled
	1	Enabled
Default Parameter Value:0		
Related Commands: KY (Encryption Key), AP (API Enable), MM (MAC Mode)		
Minimum Firmware Version Required: v1.xA0		

When encryption is enabled, the module will always use its 64-bit long address as the source address for RF packets. This does not affect how the MY (Source Address), DH (Destination Address High) and DL (Destination Address Low) parameters work

If MM (MAC Mode) > 0 and AP (API Enable) parameter > 0:
With encryption enabled and a 16-bit short address set, receiving modules will only be able to issue RX (Receive) 64-bit indicators. This is not an issue when MM = 0.

If a module with a non-matching key detects RF data, but has an incorrect key: When encryption is enabled, non-encrypted RF packets received will be rejected and will not be sent out the UART.

Transparent Operation --> All RF packets are sent encrypted if the key is set.

API Operation --> Receive frames use an option bit to indicate that the packet was encrypted.

FP (Force Poll) Command

<Networking (Association)> The FP command is used to request indirect messages being held by a Coordinator.

AT Command: ATFP
Minimum Firmware Version Required: v1.x80

FR (Software Reset) Command

<Special> The FR command is used to force a software reset on the RF module. The reset simulates powering off and then on again the module.

AT Command: ATFR
Minimum Firmware Version Required: v1.x80

GT (Guard Times) Command

<AT Command Mode Options> GT Command is used to set the DI (data in from host) time-of-silence that surrounds the AT command sequence character (CC Command) of the AT Command Mode sequence (GT + CC + GT).

The DI time-of-silence is used to prevent inadvertent entrance into AT Command Mode.

Refer to the Command Mode section for more information regarding the AT Command Mode Sequence.

AT Command: ATGT
Parameter Range:2 – 0x0CE4 [x 1 millisecond]
Default Parameter Value:0x3E8 (1000 decimal)
Related Command: CC (Command Sequence Character)

HV (Hardware Version) Command

<Diagnostics> The HV command is used to read the hardware version of the RF module.

AT Command: ATHV
Parameter Range:0 – 0xFFFF [Read–only]
Minimum Firmware Version Required: v1.x80

IA (I/O Input Address) Command

<I/O Settings {I/O Line Passing}> The IA command is used to bind a module output to a specific address. Outputs will only change if received from this address. The IA command can be used to set/read both 16 and 64-bit addresses.

Setting all bytes to 0xFF will not allow the reception of any I/O packet to change outputs. Setting the IA address to 0xFFFF will cause the module to accept all I/O packets.

AT Command: ATIA
Parameter Range:0 – 0xFFFFFFFFFFFFFFFF
Default Parameter Value:0xFFFFFFFFFFFFFFFF (will not allow any received I/O packet to change outputs)
Minimum Firmware Version Required: v1.xA0

IC (DIO Change Detect) Command

<I/O Settings> Set/Read bitfield values for change detect monitoring. Each bit enables monitoring of DIO0 - DIO7 for changes.

If detected, data is transmitted with DIO data only. Any samples queued waiting for transmission will be sent first.

AT Command: ATIC
Parameter Range:0 – 0xFF [bitfield]
Default Parameter Value:0 (disabled)
Minimum Firmware Version Required: 1.xA0

Refer to the "ADC and Digital I/O Line Support" sections of the "RF Module Operations" chapter for more information.

ID (Pan ID) Command

<Networking {Addressing}> The ID command is used to set and read the PAN (Personal Area Network) ID of the RF module. Only modules with matching PAN IDs can communicate with each other. Unique PAN IDs enable control of which RF packets are received by a module.

AT Command: ATID
Parameter Range: 0 – 0xFFFF
Default Parameter Value:0x3332 (13106 decimal)

Setting the ID parameter to 0xFFFF indicates a global transmission for all PANs. It does not indicate a global receive.

IO (Digital Output Level) Command

<I/O Settings> The IO command is used to set digital output levels. This allows DIO lines setup as outputs to be changed through Command Mode.

AT Command: ATIO
Parameter Range: 8-bit bitmap (where each bit represents the level of an I/O line that is setup as an output.)
Minimum Firmware Version Required: v1.xA0

IR (Sample Rate) Command

<I/O Settings> The IR command is used to set/read the sample rate. When set, the module will sample all enabled DIO/ADC lines at a specified interval. This command allows periodic reads of the ADC and DIO lines in a non-Sleep Mode setup. A sample rate which requires transmissions at a rate greater than once every 20ms is not recommended.

AT Command: ATIR
Parameter Range: 0 - 0xFFFF [x 1 msec] (cannot guarantee 1 ms timing when IT=1)
Default Parameter Value:0
Related Command: IT (Samples before TX)
Minimum Firmware Version Required: v1.xA0

Example: When IR = 0x14, the sample rate is 20 ms (or 50 Hz).

IS (Force Sample) Command

<I/O Settings> The IS command is used to force a read of all enabled DIO/ADC lines. The data is returned through the UART.

When operating in Transparent Mode (AP=0), the data is retuned in the following format:

AT Command: ATIS
Parameter Range: 1 - 0xFF
Default Parameter Value:1
Minimum Firmware Version Required: v1.xA0

All bytes are converted to ASCII:
number of samples<CR>
channel mask<CR>
DIO data<CR> (If DIO lines are enabled<CR>
ADC channel Data<cr> <-This will repeat for every enabled ADC channel<CR>
<CR> (end of data noted by extra <CR>)

When operating in API mode (AP > 0), the command will immediately return an 'OK' response. The data will follow in the normal API format for DIO data.

IT (Samples before TX) Command

<I/O Settings> The IT command is used to set/read the number of DIO and ADC samples to collect before transmitting data.

One ADC sample is considered complete when all enabled ADC channels have been read. The module can buffer up to 93 Bytes of sample data.

AT Command: ATIT
Parameter Range: 1 - 0xFF
Default Parameter Value:1
Minimum Firmware Version Required: v1.xA0

Since the module uses a 10-bit A/D converter, each sample uses two Bytes. This leads to a maximum buffer size of 46 samples or IT=0x2E.

When Sleep Modes are enabled and IR (Sample Rate) is set, the module will remain awake until IT samples have been collected.

IU (I/O Output Enable) Command

<I/O Settings> The IU command is used to disable/enable I/O UART output. When enabled (IU = 1), received I/O line data packets are sent out the UART. The data is sent using an API frame regardless of the current AP parameter value.

AT Command: ATIU	
Parameter Range:0 – 1	
Parameter	Configuration
0	Disabled – Received I/O line data packets will be NOT sent out UART.
1	Enabled – Received I/O line data will be sent out UART
Default Parameter Value:1	
Minimum Firmware Version Required: 1.xA0	

KY (AES Encryption Key) Command

<Networking {Security}> The KY command is used to set the 128-bit AES (Advanced Encryption Standard) key for encrypting/decrypting data. Once set, the key cannot be read out of the module by any means.

AT Command: ATKY
Parameter Range:0 – (any 16-Byte value)
Default Parameter Value:0
Related Command: EE (Encryption Enable)
Minimum Firmware Version Required: v1.xA0

The entire payload of the packet is encrypted using the key and the CRC is computed across the ciphertext. When encryption is enabled, each packet carries an additional 16 Bytes to convey the random CBC Initialization Vector (IV) to the receiver(s). The KY value may be "0" or any 128-bit value. Any other value, including entering KY by itself with no parameters, is invalid. All ATKY entries (valid or not) are received with a returned 'OK'.

A module with the wrong key (or no key) will receive encrypted data, but the data driven out the serial port will be meaningless. A module with a key and encryption enabled will receive data sent from a module without a key and the correct unencrypted data output will be sent out the serial port. Because CBC mode is utilized, repetitive data appears differently in different transmissions due to the randomly-generated IV.

When queried, the system will return an 'OK' message and the value of the key will not be returned.

M0 (PWM0 Output Level) Command

<I/O Settings> The M0 command is used to set/read the output level of the PWM0 line (pin 6).

Before setting the line as an output:
1. Enable PWM0 output (P0 = 2)
2. Apply settings (use CN or AC)

The PWM period is 64 µsec and there are 0x03FF (1023 decimal) steps within this period. When M0 = 0 (0% PWM), 0x01FF (50% PWM), 0x03FF (100% PWM), etc.

AT Command: ATM0
Parameter Range:0 – 0x03FF [steps]
Default Parameter Value:0
Related Commands: P0 (PWM0 Enable), AC (Apply Changes), CN (Exit Command Mode)
Minimum Firmware Version Required: v1.xA0

M1 (PWM1 Output Level) Command

<I/O Settings> The M1 command is used to set/read the output level of the PWM1 line (pin 7).

Before setting the line as an output:
1. Enable PWM1 output (P1 = 2)
2. Apply settings (use CN or AC)

AT Command: ATM1
Parameter Range:0 – 0x03FF
Default Parameter Value:0
Related Commands: P1 (PWM1 Enable), AC (Apply Changes), CN (Exit Command Mode)
Minimum Firmware Version Required: v1.xA0

MM (MAC Mode) Command

<Networking {Addressing}> The MM command is used to set and read the MAC Mode value. The MM command disables/enables the use of a Digi header contained in the 802.15.4 RF packet. By default (MM = 0), Digi Mode is enabled and the module adds an extra header to the data portion of the 802.15.4 packet. This enables the following features:

- ND and DN command support
- Duplicate packet detection when using ACKs
- "RR command
- "DIO/AIO sampling support

The MM command allows users to turn off the use of the extra header. Modes 1 and 2 are strict 802.15.4 modes. If the Digi header is disabled, ND and DN parameters are also disabled.

Note: When MM=0 or 3, application and CCA failure retries are not supported.

AT Command: ATMM

Parameter Range:0 – 3

Parameter	Configuration
0	Digi Mode (802.15.4 + Digi header)
1	802.15.4 (no ACKs)
2	802.15.4 (with ACKs)
3	Digi Mode (no ACKs)

Default Parameter Value:0

Related Commands: ND (Node Discover), DN (Destination Node)

Minimum Firmware Version Required: v1.x80

MY (16-bit Source Address) Command

<Networking {Addressing}> The MY command is used to set and read the 16-bit source address of the RF module.

By setting MY to 0xFFFF, the reception of RF packets having a 16-bit address is disabled. The 64-bit address is the module’s serial number and is always enabled.

AT Command: ATMY

Parameter Range: 0 – 0xFFFF

Default Parameter Value: 0

Related Commands: DH (Destination Address High), DL (Destination Address Low), CH (Channel), ID (PAN ID)

NB (Parity) Command

<Serial Interfacing> The NB command is used to select/read the parity settings of the RF module for UART communications.

Note: the module does not actually calculate and check the parity; it only interfaces with devices at the configured parity and stop bit settings.

AT Command: ATNB

Parameter Range: 0 – 4

Parameter	Configuration
0	8-bit no parity
1	8-bit even
2	8-bit odd
3	8-bit mark
4	8-bit space

Default Parameter Value: 0

Number of bytes returned: 1

ND (Node Discover) Command

AT Command: ATND	
Range: optional 20-character NI value	
Related Commands: CH (Channel), ID (Pan ID), MY (Source Address), SH (Serial Number High), SL (Serial Number Low), NI (Node Identifier), NT (Node Discover Time)	
Minimum Firmware Version Required: v1.x80	

<Networking {Identification}> The ND command is used to discover and report all modules on its current operating channel (CH parameter) and PAN ID (ID parameter). ND also accepts an NI (Node Identifier) value as a parameter. In this case, only a module matching the supplied identifier will respond.

ND uses a 64-bit long address when sending and responding to an ND request. The ND command causes a module to transmit a globally addressed ND command packet. The amount of time allowed for responses is determined by the NT (Node Discover Time) parameter.

In AT Command mode, command completion is designated by a carriage return (0x0D). Since two carriage returns end a command response, the application will receive three carriage returns at the end of the command. If no responses are received, the application should only receive one carriage return. When in API mode, the application should receive a frame (with no data) and status (set to 'OK') at the end of the command. When the ND command packet is received, the remote sets up a random time delay (up to 2.2 sec) before replying as follows:

Node Discover Response (AT command mode format - Transparent operation):
MY (Source Address) value<CR>
SH (Serial Number High) value<CR>
SL (Serial Number Low) value<CR>
DB (Received Signal Strength) value<CR>
NI (Node Identifier) value<CR>
<CR> (This is part of the response and not the end of command indicator.)

Node Discover Response (API format - data is binary (except for NI)):
2 bytes for MY (Source Address) value
4 bytes for SH (Serial Number High) value
4 bytes for SL (Serial Number Low) value
1 byte for DB (Received Signal Strength) value
NULL-terminated string for NI (Node Identifier) value (max 20 bytes w/out NULL terminator)

NI (Node Identifier) Command

AT Command: ATNI
Parameter Range: 20-character ASCII string
Related Commands: ND (Node Discover), DN (Destination Node)
Minimum Firmware Version Required: v1.x80

<Networking {Identification}> The NI command is used to set and read a string for identifying a particular node.

Rules:

- Register only accepts printable ASCII data.
- A string can not start with a space.
- A carriage return ends command
- Command will automatically end when maximum bytes for the string have been entered.

This string is returned as part of the ND (Node Discover) command. This identifier is also used with the DN (Destination Node) command.

NO (Node Discover Options) Command

AT Command: ATNO
Parameter Range: "0-1
Related Commands: ND (Node Discover), DN (Destination Node)
Minimum Firmware Version Required: v1.xC5

<Networking {Identification}> The NO command is used to suppress/include a self-response to Node Discover commands. When NO=1 a module doing a Node Discover will include a response entry for itself.

NT (Node Discover Time) Command

<Networking {Identification}> The NT command is used to set the amount of time a base node will wait for responses from other nodes when using the ND (Node Discover) command. The NT value is transmitted with the ND command.

Remote nodes will set up a random hold-off time based on this time. The remotes will adjust this time down by 250 ms to give each node the ability to respond before the base ends the command. Once the ND command has ended, any response received on the base will be discarded.

AT Command: ATNT
Parameter Range: 0x01 - 0xFC [x 100 msec]
Default: 0x19 (2.5 decimal seconds)
Related Commands: ND (Node Discover)
Minimum Firmware Version Required: 1.xA0

P0 (PWM0 Configuration) Command

<I/O Setting {I/O Line Passing}> The P0 command is used to select/read the function for PWM0 (Pulse Width Modulation output 0). This command enables the option of translating incoming data to a PWM so that the output can be translated back into analog form.

With the IA (I/O Input Address) parameter correctly set, AD0 values can automatically be passed to PWM0.

AT Command: ATP0
The second character in the command is the number zero ("0"), not the letter "O".

Parameter Range: 0 - 2

Parameter	Configuration
0	Disabled
1	RSSI
2	PWM0 Output

Default Parameter Value: 1

P1 (PWM1 Configuration) Command

<I/O Setting {I/O Line Passing}> The P1 command is used to select/read the function for PWM1 (Pulse Width Modulation output 1). This command enables the option of translating incoming data to a PWM so that the output can be translated back into analog form.

With the IA (I/O Input Address) parameter correctly set, AD1 values can automatically be passed to PWM1.

AT Command: ATP1

Parameter Range: 0 - 2

Parameter	Configuration
0	Disabled
1	RSSI
2	PWM1 Output

Default Parameter Value: 0

Minimum Firmware Version Required: v1.xA0

PL (Power Level) Command

<RF Interfacing> The PL command is used to select and read the power level at which the RF module transmits conducted power.

When operating in Europe, XBee-PRO 802.15.4 modules must operate at or below a transmit power output level of 10dBm. Customers have 2 choices for transmitting at or below 10dBm:

- Order the standard XBee-PRO module and change the PL command to "0" (10dBm),
- Order the International variant of the XBee-PRO module, which has a maximum transmit output power of 10dBm.

AT Command: ATPL

Parameter Range: 0 - 4

Parameter	XBee	XBee-PRO	XBee-PRO International variant
0	-10 dBm	10 dBm	PL=4: 10 dBm
1	-6 dBm	12 dBm	PL=3: 8 dBm
2	-4 dBm	14 dBm	PL=2: 2 dBm
3	-2 dBm	16 dBm	PL=1: -3 dBm
4	0 dBm	18 dBm	PL=0: -3 dBm

Default Parameter Value: 4

PR (Pull-up Resistor) Command

<Serial Interfacing> The PR command is used to set and read the bit field that is used to configure internal the pull-up resistor status for I/O lines. "1" specifies the pull-up resistor is enabled. "0" specifies no pull up.

AT Command: ATPR
Parameter Range: 0 – 0xFF
Default Parameter Value: 0xFF (all pull-up resistors are enabled)
Minimum Firmware Version Required: v1.x80

bit 0 - AD4/DIO4 (pin 11)
bit 1 - AD3/DIO3 (pin 17)
bit 2 - AD2/DIO2 (pin 18)
bit 3 - AD1/DIO1 (pin 19)
bit 4 - AD0/DIO0 (pin 20)
bit 5 - AD6/DIO6 (pin 16)
bit 6 - DI8 (pin 9)
bit 7 - DIN/CONFIG (pin 3)

For example: Sending the command "ATPR 6F" will turn bits 0, 1, 2, 3, 5 and 6 ON; and bits 4 & 7 will be turned OFF. (The binary equivalent of "0x6F" is "01101111". Note that 'bit 0' is the last digit in the bitfield.

PT (PWM Output Timeout) Command

<I/O Settings {I/O Line Passing}> The PT command is used to set/read the output timeout value for both PWM outputs.

When PWM is set to a non-zero value: Due to I/O line passing, a time is started which when expired will set the PWM output to zero. The timer is reset when a valid I/O packet is received.

AT Command: ATPT
Parameter Range: 0 – 0xFF [x 100 msec]
Default Parameter Value: 0xFF
Minimum Firmware Version Required: 1.xA0

RE (Restore Defaults) Command

AT Command: ATRE

<(Special)> The RE command is used to restore all configurable parameters to their factory default settings. The RE command does not write restored values to non-volatile (persistent) memory. Issue the WR (Write) command subsequent to issuing the RE command to save restored parameter values to non-volatile memory.

RN (Random Delay Slots) Command

<Networking & Security> The RN command is used to set and read the minimum value of the back-off exponent in the CSMA-CA algorithm. The CSMA-CA algorithm was engineered for collision avoidance (random delays are inserted to prevent data loss caused by data collisions).

AT Command: ATRN
Parameter Range: 0 – 3 [exponent]
Default Parameter Value: 0

If RN = 0, collision avoidance is disabled during the first iteration of the algorithm (802.15.4 - macMinBE).

CSMA-CA stands for "Carrier Sense Multiple Access - Collision Avoidance". Unlike CSMA-CD (reacts to network transmissions after collisions have been detected), CSMA-CA acts to prevent data collisions before they occur. As soon as a module receives a packet that is to be transmitted, it checks if the channel is clear (no other module is transmitting). If the channel is clear, the packet is sent over-the-air. If the channel is not clear, the module waits for a randomly selected period of time, then checks again to see if the channel is clear. After a time, the process ends and the data is lost.

RO (Packetization Timeout) Command

<Serial Interfacing> RO command is used to set and read the number of character times of inter-character delay required before transmission.

RF transmission commences when data is detected in the DI (data in from host) buffer and RO character times of silence are detected on the UART receive lines (after receiving at least 1 byte).

AT Command: ATRO
Parameter Range:0 – 0xFF [x character times]
Default Parameter Value: 3

RF transmission will also commence after 100 Bytes (maximum packet size) are received in the DI buffer.

Set the RO parameter to '0' to transmit characters as they arrive instead of buffering them into one RF packet.

RP (RSSI PWM Timer) Command

<I/O Settings {I/O Line Passing}> The RP command is used to enable PWM (Pulse Width Modulation) output on the RF module. The output is calibrated to show the level a received RF signal is above the sensitivity level of the module. The PWM pulses vary from 24 to 100%. Zero percent means PWM output is inactive. One to 24% percent means the received RF signal is at or below the published sensitivity level of the module. The following table shows levels above sensitivity and PWM values.

AT Command: ATRP
Parameter Range:0 – 0xFF [x 100 msec]
Default Parameter Value: 0x28 (40 decimal)

The total period of the PWM output is 64 µs. Because there are 445 steps in the PWM output, the minimum step size is 144 ns.

PWM Percentages

dB above Sensitivity	PWM percentage (high period / total period)
10	41%
20	58%
30	75%

A non-zero value defines the time that the PWM output will be active with the RSSI value of the last received RF packet. After the set time when no RF packets are received, the PWM output will be set low (0 percent PWM) until another RF packet is received. The PWM output will also be set low at power-up until the first RF packet is received. A parameter value of 0xFF permanently enables the PWM output and it will always reflect the value of the last received RF packet.

RR (XBee Retries) Command

<Networking {Addressing}> The RR command is used set/read the maximum number of retries the module will execute in addition to the 3 retries provided by the 802.15.4 MAC. For each XBee retry, the 802.15.4 MAC can execute up to 3 retries.

AT Command: ATRR
Parameter Range: 0 – 6
Default: 0
Minimum Firmware Version Required: 1.xA0

This values does not need to be set on all modules for retries to work. If retries are enabled, the transmitting module will set a bit in the Digi RF Packet header which requests the receiving module to send an ACK (acknowledgement). If the transmitting module does not receive an ACK within 200 msec, it will re-send the packet within a random period up to 48 msec. Each XBee retry can potentially result in the MAC sending the packet 4 times (1 try plus 3 retries). Note that retries are not attempted for packets that are purged when transmitting with a Cyclic Sleep Coordinator.

SC (Scan Channels) Command

<Networking {Association}> The SC command is used to set and read the list of channels to scan for all Active and Energy Scans as a bit field.

This affects scans initiated in command mode [AS (Active Scan) and ED (Energy Scan) commands] and during End Device Association and Coordinator startup.

AT Command: ATSC
Parameter Range: 1-0xFFFF [Bitfield] (bits 0, 14, 15 are not allowed when using the XBee-PRO)
Default Parameter Value: 0x1FFE (all XBee-PRO channels)
Related Commands: ED (Energy Scan), SD (Scan Duration)
Minimum Firmware Version Required: v1.x80

bit 0 - 0x0B	bit 4 - 0x0F	bit 8 - 0x13	bit 12 - 0x17
bit 1 - 0x0C	bit 5 - 0x10	bit 9 - 0x14	bit 13 - 0x18
bit 2 - 0x0D	bit 6 - 0x11	bit 10 - 0x15	bit 14 - 0x19
bit 3 - 0x0E	bit 7 - 0x12	bit 11 - 0x16	bit 15 - 0x1A

SD (Scan Duration) Command

<Networking {Association}> The SD command is used to set and read the exponent value that determines the duration (in time) of a scan.

End Device (Duration of Active Scan during Association) - In a Beacon system, set SD = BE of the Coordinator. SD must be set at least to the highest BE parameter of any Beaconing Coordinator with which an End Device or Coordinator wish to discover.

AT Command: ATSD
Parameter Range: 0 – 0x0F
Default Parameter Value: 4
Related Commands: ED (Energy Scan), SC (Scan Channel)
Minimum Firmware Version Required: v1.x80

Coordinator - If the 'ReassignPANID' option is set on the Coordinator [refer to A2 parameter], the SD parameter determines the length of time the Coordinator will scan channels to locate existing PANs. If the 'ReassignChannel' option is set, SD determines how long the Coordinator will perform an Energy Scan to determine which channel it will operate on.

Scan Time is measured as ((# of Channels to Scan) * (2 ^ SD) * 15.36ms). The number of channels to scan is set by the SC command. The XBee RF Module can scan up to 16 channels (SC = 0xFFFF). The XBee PRO RF Module can scan up to 12 channels (SC = 0x1FFE).

Examples: Values below show results for a 12-channel scan

If SD = 0, time = 0.18 sec	SD = 8, time = 47.19 sec
SD = 2, time = 0.74 sec	SD = 10, time = 3.15 min
SD = 4, time = 2.95 sec	SD = 12, time = 12.58 min
SD = 6, time = 11.80 sec	SD = 14, time = 50.33 min

SH (Serial Number High) Command

<Diagnostics> The SH command is used to read the high 32 bits of the RF module's unique IEEE 64-bit address.

The module serial number is set at the factory and is read-only.

AT Command: ATSH
Parameter Range: 0 – 0xFFFFFFFF [read-only]
Related Commands: SL (Serial Number Low), MY (Source Address)

SL (Serial Number Low) Command

<Diagnostics> The SL command is used to read the low 32 bits of the RF module's unique IEEE 64-bit address.

The module serial number is set at the factory and is read-only.

AT Command: ATSL
Parameter Range: 0 – 0xFFFFFFFF [read-only]
Related Commands: SH (Serial Number High), MY (Source Address)

SM (Sleep Mode) Command

<Sleep Mode (Low Power)> The SM command is used to set and read Sleep Mode settings. By default, Sleep Modes are disabled (SM = 0) and the RF module remains in Idle/Receive Mode. When in this state, the module is constantly ready to respond to either serial or RF activity.

* The Sleep Coordinator option (SM=6) only exists for backwards compatibility with firmware version 1.x06 only. In all other cases, use the CE command to enable a Coordinator.

AT Command: ATSM

Parameter Range: 0 – 6

Parameter	Configuration
0	Disabled
1	Pin Hibernate
2	Pin Doze
3	(reserved)
4	Cyclic Sleep Remote
5	Cyclic Sleep Remote (with Pin Wake-up)
6	Sleep Coordinator*

Default Parameter Value: 0

SO (Sleep Mode Command)

Sleep (Low Power) Sleep Options Set/Read the sleep mode options.

Bit 0 - Poll wakeup disable

- 0 - Normal operations. A module configured for cyclic sleep will poll for data on waking.
- 1 - Disable wakeup poll. A module configured for cyclic sleep will not poll for data on waking.

Bit 1 - ADC/DIO wakeup sampling disable.

- 0 - Normal operations. A module configured in a sleep mode with ADC/DIO sampling enabled will automatically perform a sampling on wakeup.
- 1 - Suppress sample on wakeup. A module configured in a sleep mode with ADC/DIO sampling enabled will not automatically sample on wakeup.

AT Command: ATSO

Parameter Range:	0-4
Default Parameter Value:	
Related Commands: SM (Sleep Mode), ST (Time before Sleep), DP (Disassociation Cyclic Sleep Period, BE (Beacon Order)	

SP (Cyclic Sleep Period) Command

<Sleep Mode (Low Power)> The SP command is used to set and read the duration of time in which a remote RF module sleeps. After the cyclic sleep period is over, the module wakes and checks for data. If data is not present, the module goes back to sleep. The maximum sleep period is 268 seconds (SP = 0x68B0).

The SP parameter is only valid if the module is configured to operate in Cyclic Sleep (SM = 4-6). Coordinator and End Device SP values should always be equal.

To send Direct Messages, set SP = 0.

AT Command: ATSP

Parameter Range:	NonBeacon Firmware: 0-0x68B0 [x 10 milliseconds]
Default Parameter Value:	
Related Commands: SM (Sleep Mode), ST (Time before Sleep), DP (Disassociation Cyclic Sleep Period, BE (Beacon Order)	

NonBeacon Firmware

End Device - SP determines the sleep period for cyclic sleeping remotes. Maximum sleep period is 268 seconds (0x68B0).

Coordinator - If non-zero, SP determines the time to hold an indirect message before discarding it. A Coordinator will discard indirect messages after a period of (2.5 * SP).

ST (Time before Sleep) Command

<Sleep Mode (Low Power)> The ST command is used to set and read the period of inactivity (no serial or RF data is sent or received) before activating Sleep Mode.

NonBeacon Firmware

Set/Read time period of inactivity (no serial or RF data is sent or received) before activating Sleep Mode. ST parameter is only valid with Cyclic Sleep settings (SM = 4 - 5).

Coordinator and End Device ST values must be equal.

AT Command: ATST	
Parameter Range:	NonBeacon Firmware: 1 – 0xFFFF [x 1 millisecond]
Default Parameter Value:	
Related Commands: SM (Sleep Mode), ST (Time before Sleep)	

T0 - T7 ((D0-D7) Output Timeout) Command

AT Commands: ATT0 – ATT7
Parameter Range:0 – 0xFF [x 100 msec]
Default Parameter Value:0xFF
Minimum Firmware Version Required: v1.xA0

<I/O Settings {I/O Line Passing}> The T0, T1, T2, T3, T4, T5, T6 and T7 commands are used to set/read output timeout values for the lines that correspond with the D0 - D7 parameters. When output is set (due to I/O line passing) to a non-default level, a timer is started which when expired, will set the output to its default level. The timer is reset when a valid I/O packet is received. The Tn parameter defines the permissible amount of time to stay in a non-default (active) state. If Tn = 0, Output Timeout is disabled (output levels are held indefinitely).

VL (Firmware Version - Verbose)

AT Command: ATVL
Parameter Range:0 – 0xFF [x 100 milliseconds]
Default Parameter Value: 0x28 (40 decimal)
Minimum Firmware Version Required: v1.x80 – v1.xC8

<Diagnostics> The VL command is used to read detailed version information about the RF module. The information includes:
application build date; MAC, PHY and bootloader versions; and build dates. This command was removed from firmware 1xC9 and later versions.

VR (Firmware Version) Command

AT Command: ATVR
Parameter Range: 0 – 0xFFFF [read only]

<Diagnostics> The VR command is used to read which firmware version is stored in the module.

XBee version numbers will have four significant digits. The reported number will show three or four numbers and is stated in hexadecimal notation. A version can be reported as "ABC" or "ABCD". Digits ABC are the main release number and D is the revision number from the main release. "D" is not required and if it is not present, a zero is assumed for D. "B" is a variant designator. The following variants exist:

- "0" = Non-Beacon Enabled 802.15.4 Code
- "1" = Beacon Enabled 802.15.4 Code

WR (Write) Command

AT Command: ATWR

<(Special)> The WR command is used to write configurable parameters to the RF module's non-volatile memory. Parameter values remain in the module's memory until overwritten by subsequent use of the WR Command.

If changes are made without writing them to non-volatile memory, the module reverts back to previously saved parameters the next time the module is powered-on.

NOTE: Once the WR command is sent to the module, no additional characters should be sent until after the “OK/r” response is received.

API Operation

By default, XBee®/XBee-PRO® RF Modules act as a serial line replacement (Transparent Operation) - all UART data received through the DI pin is queued up for RF transmission. When the module receives an RF packet, the data is sent out the DO pin with no additional information.

Inherent to Transparent Operation are the following behaviors:

- If module parameter registers are to be set or queried, a special operation is required for transitioning the module into Command Mode.
- In point-to-multipoint systems, the application must send extra information so that the receiving module(s) can distinguish between data coming from different remotes.

As an alternative to the default Transparent Operation, API (Application Programming Interface) Operations are available. API operation requires that communication with the module be done through a structured interface (data is communicated in frames in a defined order). The API specifies how commands, command responses and module status messages are sent and received from the module using a UART Data Frame.

API Frame Specifications

Two API modes are supported and both can be enabled using the AP (API Enable) command. Use the following AP parameter values to configure the module to operate in a particular mode:

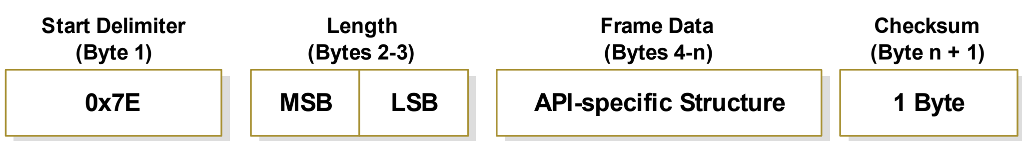
- AP = 0 (default): Transparent Operation (UART Serial line replacement)
  API modes are disabled.
- AP = 1: API Operation
- AP = 2: API Operation (with escaped characters)

Any data received prior to the start delimiter is silently discarded. If the frame is not received correctly or if the checksum fails, the data is silently discarded.

API Operation (AP parameter = 1)

When this API mode is enabled (AP = 1), the UART data frame structure is defined as follows:

Figure 3-01. UART Data Frame Structure:

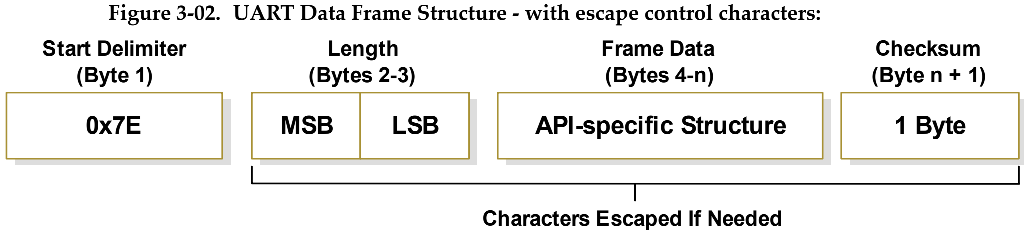


MSB = Most Significant Byte, LSB = Least Significant Byte

API Operation - with Escape Characters (AP parameter = 2)

When this API mode is enabled (AP = 2), the UART data frame structure is defined as follows:

Figure 3-02. UART Data Frame Structure - with escape control characters:



MSB = Most Significant Byte, LSB = Least Significant Byte

Escape characters. When sending or receiving a UART data frame, specific data values must be escaped (flagged) so they do not interfere with the UART or UART data frame operation. To escape an interfering data byte, insert 0x7D and follow it with the byte to be escaped XOR'd with 0x20.

Data bytes that need to be escaped:

- 0x7E – Frame Delimiter
- 0x7D – Escape
- 0x11 – XON
- 0x13 – XOFF

Example - Raw UART Data Frame (before escaping interfering bytes):
0x7E 0x00 0x02 0x23 0x11 0xCB

0x11 needs to be escaped which results in the following frame:
0x7E 0x00 0x02 0x23 0x7D 0x31 0xCB

Note: In the above example, the length of the raw data (excluding the checksum) is 0x0002 and the checksum of the non-escaped data (excluding frame delimiter and length) is calculated as: 0xFF - (0x23 + 0x11) = (0xFF - 0x34) = 0xCB.

Checksum

To test data integrity, a checksum is calculated and verified on non-escaped data.

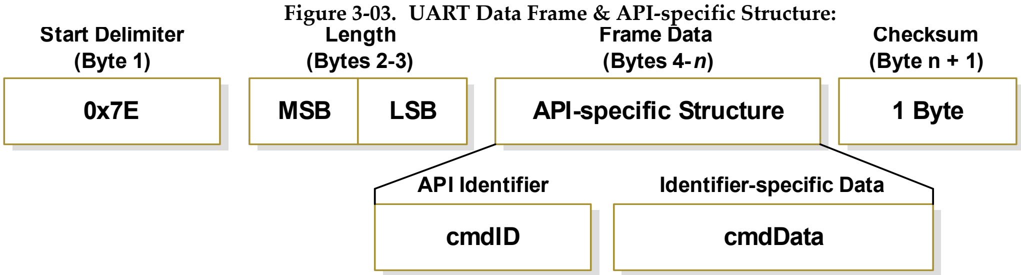
To calculate: Not including frame delimiters and length, add all bytes keeping only the lowest 8 bits of the result and subtract from 0xFF.

To verify: Add all bytes (include checksum, but not the delimiter and length). If the checksum is correct, the sum will equal 0xFF.

API Types

Frame data of the UART data frame forms an API-specific structure as follows:

Figure 3-03. UART Data Frame & API-specific Structure:

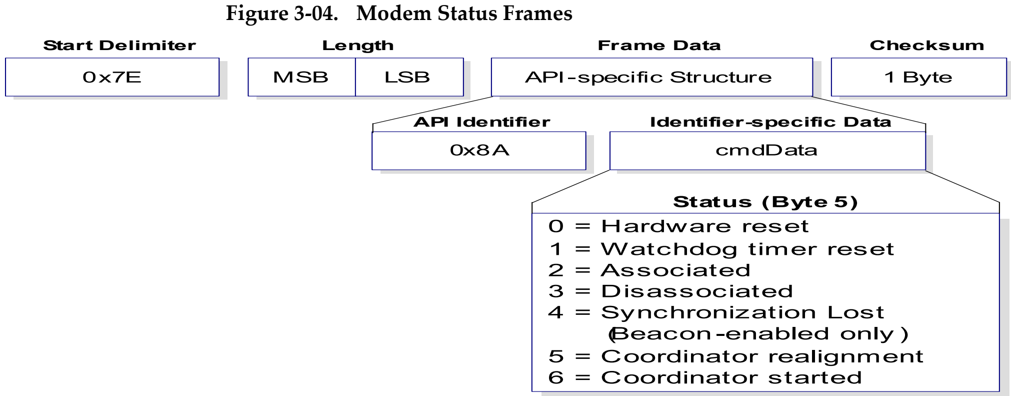


The cmdID frame (API-identifier) indicates which API messages will be contained in the cmdData frame (Identifier-specific data). Refer to the sections that follow for more information regarding the supported API types. Note that multi-byte values are sent big endian.

Modem Status

API Identifier: 0x8A
RF module status messages are sent from the module in response to specific conditions.

Figure 3-04. Modem Status Frames



AT Command

API Identifier Value: 0x08

The "AT Command" API type allows for module parameters to be queried or set. When using this command ID, new parameter values are applied immediately. This includes any register set with the "AT Command - Queue Parameter Value" (0x09) API type.

Figure 3-05. AT Command Frames

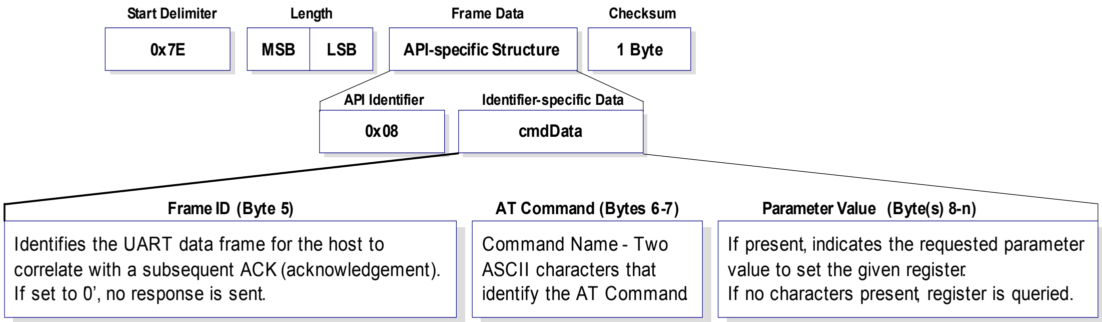


Figure 3-06. Example: API frames when reading the DL parameter value of the module.

Byte 1	Bytes 2-3		Byte 4	Byte 5	Bytes 6-7		Byte 8
0x7E	0x00	0x04	0x08	0x52 (R)	0x44 (D)	0x4C (L)	0x15
Start Delimiter	Length*		API Identifier	Frame ID**	AT Command		Checksum

** Length [Bytes] = API Identifier + Frame ID + AT Command*

*** "R" value was arbitrarily selected.*

Figure 3-07. Example: API frames when modifying the DL parameter value of the module.

Byte 1	Bytes 2-3		Byte 4	Byte 5	Bytes 6-7		Bytes 8-11	Byte 12
0x7E	0x00	0x08	0x08	0x4D (M)	0x44 (D)	0x4C (L)	0x00000FFF	0x0C
Start Delimiter	Length*		API Identifier	Frame ID**	AT Command		Parameter Value	Checksum

** Length [Bytes] = API Identifier + Frame ID + AT Command + Parameter Value*

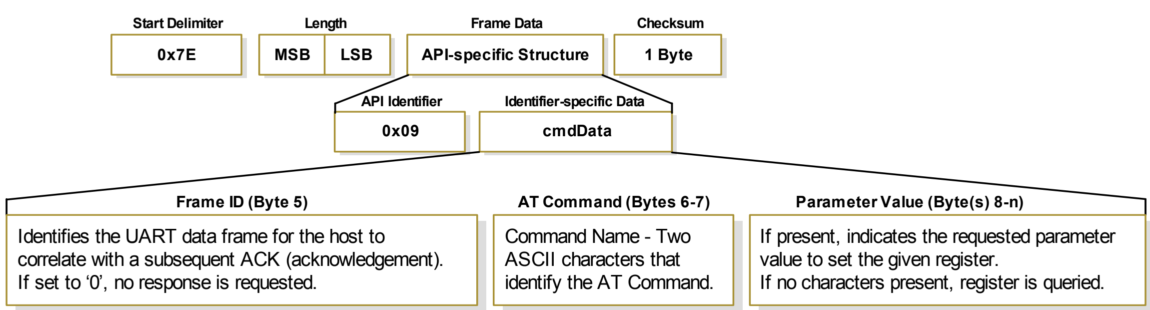
*** "M" value was arbitrarily selected.*

AT Command - Queue Parameter Value

API Identifier Value: 0x09

This API type allows module parameters to be queried or set. In contrast to the "AT Command" API type, new parameter values are queued and not applied until either the "AT Command" (0x08) API type or the AC (Apply Changes) command is issued. Register queries (reading parameter values) are returned immediately.

Figure 3-08. AT Command Frames
(Note that frames are identical to the "AT Command" API type except for the API identifier.)



AT Command Response

API Identifier Value: 0x88

Response to previous command.

In response to an AT Command message, the module will send an AT Command Response message. Some commands will send back multiple frames (for example, the ND (Node Discover) and AS (Active Scan) commands). These commands will end by sending a frame with a status of ATCMD_OK and no cmdData.

Figure 3-09. AT Command Response Frames.

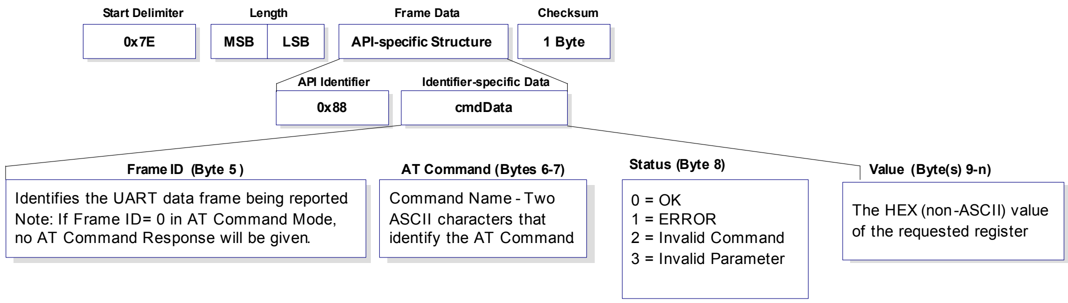
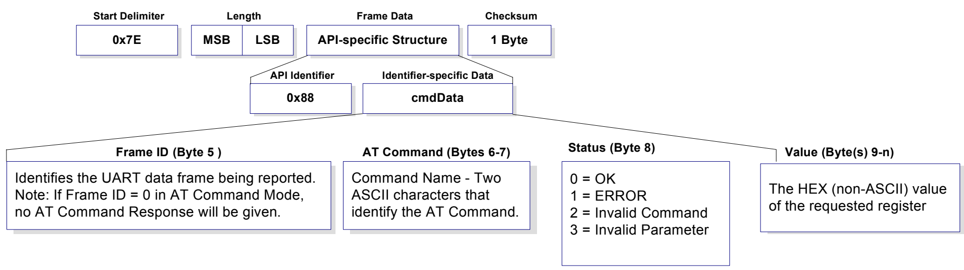


Figure 3-10. AT Command Response Frames.

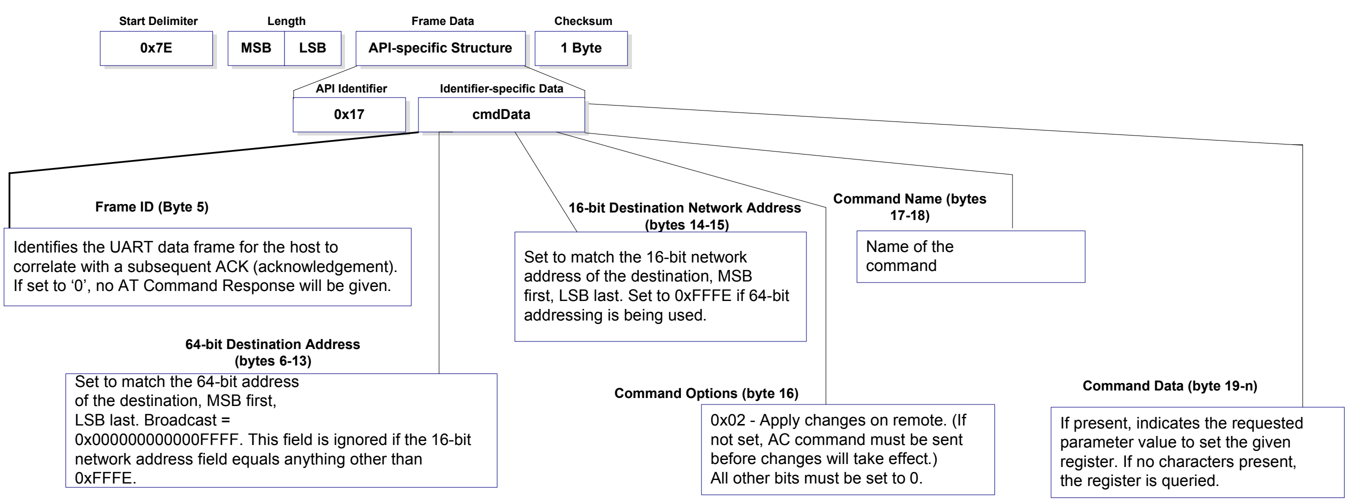


Remote AT Command Request

API Identifier Value: 0x17

Allows for module parameter registers on a remote device to be queried or set

Figure 3-11. Remote AT Command Request

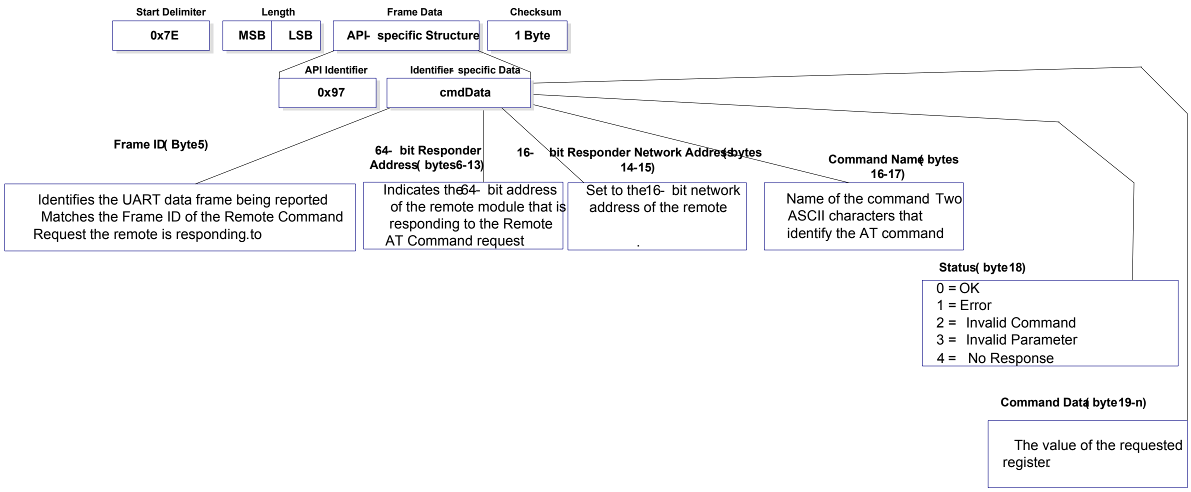


Remote Command Response

API Identifier Value: 0x97

If a module receives a remote command response RF data frame in response to a Remote AT Command Request, the module will send a Remote AT Command Response message out the UART. Some commands may send back multiple frames--for example, Node Discover (ND) command.

Figure 3-12. Remote AT Command Response.

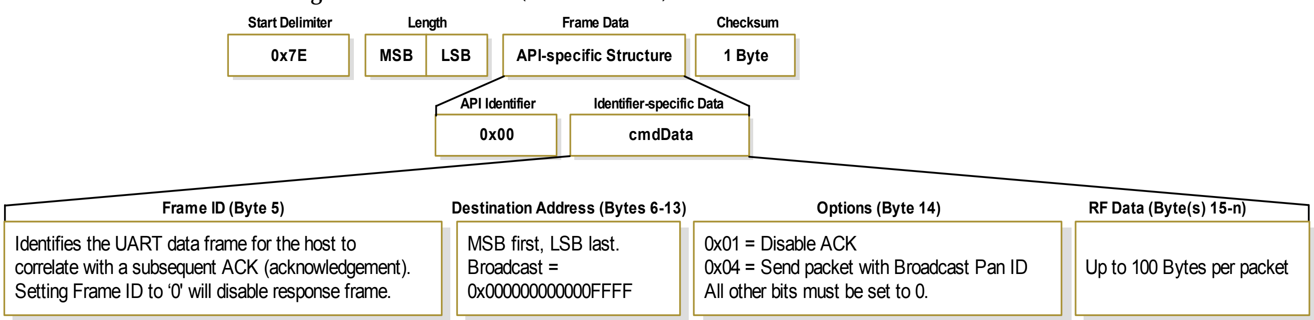


TX (Transmit) Request: 64-bit address

API Identifier Value: 0x00

A TX Request message will cause the module to send RF Data as an RF Packet.

Figure 3-13. TX Packet (64-bit address) Frames

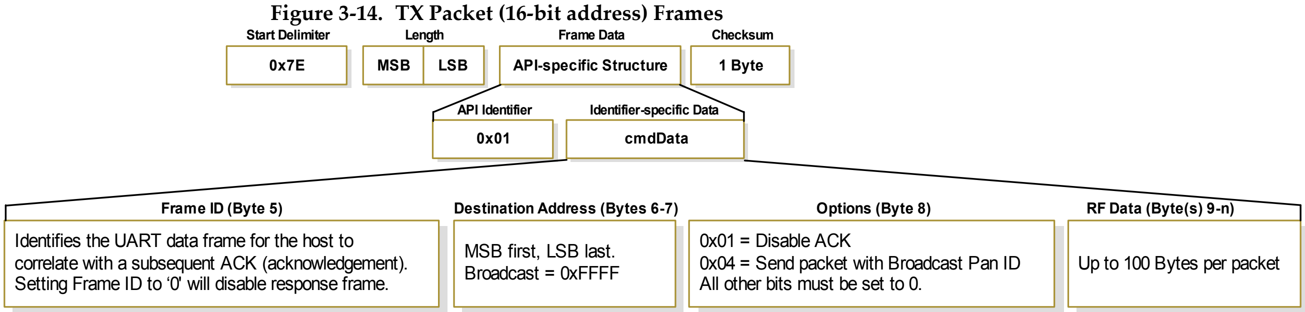


TX (Transmit) Request: 16-bit address

API Identifier Value: 0x01

A TX Request message will cause the module to send RF Data as an RF Packet.

Figure 3-14. TX Packet (16-bit address) Frames

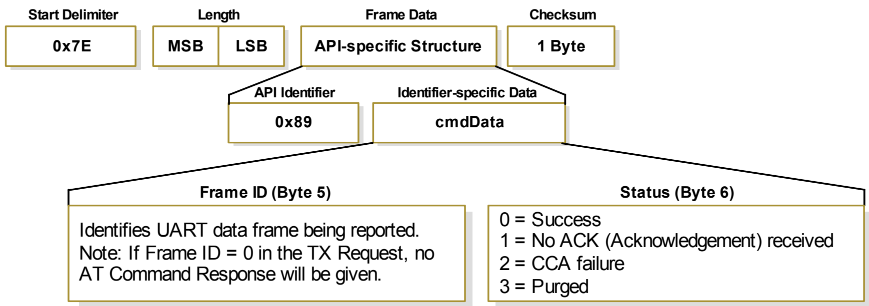


TX (Transmit) Status

API Identifier Value: 0x89

When a TX Request is completed, the module sends a TX Status message. This message will indicate if the packet was transmitted successfully or if there was a failure.

Figure 3-15. TX Status Frames



NOTES:

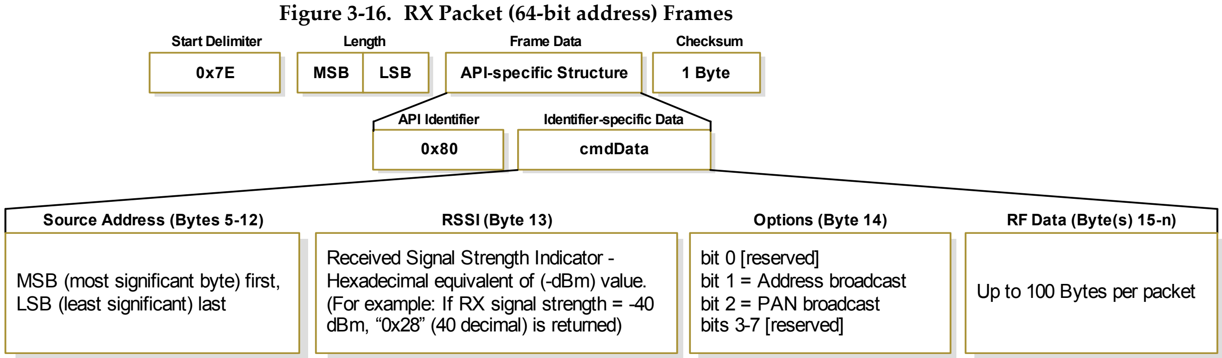
- “STATUS = 1” occurs when all retries are expired and no ACK is received.
- If transmitter broadcasts (destination address = 0x000000000000FFFF), only “STATUS = 0 or 2” will be returned.
- “STATUS = 3” occurs when Coordinator times out of an indirect transmission. Timeout is defined as (2.5 x SP (Cyclic Sleep Period) parameter value).

RX (Receive) Packet: 64-bit Address

API Identifier Value: 0x80

When the module receives an RF packet, it is sent out the UART using this message type.

Figure 3-16. RX Packet (64-bit address) Frames

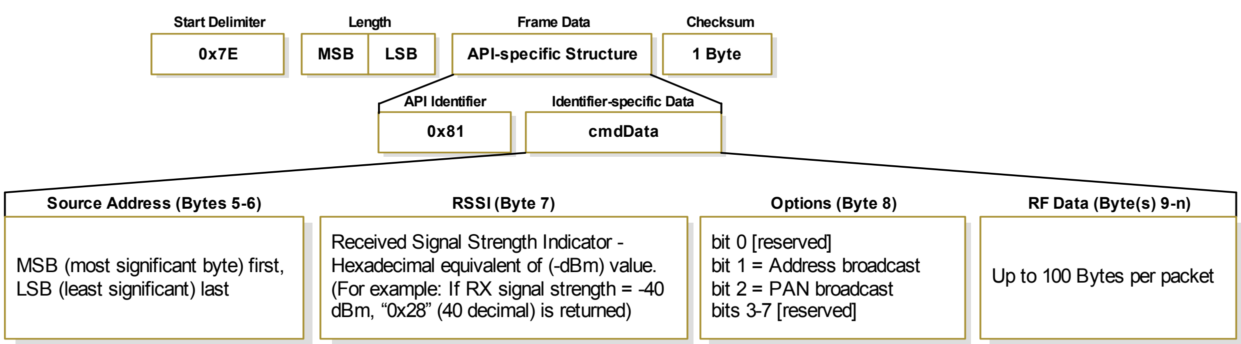


RX (Receive) Packet: 16-bit Address

API Identifier Value: 0x81

When the module receives an RF packet, it is sent out the UART using this message type.

Figure 3-17. RX Packet (16-bit address) Frames



Appendix A: Agency Certifications

United States (FCC)

XBee®/XBee-PRO® RF Modules comply with Part 15 of the FCC rules and regulations. Compliance with the labeling requirements, FCC notices and antenna usage guidelines is required.

To fulfill FCC Certification requirements, the OEM must comply with the following regulations:

1. The system integrator must ensure that the text on the external label provided with this device is placed on the outside of the final product [Figure A-01].
2. XBee®/XBee-PRO® RF Modules may only be used with antennas that have been tested and approved for use with this module [refer to the antenna tables in this section].

OEM Labeling Requirements

WARNING: The Original Equipment Manufacturer (OEM) must ensure that FCC labeling requirements are met. This includes a clearly visible label on the outside of the final product enclosure that displays the contents shown in the figure below.

Figure 4-01. Required FCC Label for OEM products containing the XBee®/XBee-PRO® RF Module

Contains FCC ID: OUR-XBEE/OUR-XBEEPRO**

The enclosed device complies with Part 15 of the FCC Rules. Operation is subject to the following two conditions: (*i.*) this device may not cause harmful interference and (*ii.*) this device must accept any interference received, including interference that may cause undesired operation.

* The FCC ID for the XBee is "OUR-XBEE". The FCC ID for the XBee-PRO is "OUR-XBEEPRO".

FCC Notices

IMPORTANT: The XBee®/XBee-PRO® RF Module has been certified by the FCC for use with other products without any further certification (as per FCC section 2.1091). Modifications not expressly approved by Digi could void the user's authority to operate the equipment.

IMPORTANT: OEMs must test final product to comply with unintentional radiators (FCC section 15.107 & 15.109) before declaring compliance of their final product to Part 15 of the FCC Rules.

IMPORTANT: The RF module has been certified for remote and base radio applications. If the module will be used for portable applications, the device must undergo SAR testing.

This equipment has been tested and found to comply with the limits for a Class B digital device, pursuant to Part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates, uses and can radiate radio frequency energy and, if not installed and used in accordance with the instructions, may cause harmful interference to radio communications. However, there is no guarantee that interference will not occur in a particular installation.

If this equipment does cause harmful interference to radio or television reception, which can be determined by turning the equipment off and on, the user is encouraged to try to correct the interference by one or more of the following measures: Re-orient or relocate the receiving antenna, Increase the separation between the equipment and receiver, Connect equipment and receiver to outlets on different circuits, or Consult the dealer or an experienced radio/TV technician for help.

FCC-Approved Antennas (2.4 GHz)

XBee/XBee-PRO RF Modules can be installed using antennas and cables constructed with standard connectors (Type-N, SMA, TNC, etc.) if the installation is performed professionally and according to FCC guidelines. For installations not performed by a professional, non-standard connectors (RPSMA, RPTNC, etc) must be used.

The modules are FCC-approved for fixed base station and mobile applications on channels 0x0B - 0x1A (XBee) and 0x0C - 0x17 (XBee-PRO). If the antenna is mounted at least 20cm (8 in.) from nearby persons, the application is considered a mobile application. Antennas not listed in the table must be tested to comply with FCC Section 15.203 (Unique Antenna Connectors) and Section 15.247 (Emissions).

XBee RF Modules (1 mW): XBee Modules have been tested and approved for use with all of the antennas listed in the tables below (Cable-loss IS NOT required).

XBee-PRO RF Modules (60 mW): XBee-PRO Modules have been tested and approved for use with the antennas listed in the tables below (Cable-loss IS required when using antennas listed in the second table.

The antennas in the tables below have been approved for use with this module. Digi does not carry all of these antenna variants. Contact Digi Sales for available antennas.

Antennas approved for use with the XBee®/XBee-PRO® RF Modules (Cable-loss is not required.)

Part Number	Type (Description)	Gain	Application*	Min. Separation
A24-HASM-450	Dipole (Half-wave articulated RPSMA - 4.5")	2.1 dBi	Fixed/Mobile	20 cm
A24-HABSM	Dipole (Articulated RPSMA)	2.1 dBi	Fixed	20 cm
A24-HABUF-P5I	Dipole (Half-wave articulated bulkhead mount U.FL. w/ 5" pigtail)	2.1 dBi	Fixed	20 cm
A24-HASM-525	Dipole (Half-wave articulated RPSMA - 5.25")	2.1 dBi	Fixed/Mobile	20 cm
A24-QI	Monopole (Integrated whip)	1.5 dBi	Fixed	20 cm

Antennas approved for use with the XBee RF Modules (Cable-loss is required)

Part Number	Type (Description)	Gain	Application*	Min. Separation	Required Cable-loss
Omni-Directional Class Antennas					
A24-Y6NF	Yagi (6-element)	8.8 dBi	Fixed	2 m	1.7 dB
A24-Y7NF	Yagi (7-element)	9.0 dBi	Fixed	2 m	1.9 dB
A24-Y9NF	Yagi (9-element)	10.0 dBi	Fixed	2 m	2.9 dB
A24-Y10NF	Yagi (10-element)	11.0 dBi	Fixed	2 m	3.9 dB
A24-Y12NF	Yagi (12-element)	12.0 dBi	Fixed	2 m	4.9 dB
A24-Y13NF	Yagi (13-element)	12.0 dBi	Fixed	2 m	4.9 dB
A24-Y15NF	Yagi (15-element)	12.5 dBi	Fixed	2 m	5.4 dB
A24-Y16NF	Yagi (16-element)	13.5 dBi	Fixed	2 m	6.4 dB
A24-Y16RM	Yagi (16-element, RPSMA connector)	13.5 dBi	Fixed	2 m	6.4 dB
A24-Y18NF	Yagi (18-element)	15.0 dBi	Fixed	2 m	7.9 dB
Omni-Directional Class Antennas					
A24-C1	Surface Mount	-1.5 dBi	Fixed/Mobile	20 cm	-
A24-F2NF	Omni-directional (Fiberglass base station)	2.1 dBi	Fixed/Mobile	20 cm	
A24-F3NF	Omni-directional (Fiberglass base station)	3.0 dBi	Fixed/Mobile	20 cm	
A24-F5NF	Omni-directional (Fiberglass base station)	5.0 dBi	Fixed/Mobile	20 cm	
A24-F8NF	Omni-directional (Fiberglass base station)	8.0 dBi	Fixed	2 m	
A24-F9NF	Omni-directional (Fiberglass base station)	9.5 dBi	Fixed	2 m	0.2 dB
A24-F10NF	Omni-directional (Fiberglass base station)	10.0 dBi	Fixed	2 m	0.7 dB
A24-F12NF	Omni-directional (Fiberglass base station)	12.0 dBi	Fixed	2 m	2.7 dB
A24-F15NF	Omni-directional (Fiberglass base station)	15.0 dBi	Fixed	2 m	5.7 dB
A24-W7NF	Omni-directional (Base station)	7.2 dBi	Fixed	2 m	
A24-M7NF	Omni-directional (Mag-mount base station)	7.2 dBi	Fixed	2 m	
Panel Class Antennas					
A24-P8SF	Flat Panel	8.5 dBi	Fixed	2 m	1.5 dB
A24-P8NF	Flat Panel	8.5 dBi	Fixed	2 m	1.5 dB
A24-P13NF	Flat Panel	13.0 dBi	Fixed	2 m	6 dB
A24-P14NF	Flat Panel	14.0 dBi	Fixed	2 m	7 dB
A24-P15NF	Flat Panel	15.0 dBi	Fixed	2 m	8 dB
A24-P16NF	Flat Panel	16.0 dBi	Fixed	2 m	9 dB

Antennas approved for use with the XBee®/XBee-PRO® RF Modules (Cable-loss is required)

Part Number	Type (Description)	Gain	Application*	Min. Separation	Required Cable-loss
A24-C1	Surface Mount	-1.5 dBi	Fixed/Mobile	20 cm	-
A24-Y4NF	Yagi (4-element)	6.0 dBi	Fixed	2 m	8.1 dB
A24-Y6NF	Yagi (6-element)	8.8 dBi	Fixed	2 m	10.9 dB
A24-Y7NF	Yagi (7-element)	9.0 dBi	Fixed	2 m	11.1 dB
A24-Y9NF	Yagi (9-element)	10.0 dBi	Fixed	2 m	12.1 dB
A24-Y10NF	Yagi (10-element)	11.0 dBi	Fixed	2 m	13.1 dB
A24-Y12NF	Yagi (12-element)	12.0 dBi	Fixed	2 m	14.1 dB
A24-Y13NF	Yagi (13-element)	12.0 dBi	Fixed	2 m	14.1 dB
A24-Y15NF	Yagi (15-element)	12.5 dBi	Fixed	2 m	14.6 dB
A24-Y16NF	Yagi (16-element)	13.5 dBi	Fixed	2 m	15.6 dB
A24-Y16RM	Yagi (16-element, RPSMA connector)	13.5 dBi	Fixed	2 m	15.6 dB
A24-Y18NF	Yagi (18-element)	15.0 dBi	Fixed	2 m	17.1 dB
A24-F2NF	Omni-directional (Fiberglass base station)	2.1 dBi	Fixed/Mobile	20 cm	4.2 dB
A24-F3NF	Omni-directional (Fiberglass base station)	3.0 dBi	Fixed/Mobile	20 cm	5.1 dB
A24-F5NF	Omni-directional (Fiberglass base station)	5.0 dBi	Fixed/Mobile	20 cm	7.1 dB
A24-F8NF	Omni-directional (Fiberglass base station)	8.0 dBi	Fixed	2 m	10.1 dB
A24-F9NF	Omni-directional (Fiberglass base station)	9.5 dBi	Fixed	2 m	11.6 dB
A24-F10NF	Omni-directional (Fiberglass base station)	10.0 dBi	Fixed	2 m	12.1 dB
A24-F12NF	Omni-directional (Fiberglass base station)	12.0 dBi	Fixed	2 m	14.1 dB
A24-F15NF	Omni-directional (Fiberglass base station)	15.0 dBi	Fixed	2 m	17.1 dB
A24-W7NF	Omni-directional (Base station)	7.2 dBi	Fixed	2 m	9.3 dB
A24-M7NF	Omni-directional (Mag-mount base station)	7.2 dBi	Fixed	2 m	9.3 dB
A24-P8SF	Flat Panel	8.5 dBi	Fixed	2 m	8.6 dB
A24-P8NF	Flat Panel	8.5 dBi	Fixed	2 m	8.6 dB
A24-P13NF	Flat Panel	13.0 dBi	Fixed	2 m	13.1 dB
A24-P14NF	Flat Panel	14.0 dBi	Fixed	2 m	14.1 dB
A24-P15NF	Flat Panel	15.0 dBi	Fixed	2 m	15.1 dB
A24-P16NF	Flat Panel	16.0 dBi	Fixed	2 m	16.1 dB
A24-P19NF	Flat Panel	19.0 dBi	Fixed	2 m	19.1 dB

*** If using the RF module in a portable application** (For example - If the module is used in a handheld device and the antenna is less than 20cm from the human body when the device is operation): The integrator is responsible for passing additional SAR (Specific Absorption Rate) testing based on FCC rules 2.1091 and FCC Guidelines for Human Exposure to Radio Frequency Electromagnetic Fields, OET Bulletin and Supplement C. The testing results will be submitted to the FCC for approval prior to selling the integrated unit. The required SAR testing measures emissions from the module and how they affect the person.

RF Exposure

WARNING: To satisfy FCC RF exposure requirements for mobile transmitting devices, a separation distance of 20 cm or more should be maintained between the antenna of this device and persons during device operation. To ensure compliance, operations at closer than this distance is not recommended. The antenna used for this transmitter must not be co-located in conjunction with any other antenna or transmitter.

The preceding statement must be included as a CAUTION statement in OEM product manuals in order to alert users of FCC RF Exposure compliance.

Europe (ETSI)

The XBee RF Modules have been certified for use in several European countries. For a complete list, refer to www.digi.com

If the XBee RF Modules are incorporated into a product, the manufacturer must ensure compliance of the final product to the European harmonized EMC and low-voltage/safety standards. A Declaration of Conformity must be issued for each of these standards and kept on file as described in Annex II of the R&TTE Directive.

Furthermore, the manufacturer must maintain a copy of the XBee user manual documentation and ensure the final product does not exceed the specified power ratings, antenna specifications, and/or installation requirements as specified in the user manual. If any of these specifications are exceeded in the final product, a submission must be made to a notified body for compliance testing to all required standards.

OEM Labeling Requirements

The 'CE' marking must be affixed to a visible location on the OEM product.

CE Labeling Requirements

The CE mark shall consist of the initials "CE" taking the following form:

- If the CE marking is reduced or enlarged, the proportions given in the above graduated drawing must be respected.
- The CE marking must have a height of at least 5mm except where this is not possible on account of the nature of the apparatus.
- The CE marking must be affixed visibly, legibly, and indelibly.

Restrictions

Power Output: When operating in Europe, XBee-PRO 802.15.4 modules must operate at or below a transmit power output level of 10dBm. Customers have two choices for transmitting at or below 10dBm:

a. Order the standard XBee-PRO module and change the PL command to 0 (10dBm)

b. Order the International variant of the XBee-PRO module, which has a maximum transmit output power of 10dBm (@ PL=4).

Additionally, European regulations stipulate an EIRP power maximum of 12.86 dBm (19 mW) for the XBee-PRO and 12.11 dBm for the XBee when integrating antennas.

France: Outdoor use limited to 10 mW EIRP within the band 2454-2483.5 MHz.

Norway: Norway prohibits operation near Ny-Alesund in Svalbard. More information can be found at the Norway Posts and Telecommunications site (www.npt.no).

Declarations of Conformity

Digi has issued Declarations of Conformity for the XBee RF Modules concerning emissions, EMC and safety. Files can be obtained by contacting Digi Support.

Important Note:

Digi does not list the entire set of standards that must be met for each country. Digi customers assume full responsibility for learning and meeting the required guidelines for each country in their distribution market. For more information relating to European compliance of an OEM product incorporating the XBee RF Module, contact Digi, or refer to the following web sites:

CEPT ERC 70-03E - Technical Requirements, European restrictions and general requirements: Available at www.ero.dk/.

R&TTE Directive - Equipment requirements, placement on market: Available at www.ero.dk/.

Approved Antennas

When integrating high-gain antennas, European regulations stipulate EIRP power maximums. Use the following guidelines to determine which antennas to design into an application.

XBee-PRO RF Module

The following antenna types have been tested and approved for use with the XBee Module:

Antenna Type: Yagi
RF module was tested and approved with 15 dBi antenna gain with 1 dB cable-loss (EIRP Maximum of 14 dBm). Any Yagi type antenna with 14 dBi gain or less can be used with no cable-loss.

Antenna Type: Omni-directional
RF module was tested and approved with 15 dBi antenna gain with 1 dB cable-loss (EIRP Maxi-

mum of 14 dBm). Any Omni-directional type antenna with 14 dBi gain or less can be used with no cable-loss.

Antenna Type: Flat Panel

RF module was tested and approved with 19 dBi antenna gain with 4.8 dB cable-loss (EIRP Maximum of 14.2 dBm). Any Flat Panel type antenna with 14.2 dBi gain or less can be used with no cable-loss.

XBee-PRO RF Module (@ 10 dBm Transmit Power, PL parameter value must equal 0, or use International variant)

The following antennas have been tested and approved for use with the embedded XBee-PRO RF Module:

- Dipole (2.1 dBi, Omni-directional, Articulated RPSMA, Digi part number A24-HABSM)
- Chip Antenna (-1.5 dBi)
- Attached Monopole Whip (1.5 dBi)

The RF modem encasement was designed to accommodate the RPSMA antenna option.

Canada (IC)

Labeling Requirements

Labeling requirements for Industry Canada are similar to those of the FCC. A clearly visible label on the outside of the final product enclosure must display the following text:

Contains Model XBee Radio, IC: 4214A-XBEE
Contains Model XBee-PRO Radio, IC: 4214A-XBEEPRO

The integrator is responsible for its product to comply with IC ICES-003 & FCC Part 15, Sub. B - Unintentional Radiators. ICES-003 is the same as FCC Part 15 Sub. B and Industry Canada accepts FCC test report or CISPR 22 test report for compliance with ICES-003.

Japan

In order to gain approval for use in Japan, the XBee RF module or the International variant of the XBee-PRO RF module (which has 10 dBm transmit output power) must be used.

Labeling Requirements

A clearly visible label on the outside of the final product enclosure must display the following text:

ID: 005NYCA0378

Appendix B. Additional Information

1-Year Warranty

XBee®/XBee-PRO® RF Modules from Digi Intenational, Inc. (the "Product") are warranted against defects in materials and workmanship under normal use, for a period of 1-year from the date of purchase. In the event of a product failure due to materials or workmanship, Digi will repair or replace the defective product. For warranty service, return the defective product to Digi, shipping prepaid, for prompt repair or replacement.

The foregoing sets forth the full extent of Digi's warranties regarding the Product. Repair or replacement at Digi's option is the exclusive remedy. THIS WARRANTY IS GIVEN IN LIEU OF ALL OTHER WARRANTIES, EXPRESS OR IMPLIED, AND DIGI SPECIFICALLY DISCLAIMS ALL WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. IN NO EVENT SHALL DIGI, ITS SUPPLIERS OR LICENSORS BE LIABLE FOR DAMAGES IN EXCESS OF THE PURCHASE PRICE OF THE PRODUCT, FOR ANY LOSS OF USE, LOSS OF TIME, INCONVENIENCE, COMMERCIAL LOSS, LOST PROFITS OR SAVINGS, OR OTHER INCIDENTAL, SPECIAL OR CONSEQUENTIAL DAMAGES ARISING OUT OF THE USE OR INABILITY TO USE THE PRODUCT, TO THE FULL EXTENT SUCH MAY BE DISCLAIMED BY LAW. SOME STATES DO NOT ALLOW THE EXCLUSION OR LIMITATION OF INCIDENTAL OR CONSEQUENTIAL DAMAGES. THEREFORE, THE FOREGOING EXCLUSIONS MAY NOT APPLY IN ALL CASES. This warranty provides specific legal rights. Other rights which vary from state to state may also apply.

ANEXO 1. PROGRAMACIÓN PIC18F4550

```
#include <18f4550.h>
#device adc=10
#fuses HS, NOWDT, NOPROTECT,CPUDIV1
#use delay(clock=20000000)
#use rs232(baud=9600,parity=N,xmit=PIN_C6,rcv=PIN_C7,bits=8)
#define  LED     PIN_B4
#define  LED_ON  output_high
#define  LED_OFF output_low
int16 uni,dec,cen,t_tost, read2,read3,fase1,Tr1;
float read1=0,peso=0,eT_1=0,eT_2=0,uT_1=0, fase,num, t_tost_seg;
float Kp,Ti,Td,q0,q1,q2,p0,p00, eT,uT,rT,Tiempo;     // Variables para control PID
float TempRef,temp_amb,Tt,Lin_t,Tr,Tt1;  // Variables para el control realimentado
float contador=0, contador1=0, contador2=0;
int1 cambio=0;
char k;

#int_TIMER0
void TIMER0_isr(void)   //timer en cada segundo
{
set_adc_channel(0);  //lectura del convertidor analogo digital
read1=read_adc();
set_adc_channel(1);
read2=read_adc();
set_adc_channel(2);
read3=read_adc();
set_timer0(128);
peso=((read3*0.0048875855327468));
}
#int_TIMER1
void TIMER1_isr(void){
 output_toggle(PIN_C5);
 LED_ON(LED);
}
#INT_EXT
void ext_isr(void){
output_toggle(PIN_C4);
LED_OFF(LED);
set_timer1(fase1);
enable_interrupts(INT_TIMER1);
  if(cambio==0){
           ext_int_edge(H_TO_L);
          cambio=1;
 }else{
```

```
         ext_int_edge(L_TO_H);
         cambio=0;   }
}
 #int_TIMER2
void TIMER2_isr(void){
output_toggle(PIN_C4);
contador=contador+1;
 if(contador==3846){
          contador1=contador1+1;
         contador=0;
 if(contador1==60){
         contador2=contador2+1;
         contador1=0;
 } }
 Tiempo=((contador2*60) + contador1);
 set_timer2(0); }
void main(){
    setup_adc_ports(AN0_TO_AN2|VSS_VDD);
   TRISA  = 0x007;
   TRISC  = 0x002;
   setup_adc(ADC_CLOCK_DIV_8);
   set_adc_channel(0);
   setup_timer_0(RTCC_INTERNAL|RTCC_DIV_32);
   setup_timer_1(T1_INTERNAL|T1_DIV_BY_1);
   setup_comparator(NC_NC_NC_NC);
   setup_vref(FALSE);
   enable_interrupts(INT_TIMER0);
   enable_interrupts(GLOBAL);
   set_timer1(0);
   port_b_pullups(TRUE);
   ext_int_edge(L_TO_H);
   set_timer0(128);
   setup_timer_2(T2_DIV_BY_4,255,1);
   disable_interrupts(INT_TIMER2);

   while(1)  {

   /////////////// MENÚ////////////////
   inicio:
   output_low(PIN_B1);//ALARMA1
   output_low(PIN_B2);//ALARMA2
   output_high(PIN_B3);//GIRO
   output_high(PIN_B5);//EXTRACTOR
   lcd_gotoxy(1,1);
   printf(lcd_putc,"\fCOFFEE ROASTER");
   lcd_gotoxy(6,2);
   printf(lcd_putc,"USCO");
```

```
 output_high(PIN_B6);//PIN 39
output_low(PIN_B7);// PIN 40
output_low(PIN_B6);//PIN 39
ingresa_tiempo:    ///////////tiempo de tostion
lcd_gotoxy(1,1);
printf(lcd_putc,"Ingrese tiempo");
lcd_gotoxy(1,2);
printf(lcd_putc,"de tostion:");
k=0;

while  (k==0)
  {
  k=kbd_getc();
  if(k!=0)
      {
         uni=(k-48);
         num=((dec*10)+uni);
         t_tost=num;
         t_tost_seg=t_tost*60; // TIEMPO DE TOSTIÓN
         lcd_gotoxy(13,2);
         printf(lcd_putc,"%Lu ",uni);
         lcd_gotoxy(14,2);
         printf(lcd_putc,"min");
         delay_ms(200);
      }
  }k=0;
lcd_putc("\f");
lcd_gotoxy(1,1);
printf(lcd_putc,"*: Continuar");
lcd_gotoxy(1,2);
printf(lcd_putc,"#: Atrás");
delay_ms(200);
  while  (k==0)
  {
  k=kbd_getc();
  if(k=='*')
      {
      continue;
      }
   if(k=='#')
      {
      goto ingresa_tiempo;
      }
  }k=0;

lcd_putc("\f");
ingresa_temperatura:  /// temperatura de tostion////////////////
```

```
 lcd_gotoxy(1,1);
 printf(lcd_putc,"Ingrese temp de");
 lcd_gotoxy(1,2);
 printf(lcd_putc,"tostion:");
 k=0;
while  (k==0)
   {
   k=kbd_getc();
   if(k!=0)
       {  cen=k-48;
          lcd_gotoxy(9,2);
          printf(lcd_putc,"%Lu ",cen);
       }
   }k=0;

while  (k==0)
   {
   k=kbd_getc();
   if(k!=0)
       {  dec=k-48;
          lcd_gotoxy(10,2);
          printf(lcd_putc,"%Lu ",dec);
       }
   }k=0;

 while  (k==0)
   {
   k=kbd_getc();
   if(k!=0)
       {  uni=(k-48);
          num=((cen*100)+(dec*10)+uni);
          TempRef=num;
          lcd_gotoxy(11,2);
          printf(lcd_putc,"%Lu ",uni);
          lcd_gotoxy(12,2);
          printf(lcd_putc," oC");
          delay_ms(200);
       }
   }k=0;

 lcd_putc("\f");
 lcd_gotoxy(1,1);
 printf(lcd_putc,"*: Continuar");
 lcd_gotoxy(1,2);
 printf(lcd_putc,"#: Atrás");

   while  (k==0)
```

```
{
k=kbd_getc();
if(k=='*')
   {
   continue;
   }
 if(k=='#')
   {
   goto ingresa_tiempo;
   }
}k=0;

while  (k==0)     { ///////precalentamiento//////////
k=kbd_getc();
if(k=='*')
   {
   output_low(PIN_B3); // GIRO DEL CILINDRO ACTIVO EN BAJO
   enable_interrupts(INT_EXT);
   set_adc_channel(0);
   delay_us(50);
   fase = 57526; //
   fase1=(int16)fase;
   delay_ms(1);
   printf(lcd_putc,"Precalentando...");
   output_high(PIN_B3); //GIRO DEL CILINDRO DESACTIVADO
   disable_interrupts(INT_EXT);
   }
 if(k=='#')
   {
   continue;
   }
}k=0;
   printf(lcd_putc,"Ingrese el grano");
    printf(lcd_putc,"de cafe");
   output_high(PIN_B2);//ALARMA2
   output_low(PIN_B2);//APAGA ALARMA 2
   lcd_putc("\f");
   lcd_gotoxy(1,1);
   printf(lcd_putc,"*: Continuar");
   lcd_gotoxy(1,2);
   printf(lcd_putc,"#: Atras");

     contador=0, contador1=0, contador2=0;
     enable_interrupts(INT_TIMER2);
     set_timer2(0);
     while (Tiempo < t_tost_seg)          {
     printf("$%f|%01.4f-%f/%f",Tr,Peso,t_tost_seg,Tiempo); //manda datos por tx
```

```
   output_low(PIN_B3); // GIRO DEL CILINDRO ACTIVO EN BAJO
   output_high(PIN_B1);//ALARMA 1
////////////control de temperatura/////////////////////////

/////////// LINEALIZACIÓN TERMOCUPLA ///////////////////////
      temp_amb=((read2*0.0048875855327468)*100);
      Tt=((read1*0.0048875855327468));
      Tt1=((Tt*1000000)/158.772);
       Lin_t=(0.01978425*Tt1-
   0.0000002001204*(pow(Tt1,2))+0.00000000001036969*(pow(Tt1,3))-
   2.549687E-16*(pow(Tt1,4))+3.585153E-21*(pow(Tt1,5))-5.344285E-
   26*(pow(Tt1,6))+5.09989E-31*(pow(Tt1,7)));
      Tr=(temp_amb+Lin_t);

        Kp=0.013; Ti=0.0022; Td=0.01;    // valores iniciales del control PID.-
        eT_1=0.0; eT_2=0.0; uT_1=0.0;
        q0=Kp*(1+(0.1/Ti)+(Td*10));
        q1=Kp*(1+(Td*20));
        q2=Kp*Td*10;
        p0=0.1/Ti;
        p00=1/(1+p0);
        eT=(TempRef-Tr);                  //Cálculo error
          uT=q0*eT - q1*eT_1 + q2*eT_2 + uT_1;  //Cálculo de la salida PID
          rT=(uT*1024)/500;                    //duty cycle maximo 1000 -> 5V.-
         /*  <<<<< AntiWindup  >>>>>*/
          if (rT>1023){                     //Salida PID si es mayor que el 1000.-
            uT=(uT + 5*p0)*p00;
            rT=1024;
          }
          if (rT<0){                        //Salida PID si es menor que el 0
            uT=uT*p00;
            rT=0;
          }

          /*  <<<<< Guardar variables para proximo estado >>>>>*/
          eT_2=eT_1;
          eT_1=eT;
          uT_1=uT;
      // FASE//////////////////////////////////////////////////////////////
            enable_interrupts(INT_EXT);
            fase = ((1024-rT)*39) + 25536; //
            fase1=(int16)fase;
            delay_ms(1);
            printf(lcd_putc,"Tostando..... ");
           lcd_gotoxy(1,2);
           Tr1=(int16)Tr;
          printf(lcd_putc,"%LuoC \%01.4fKg",Tr1,Peso);
```

```
        output_high(PIN_B3); // GIRO DEL CILINDRO ACTIVO EN BAJO
        output_low(PIN_B1);// ALARMA ENVIO DE DATOS PC APAGADA
        contador=0, contador1=0, contador2=0, Tiempo=0;
        disable_interrupts(INT_TIMER2);
        disable_interrupts(INT_EXT);
         printf(lcd_putc,"TOSTION");
         printf(lcd_putc,"FINALIZADA");
         delay_ms(1000);
       printf(lcd_putc,"*:Descargar cafe");

        while (((bit_test(portc,1)== 1) && (bit_test(portc,0)== 0))||
((bit_test(portc,1)== 0) && (bit_test(portc,0)== 0)))
        {
        output_high(PIN_A5);//puente h b
        output_low(PIN_C2);//puente h a
        lcd_putc("\f");
        lcd_gotoxy(1,1);
        printf(lcd_putc,"DESCARGANDO...");
        }delay_ms(1000);
        output_low(PIN_A5);// puente h
         lcd_putc("\f");
         lcd_gotoxy(4,1);
         printf(lcd_putc,"DESCARGA");
         lcd_gotoxy(4,2);
         printf(lcd_putc,"COMPLETA");
         output_low(PIN_B6);//PIN 39
         output_high(PIN_B7);// PIN 40
         output_low(PIN_B5);// activa EXTRACTOR
         delay_ms(500);
         output_low(PIN_B7);// PIN 40
         output_high(PIN_B5);
         while (((bit_test(portc,1)== 0) && (bit_test(portc,0)== 1))||
((bit_test(portc,1)== 0) && (bit_test(portc,0)== 0)))
           {
           output_high(PIN_C2);//puente h b
           output_low(PIN_A5);//puente h a
           lcd_putc("\f");
           lcd_gotoxy(1,1);
           printf(lcd_putc,"REINICIANDO...");
           }output_low(PIN_C2);

  }
}
```

National Semiconductor

July 2004

LM117/LM317A/LM317
3-Terminal Adjustable Regulator

General Description

The LM117 series of adjustable 3-terminal positive voltage regulators is capable of supplying in excess of 1.5A over a 1.2V to 37V output range. They are exceptionally easy to use and require only two external resistors to set the output voltage. Further, both line and load regulation are better than standard fixed regulators. Also, the LM117 is packaged in standard transistor packages which are easily mounted and handled.

In addition to higher performance than fixed regulators, the LM117 series offers full overload protection available only in IC's. Included on the chip are current limit, thermal overload protection and safe area protection. All overload protection circuitry remains fully functional even if the adjustment terminal is disconnected.

Normally, no capacitors are needed unless the device is situated more than 6 inches from the input filter capacitors in which case an input bypass is needed. An optional output capacitor can be added to improve transient response. The adjustment terminal can be bypassed to achieve very high ripple rejection ratios which are difficult to achieve with standard 3-terminal regulators.

Besides replacing fixed regulators, the LM117 is useful in a wide variety of other applications. Since the regulator is "floating" and sees only the input-to-output differential voltage, supplies of several hundred volts can be regulated as long as the maximum input to output differential is not exceeded, i.e., avoid short-circuiting the output.

Also, it makes an especially simple adjustable switching regulator, a programmable output regulator, or by connecting a fixed resistor between the adjustment pin and output, the LM117 can be used as a precision current regulator. Supplies with electronic shutdown can be achieved by clamping the adjustment terminal to ground which programs the output to 1.2V where most loads draw little current.

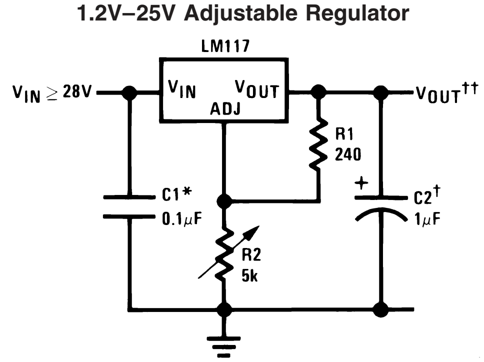
For applications requiring greater output current, see LM150 series (3A) and LM138 series (5A) data sheets. For the negative complement, see LM137 series data sheet.

Features

- Guaranteed 1% output voltage tolerance (LM317A)
- Guaranteed max. 0.01%/V line regulation (LM317A)
- Guaranteed max. 0.3% load regulation (LM117)
- Guaranteed 1.5A output current
- Adjustable output down to 1.2V
- Current limit constant with temperature
- P^+ Product Enhancement tested
- 80 dB ripple rejection
- Output is short-circuit protected

Typical Applications

1.2V–25V Adjustable Regulator



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Full output current not available at high input-output voltages

*Needed if device is more than 6 inches from filter capacitors.

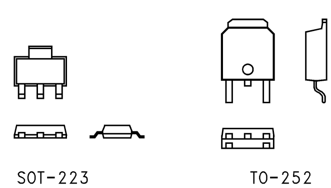
†Optional — improves transient response. Output capacitors in the range of 1μF to 1000μF of aluminum or tantalum electrolytic are commonly used to provide improved output impedance and rejection of transients.

$$††V_{OUT} = 1.25V\left(1+\frac{R2}{R1}\right) + I_{ADJ}(R_2)$$

LM117 Series Packages

Part Number Suffix	Package	Design Load Current
K	TO-3	1.5A
H	**TO-39**	**0.5A**
T	TO-220	1.5A
E	**LCC**	**0.5A**
S	TO-263	1.5A
EMP	SOT-223	1A
MDT	**TO-252**	**0.5A**

SOT-223 vs. D-Pak (TO-252) Packages



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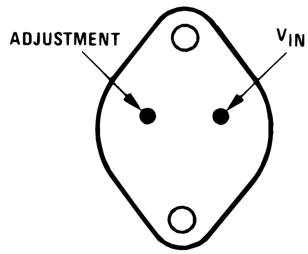
Scale 1:1

Connection Diagrams

(TO-3)
Metal Can Package



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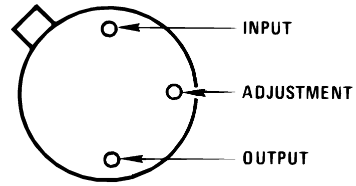
CASE IS OUTPUT

Bottom View
Steel Package
NS Package Number K02A or K02C

(TO-39)
Metal Can Package



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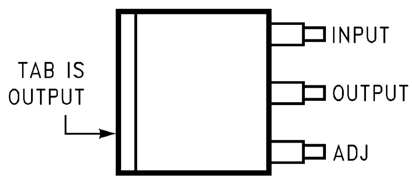
CASE IS OUTPUT

Bottom View
NS Package Number H03A

(TO-263) Surface-Mount Package



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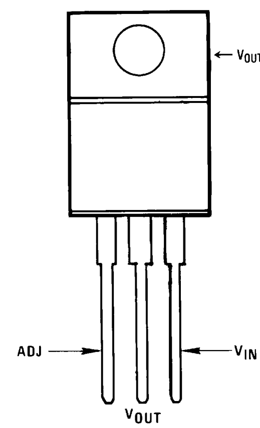
Top View

(TO-220)
Plastic Package



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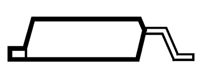
Front View
NS Package Number T03B



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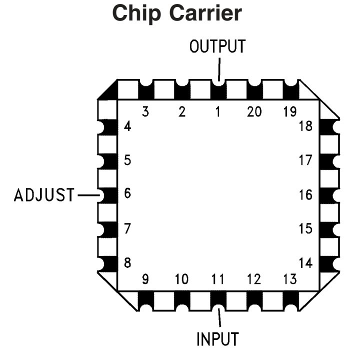
Side View
NS Package Number TS3B

Ceramic Leadless
Chip Carrier



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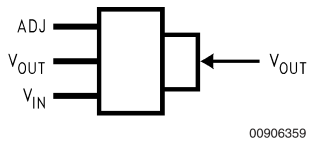
Top View
NS Package Number E20A

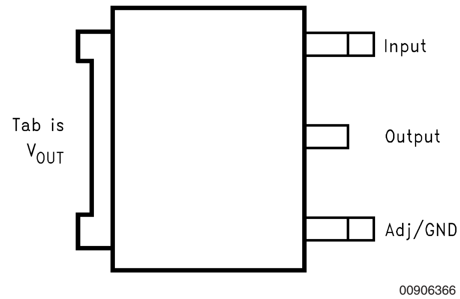
Connection Diagrams (Continued)

4-Lead SOT-223



Front View
NS Package Number MP04A

TO-252 (D-Pak)



Front View
NS Package Number TD03B

Ordering Information

Package	Temperature Range	Part Number	Package Marking	Transport Media	NSC Drawing
Metal Can (TO-3)	$-55^{\circ}C \leq T_J \leq +150^{\circ}C$	LM117K STEEL	LM117K STEEL P+	50 Per Bag	K02A
	$0^{\circ}C \leq T_J \leq +125^{\circ}C$	LM317K STEEL	LM317K STEEL P+	50 Per Bag	
	$-55^{\circ}C \leq T_J \leq +150^{\circ}C$	LM117K/883	LM117K/883	50 Per Bag	K02C
Metal Can (TO-39)	$-55^{\circ}C \leq T_J \leq +150^{\circ}C$	LM117H	LM117H P+	500 Per Box	H03A
	$-55^{\circ}C \leq T_J \leq +150^{\circ}C$	LM117H/883	LM117H/883	20 Per Tray	
	$-40^{\circ}C \leq T_J \leq +125^{\circ}C$	LM317AH	LM317AH P+	500 Per Box	
	$0^{\circ}C \leq T_J \leq +125^{\circ}C$	LM317H	LM317H P+	500 Per Box	
TO-220 3- Lead	$-40^{\circ}C \leq T_J \leq +125^{\circ}C$	LM317AT	LM317AT P+	45 Units/Rail	T03B
	$0^{\circ}C \leq T_J \leq +125^{\circ}C$	LM317T	LM317T P+	45 Units/Rail	
TO-263 3- Lead	$0^{\circ}C \leq T_J \leq +125^{\circ}C$	LM317S	LM317S P+	45 Units/Rail	TS3B
		LM317SX		500 Units Tape and Reel	
LCC	$-55^{\circ}C \leq T_J \leq +150^{\circ}C$	LM117E/883	LM117E/883	50 Units/Rail	E20A
SOT-223 4- Lead	$0^{\circ}C \leq T_J \leq +125^{\circ}C$	LM317EMP	N01A	1k Units Tape and Reel	MP04A
		LM317EMPX		2k Units Tape and Reel	
	$-40^{\circ}C \leq T_J \leq +125^{\circ}C$	LM317AEMP	N07A	1k Units Tape and Reel	
		LM317AEMPX		2k Units Tape and Reel	
D- Pack 3- Lead	$0^{\circ}C \leq T_J \leq +125^{\circ}C$	LM317MDT	LM317MDT	75 Units/Rail	TD03B
		LM317MDTX		2.5k Units Tape and Reel	
	$-40^{\circ}C \leq T_J \leq +125^{\circ}C$	LM317AMDT	LM317AMDT	75 Units/Rail	
		LM317AMDTX		2.5k Units Tape and Reel	

Absolute Maximum Ratings (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

Power Dissipation	Internally Limited
Input-Output Voltage Differential	+40V, −0.3V
Storage Temperature	−65˚C to +150˚C
Lead Temperature	
Metal Package (Soldering, 10 seconds)	300˚C
Plastic Package (Soldering, 4 seconds)	260˚C
ESD Tolerance (Note 5)	3 kV

Operating Temperature Range

LM117	$-55˚C \leq T_J \leq +150˚C$
LM317A	$-40˚C \leq T_J \leq +125˚C$
LM317	$0˚C \leq T_J \leq +125˚C$

Preconditioning

Thermal Limit Burn-In	All Devices 100%

Electrical Characteristics (Note 3)

Specifications with standard type face are for T_J = 25˚C, and those with **boldface type** apply over **full Operating Temperature Range**. Unless otherwise specified, $V_{IN} - V_{OUT}$ = 5V, and I_{OUT} = 10 mA.

Parameter	Conditions	**LM117** (Note 2)			Units
		Min	Typ	Max	
Reference Voltage					V
	$3V \leq (V_{IN} - V_{OUT}) \leq 40V$, $10\ mA \leq I_{OUT} \leq I_{MAX}$, $P \leq P_{MAX}$	**1.20**	**1.25**	**1.30**	V
Line Regulation	$3V \leq (V_{IN} - V_{OUT}) \leq 40V$ (Note 4)		0.01	0.02	%/V
			0.02	**0.05**	%/V
Load Regulation	$10\ mA \leq I_{OUT} \leq I_{MAX}$ (Note 4)		0.1	0.3	%
			0.3	**1**	%
Thermal Regulation	20 ms Pulse		0.03	0.07	%/W
Adjustment Pin Current			**50**	**100**	μA
Adjustment Pin Current Change	$10\ mA \leq I_{OUT} \leq I_{MAX}$ $3V \leq (V_{IN} - V_{OUT}) \leq 40V$		**0.2**	**5**	μA
Temperature Stability	$T_{MIN} \leq T_J \leq T_{MAX}$		**1**		%
Minimum Load Current	$(V_{IN} - V_{OUT}) = 40V$		**3.5**	**5**	mA
Current Limit	$(V_{IN} - V_{OUT}) \leq 15V$				
	K Package	**1.5**	**2.2**	**3.4**	A
	H Package	**0.5**	**0.8**	**1.8**	A
	$(V_{IN} - V_{OUT}) = 40V$				
	K Package	0.3	0.4		A
	H Package	0.15	0.2		A
RMS Output Noise, % of V_{OUT}	$10\ Hz \leq f \leq 10\ kHz$		0.003		%
Ripple Rejection Ratio	V_{OUT} = 10V, f = 120 Hz, C_{ADJ} = 0 μF		**65**		dB
	V_{OUT} = 10V, f = 120 Hz, C_{ADJ} = 10 μF	**66**	**80**		dB
Long-Term Stability	T_J = 125˚C, 1000 hrs		0.3	1	%
Thermal Resistance, Junction-to-Case	K Package		2.3	3	˚C/W
	H Package		12	15	˚C/W
	E Package				˚C/W
Thermal Resistance, Junction-to-Ambient (No Heat Sink)	K Package		35		˚C/W
	H Package		140		˚C/W
	E Package				˚C/W

Electrical Characteristics (Note 3)

Specifications with standard type face are for T_J = 25˚C, and those with **boldface type** apply over **full Operating Temperature Range**. Unless otherwise specified, $V_{IN} - V_{OUT}$ = 5V, and I_{OUT} = 10 mA.

Parameter	Conditions	LM317A			LM317			Units
		Min	Typ	Max	Min	Typ	Max	
Reference Voltage		1.238	1.250	1.262				V
	3V ≤ $(V_{IN} - V_{OUT})$ ≤ 40V, 10 mA ≤ I_{OUT} ≤ I_{MAX}, P ≤ P_{MAX}	**1.225**	**1.250**	**1.270**	**1.20**	**1.25**	**1.30**	V
Line Regulation	3V ≤ $(V_{IN} - V_{OUT})$ ≤ 40V (Note 4)		0.005	0.01		0.01	0.04	%/V
			0.01	**0.02**		**0.02**	**0.07**	%/V
Load Regulation	10 mA ≤ I_{OUT} ≤ I_{MAX} (Note 4)		0.1	0.5		0.1	0.5	%
			0.3	**1**		**0.3**	**1.5**	%
Thermal Regulation	20 ms Pulse		0.04	0.07		0.04	0.07	%/W
Adjustment Pin Current			**50**	**100**		**50**	**100**	μA
Adjustment Pin Current Change	10 mA ≤ I_{OUT} ≤ I_{MAX} 3V ≤ $(V_{IN} - V_{OUT})$ ≤ 40V		**0.2**	**5**		**0.2**	**5**	μA
Temperature Stability	T_{MIN} ≤ T_J ≤ T_{MAX}		**1**			**1**		%
Minimum Load Current	$(V_{IN} - V_{OUT})$ = 40V		**3.5**	**10**		**3.5**	**10**	mA
Current Limit	$(V_{IN} - V_{OUT})$ ≤ 15V							
	K, T, S Packages	**1.5**	**2.2**	**3.4**	**1.5**	**2.2**	**3.4**	A
	H Package	**0.5**	**0.8**	**1.8**	**0.5**	**0.8**	**1.8**	A
	MP Package	**1.5**	**2.2**	**3.4**	**1.5**	**2.2**	**3.4**	A
	$(V_{IN} - V_{OUT})$ = 40V							
	K, T, S Packages	0.15	0.4		0.15	0.4		A
	H Package	0.075	0.2		0.075	0.2		A
	MP Package	0.15	0.4		0.15	0.4		A
RMS Output Noise, % of V_{OUT}	10 Hz ≤ f ≤ 10 kHz		0.003			0.003		%
Ripple Rejection Ratio	V_{OUT} = 10V, f = 120 Hz, C_{ADJ} = 0 μF		**65**			**65**		dB
	V_{OUT} = 10V, f = 120 Hz, C_{ADJ} = 10 μF	**66**	**80**		**66**	**80**		dB
Long-Term Stability	T_J = 125˚C, 1000 hrs		0.3	1		0.3	1	%
Thermal Resistance, Junction-to-Case	K Package					2.3	3	˚C/W
	MDT Package					5		˚C/W
	H Package		12	15		12	15	˚C/W
	T Package		4	5		4		˚C/W
	MP Package		23.5			23.5		˚C/W
Thermal Resistance, Junction-to-Ambient (No Heat Sink)	K Package		35			35		˚C/W
	MDT Package(Note 6)					92		˚C/W
	H Package		140			140		˚C/W
	T Package		50			50		˚C/W
	S Package (Note 6)		50			50		˚C/W

Note 1: Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is intended to be functional, but do not guarantee specific performance limits. For guaranteed specifications and test conditions, see the Electrical Characteristics. The guaranteed specifications apply only for the test conditions listed.

Note 2: Refer to RETS117H drawing for the LM117H, or the RETS117K for the LM117K military specifications.

Note 3: Although power dissipation is internally limited, these specifications are applicable for maximum power dissipations of 2W for the TO-39 and SOT-223 and 20W for the TO-3, TO-220, and TO-263. I_{MAX} is 1.5A for the TO-3, TO-220, and TO-263 packages, 0.5A for the TO-39 package and 1A for the SOT-223 Package. All limits (i.e., the numbers in the Min. and Max. columns) are guaranteed to National's AOQL (Average Outgoing Quality Level).

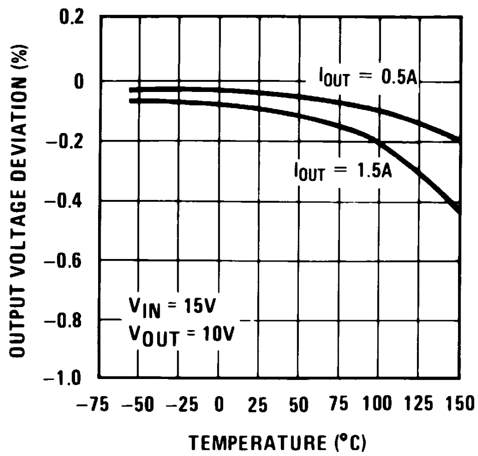
Note 4: Regulation is measured at a constant junction temperature, using pulse testing with a low duty cycle. Changes in output voltage due to heating effects are covered under the specifications for thermal regulation.

Note 5: Human body model, 100 pF discharged through a 1.5 kΩ resistor.

Note 6: If the TO-263 or TO-252 packages are used, the thermal resistance can be reduced by increasing the PC board copper area thermally connected to the package. Using 0.5 square inches of copper area. θ_{JA} is 50˚C/W; with 1 square inch of copper area, θ_{JA} is 37˚C/W; and with 1.6 or more square inches of copper area, θ_{JA} is 32˚C/W. If the SOT-223 package is used, the thermal resistance can be reduced by increasing the PC board copper area (see applications hints for heatsinking).

Typical Performance Characteristics Output Capacitor = 0µF unless otherwise noted

Load Regulation



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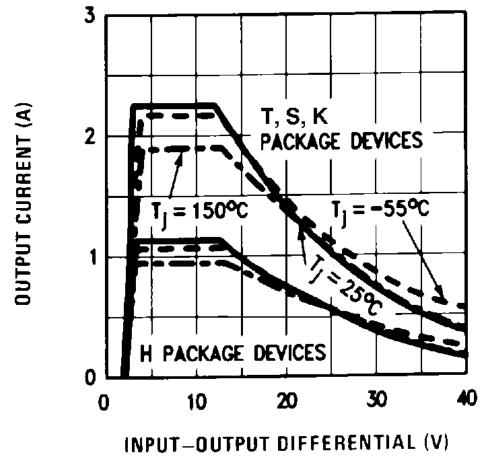
Current Limit



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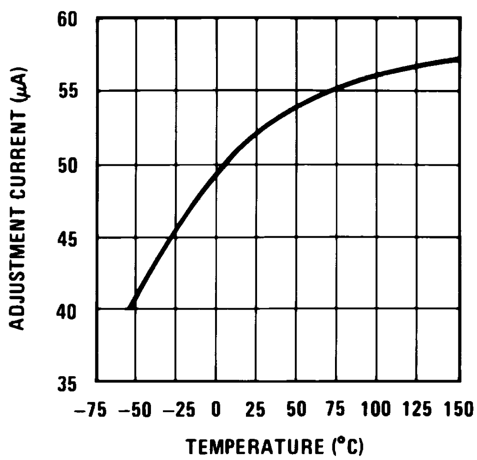
Adjustment Current



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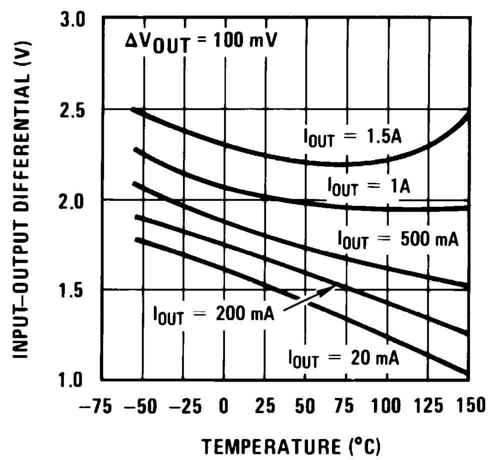
Dropout Voltage



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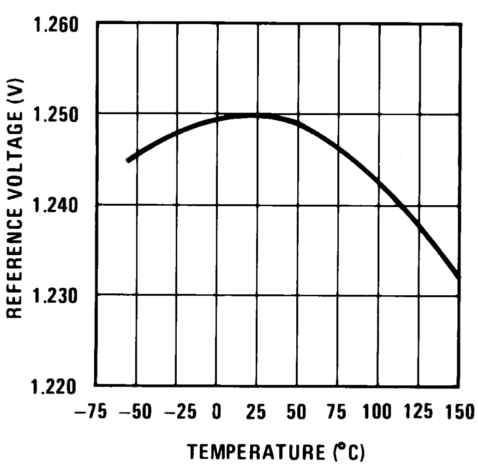
Temperature Stability



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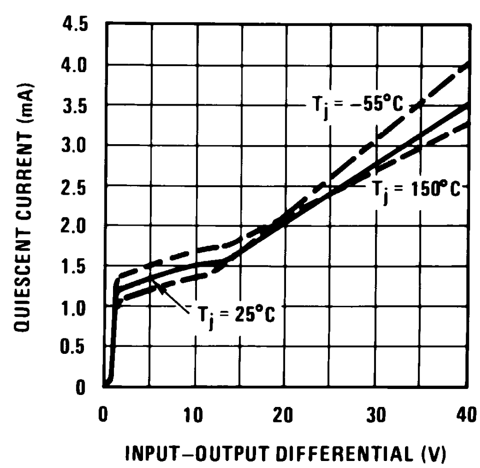
Minimum Operating Current



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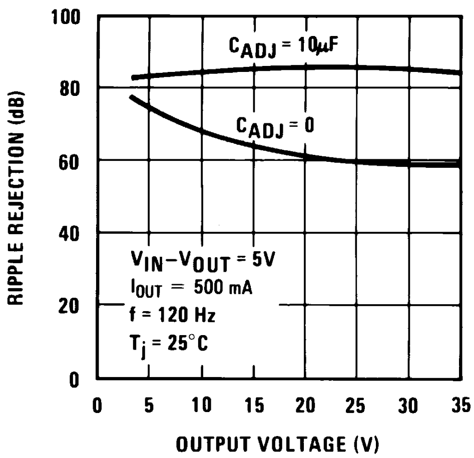
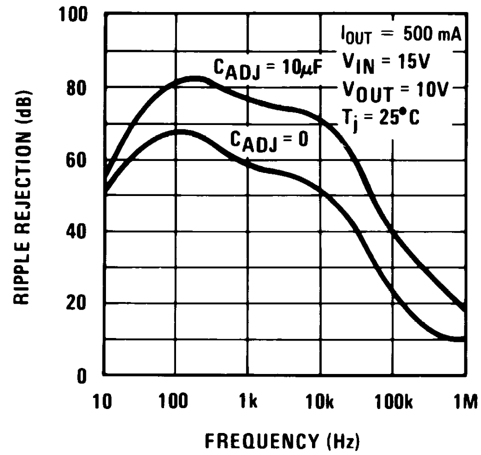
Typical Performance Characteristics Output Capacitor = 0µF unless otherwise noted (Continued)

Ripple Rejection



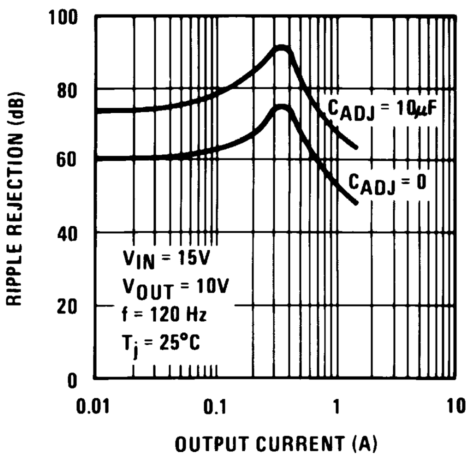
00906343

Ripple Rejection



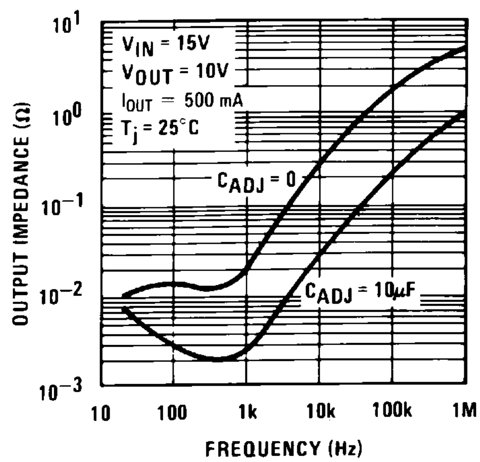
00906344

Ripple Rejection



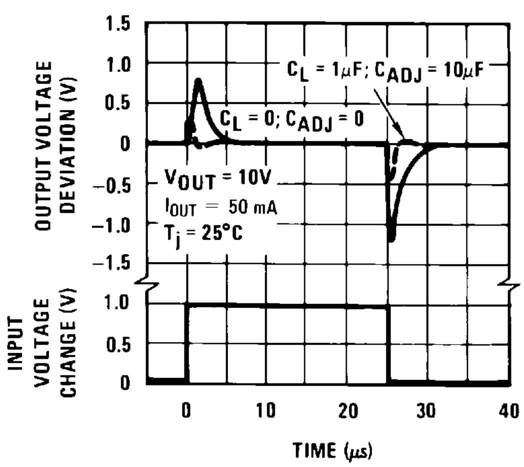
00906345

Output Impedance



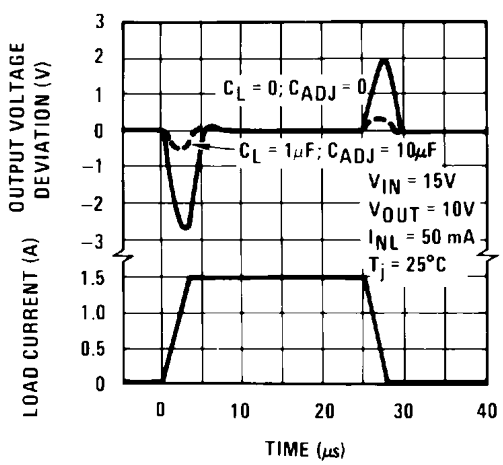
00906346

Line Transient Response



00906347

Load Transient Response



00906348

Application Hints

In operation, the LM117 develops a nominal 1.25V reference voltage, V_{REF}, between the output and adjustment terminal. The reference voltage is impressed across program resistor R1 and, since the voltage is constant, a constant current I_1 then flows through the output set resistor R2, giving an output voltage of

$$V_{OUT} = V_{REF}\left(1 + \frac{R2}{R1}\right) + I_{ADJ}R2$$

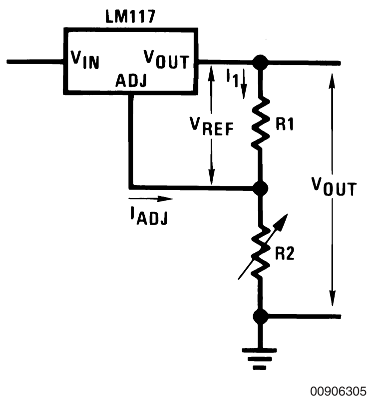


FIGURE 1.

Since the 100µA current from the adjustment terminal represents an error term, the LM117 was designed to minimize I_{ADJ} and make it very constant with line and load changes. To do this, all quiescent operating current is returned to the output establishing a minimum load current requirement. If there is insufficient load on the output, the output will rise.

EXTERNAL CAPACITORS

An input bypass capacitor is recommended. A 0.1µF disc or 1µF solid tantalum on the input is suitable input bypassing for almost all applications. The device is more sensitive to the absence of input bypassing when adjustment or output capacitors are used but the above values will eliminate the possibility of problems.

The adjustment terminal can be bypassed to ground on the LM117 to improve ripple rejection. This bypass capacitor prevents ripple from being amplified as the output voltage is increased. With a 10µF bypass capacitor 80dB ripple rejection is obtainable at any output level. Increases over 10µF do not appreciably improve the ripple rejection at frequencies above 120Hz. If the bypass capacitor is used, it is sometimes necessary to include protection diodes to prevent the capacitor from discharging through internal low current paths and damaging the device.

In general, the best type of capacitors to use is solid tantalum. Solid tantalum capacitors have low impedance even at high frequencies. Depending upon capacitor construction, it takes about 25µF in aluminum electrolytic to equal 1µF solid tantalum at high frequencies. Ceramic capacitors are also good at high frequencies; but some types have a large decrease in capacitance at frequencies around 0.5MHz. For this reason, 0.01µF disc may seem to work better than a 0.1µF disc as a bypass.

Although the LM117 is stable with no output capacitors, like any feedback circuit, certain values of external capacitance can cause excessive ringing. This occurs with values between 500 pF and 5000 pF. A 1µF solid tantalum (or 25µF aluminum electrolytic) on the output swamps this effect and insures stability. Any increase of the load capacitance larger than 10µF will merely improve the loop stability and output impedance.

LOAD REGULATION

The LM117 is capable of providing extremely good load regulation but a few precautions are needed to obtain maximum performance. The current set resistor connected between the adjustment terminal and the output terminal (usually 240Ω) should be tied directly to the output (case) of the regulator rather than near the load. This eliminates line drops from appearing effectively in series with the reference and degrading regulation. For example, a 15V regulator with 0.05Ω resistance between the regulator and load will have a load regulation due to line resistance of 0.05Ω x I_L. If the set resistor is connected near the load the effective line resistance will be 0.05Ω (1 + R2/R1) or in this case, 11.5 times worse.

Figure 2 shows the effect of resistance between the regulator and 240Ω set resistor.

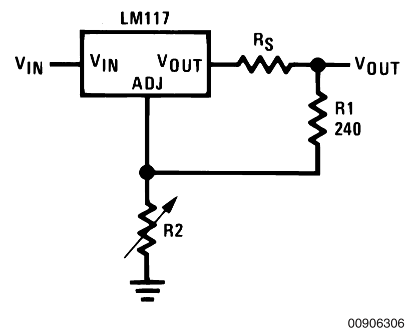


FIGURE 2. Regulator with Line Resistance in Output Lead

With the TO-3 package, it is easy to minimize the resistance from the case to the set resistor, by using two separate leads to the case. However, with the TO-39 package, care should be taken to minimize the wire length of the output lead. The ground of R2 can be returned near the ground of the load to provide remote ground sensing and improve load regulation.

PROTECTION DIODES

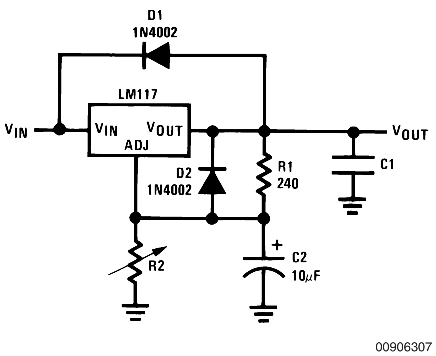
When external capacitors are used with *any* IC regulator it is sometimes necessary to add protection diodes to prevent the capacitors from discharging through low current points into the regulator. Most 10µF capacitors have low enough internal series resistance to deliver 20A spikes when shorted. Although the surge is short, there is enough energy to damage parts of the IC.

When an output capacitor is connected to a regulator and the input is shorted, the output capacitor will discharge into the output of the regulator. The discharge current depends on the value of the capacitor, the output voltage of the regulator, and the rate of decrease of V_{IN}. In the LM117, this discharge path is through a large junction that is able to sustain 15A surge with no problem. This is not true of other types of positive regulators. For output capacitors of 25µF or less, there is no need to use diodes.

The bypass capacitor on the adjustment terminal can discharge through a low current junction. Discharge occurs

Application Hints (Continued)

when *either* the input or output is shorted. Internal to the LM117 is a 50Ω resistor which limits the peak discharge current. No protection is needed for output voltages of 25V or less and 10µF capacitance. *Figure 3* shows an LM117 with protection diodes included for use with outputs greater than 25V and high values of output capacitance.



$$V_{OUT} = 1.25V\left(1 + \frac{R2}{R1}\right) + I_{ADJ}R2$$

D1 protects against C1

D2 protects against C2

FIGURE 3. Regulator with Protection Diodes

When a value for $\theta_{(H-A)}$ is found using the equation shown, *a heatsink must be selected that has a value that is less than or equal to this number.*

$\theta_{(H-A)}$ is specified numerically by the heatsink manufacturer in the catalog, or shown in a curve that plots temperature rise vs power dissipation for the heatsink.

HEATSINKING TO-263, SOT-223 AND TO-252 PACKAGE PARTS

The TO-263 ("S"), SOT-223 ("MP") and TO-252 ("DT") packages use a copper plane on the PCB and the PCB itself as a heatsink. To optimize the heat sinking ability of the plane and PCB, solder the tab of the package to the plane.

Figure 4 shows for the TO-263 the measured values of $\theta_{(J-A)}$ for different copper area sizes using a typical PCB with 1 ounce copper *and no solder mask over the copper area used for heatsinking.*

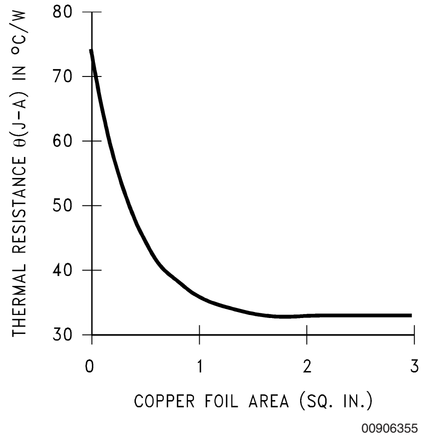


FIGURE 4. $\theta_{(J-A)}$ vs Copper (1 ounce) Area for the TO-263 Package

As shown in the figure, increasing the copper area beyond 1 square inch produces very little improvement. It should also be observed that the minimum value of $\theta_{(J-A)}$ for the TO-263 package mounted to a PCB is 32˚C/W.

As a design aid, *Figure 5* shows the maximum allowable power dissipation compared to ambient temperature for the TO-263 device (assuming $\theta_{(J-A)}$ is 35˚C/W and the maximum junction temperature is 125˚C).

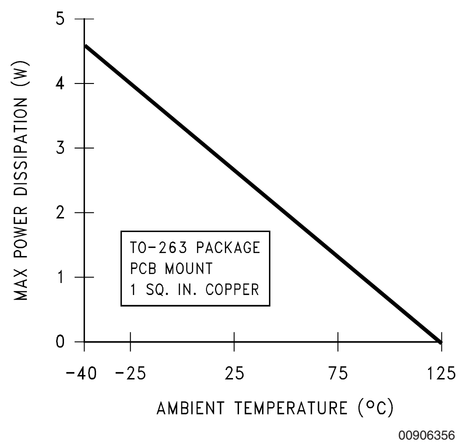


FIGURE 5. Maximum Power Dissipation vs T_{AMB} for the TO-263 Package

Figure 6 and *Figure 7* show the information for the SOT-223 package. *Figure 7* assumes a $\theta_{(J-A)}$ of 74˚C/W for 1 ounce copper and 51˚C/W for 2 ounce copper and a maximum junction temperature of 125˚C.

Application Hints (Continued)

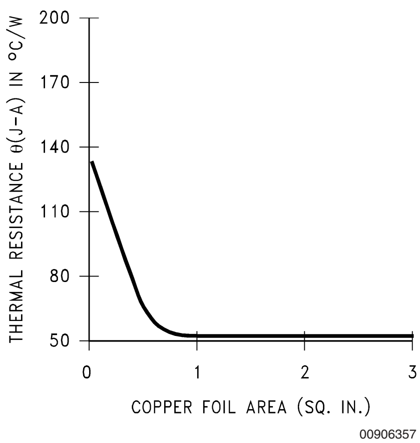


FIGURE 6. $\theta_{(J-A)}$ vs Copper (2 ounce) Area for the SOT-223 Package

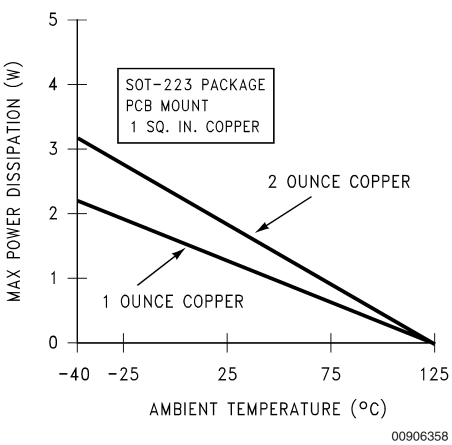


FIGURE 7. Maximum Power Dissipation vs T_{AMB} for the SOT-223 Package

The LM317 regulators have internal thermal shutdown to protect the device from over-heating. Under all possible operating conditions, the junction temperature of the LM317 must be within the range of 0˚C to 125˚C. A heatsink may be required depending on the maximum power dissipation and maximum ambient temperature of the application. To determine if a heatsink is needed, the power dissipated by the regulator, P_D, must be calculated:

$I_{IN} = I_L + I_G$

$P_D = (V_{IN} - V_{OUT}) I_L + V_{IN}I_G$

Figure 8 shows the voltage and currents which are present in the circuit.

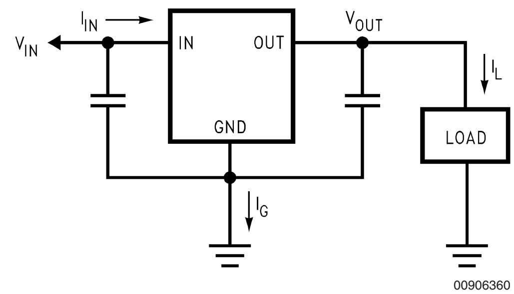


FIGURE 8. Power Dissipation Diagram

The next parameter which must be calculated is the maximum allowable temperature rise, T_R(max):

$T_R(max) = T_J(max) - T_A(max)$

where T_J(max) is the maximum allowable junction temperature (125˚C), and T_A(max) is the maximum ambient temperature which will be encountered in the application.

Using the calculated values for T_R(max) and P_D, the maximum allowable value for the junction-to-ambient thermal resistance (θ_{JA}) can be calculated:

$\theta_{JA} = T_R(max)/P_D$

If the maximum allowable value for θ_{JA} is found to be ≥92˚C/W (Typical Rated Value) for TO-252 package, no heatsink is needed since the package alone will dissipate enough heat to satisfy these requirements. If the calculated value for θ_{JA} falls below these limits, a heatsink is required.

As a design aid, *Table 1* shows the value of the θ_{JA} of TO-252 for different heatsink area. The copper patterns that we used to measure these θ_{JA}s are shown at the end of the Application Notes Section. *Figure 9* reflects the same test results as what are in the *Table 1*

Figure 10 shows the maximum allowable power dissipation vs. ambient temperature for the TO-252 device. *Figure 11* shows the maximum allowable power dissipation vs. copper area (in^2) for the TO-252 device. Please see AN1028 for power enhancement techniques to be used with SOT-223 and TO-252 packages.

TABLE 1. θ_{JA} Different Heatsink Area

Layout	Copper Area		Thermal Resistance
	Top Side (in^2)*	Bottom Side (in^2)	(θ_{JA}˚C/W) TO-252
1	0.0123	0	103
2	0.066	0	87
3	0.3	0	60
4	0.53	0	54
5	0.76	0	52
6	1	0	47
7	0	0.2	84
8	0	0.4	70
9	0	0.6	63

Application Hints (Continued)

TABLE 1. θ_{JA} Different Heatsink Area (Continued)

Layout	Copper Area		Thermal Resistance
10	0	0.8	57
11	0	1	57
12	0.066	0.066	89
13	0.175	0.175	72
14	0.284	0.284	61
15	0.392	0.392	55
16	0.5	0.5	53

Note: * Tab of device attached to topside of copper.

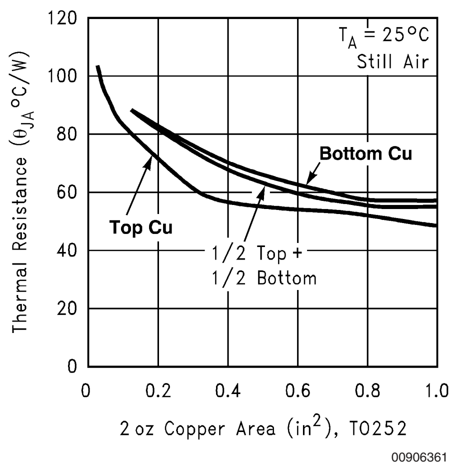


FIGURE 9. θ_{JA} vs 2oz Copper Area for TO-252

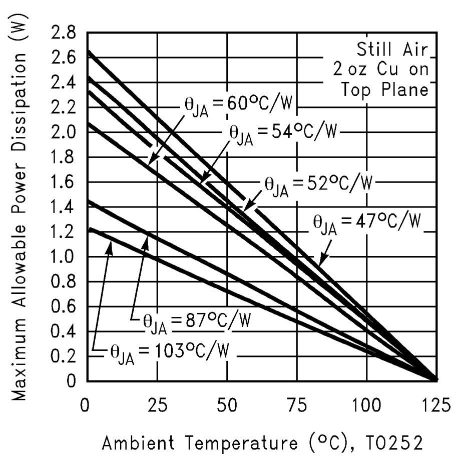


FIGURE 10. Maximum Allowable Power Dissipation vs. Ambient Temperature for TO-252

Application Hints (Continued)

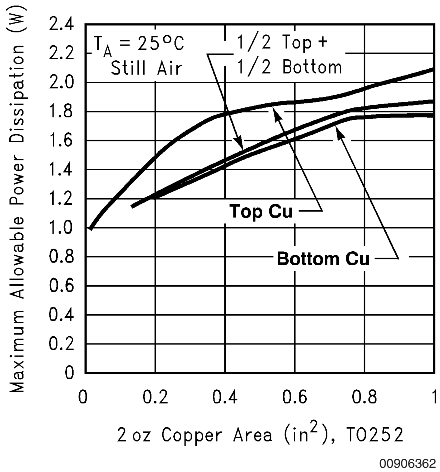


FIGURE 11. Maximum Allowable Power Dissipation vs. 2oz Copper Area for TO-252

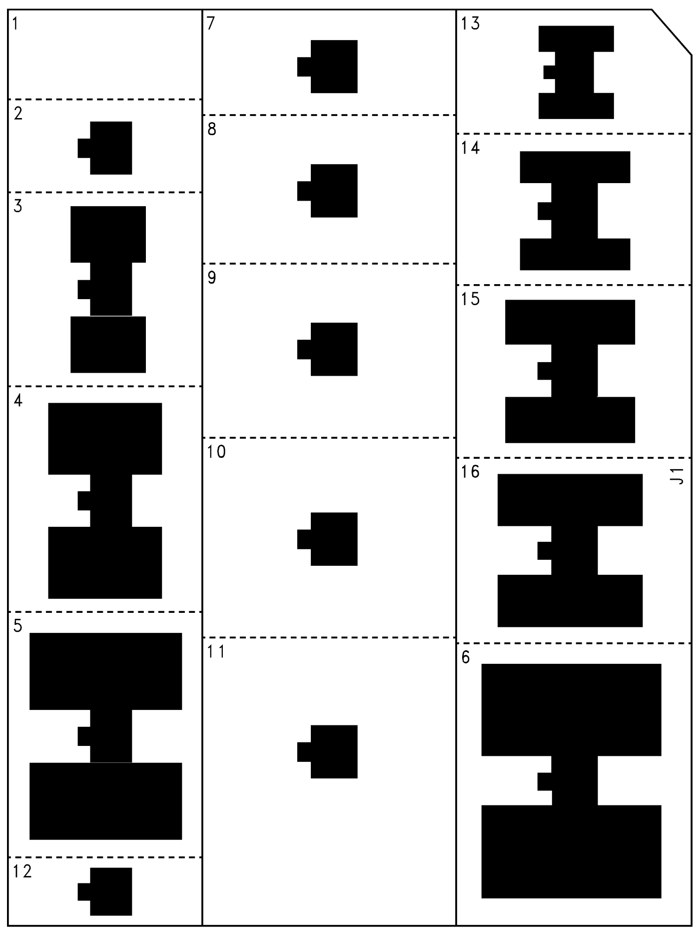


FIGURE 12. Top View of the Thermal Test Pattern in Actual Scale

Application Hints (Continued)

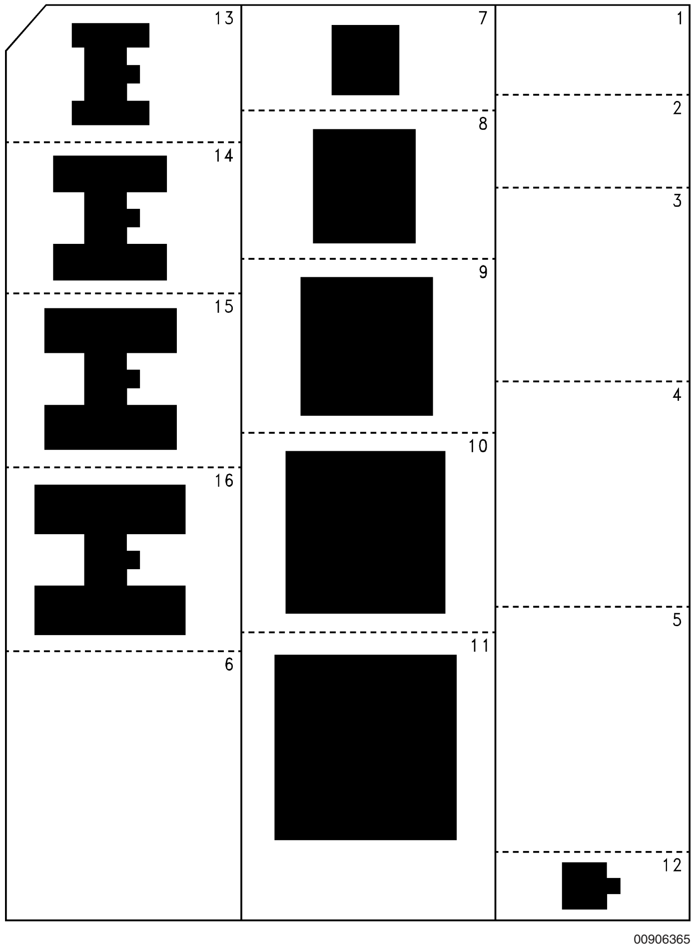
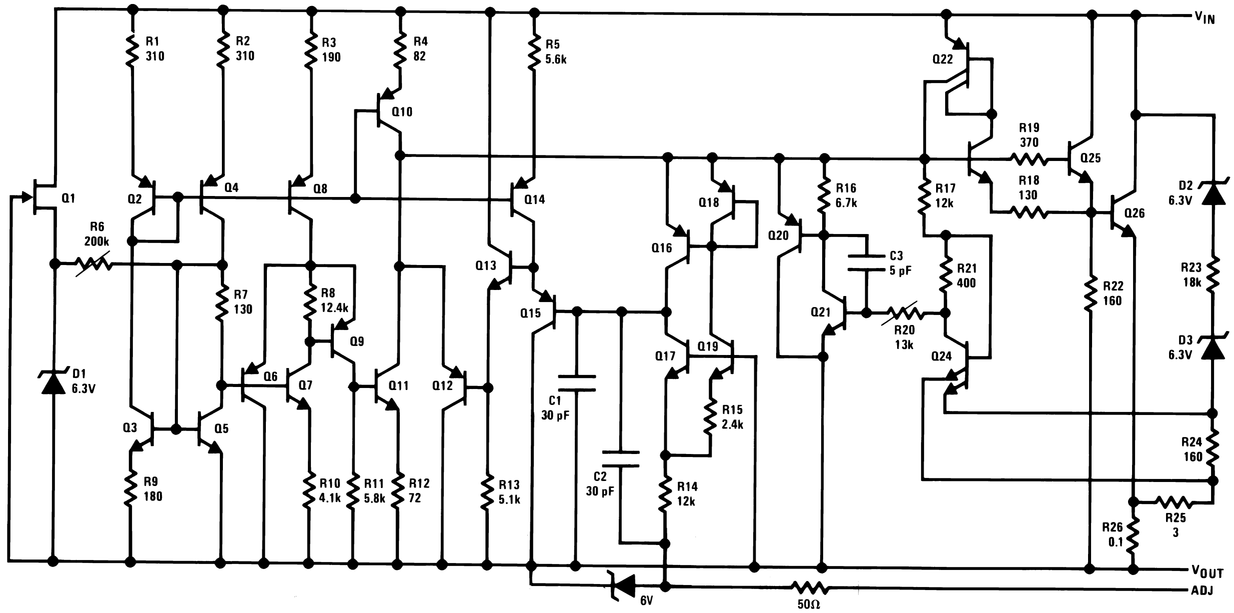


FIGURE 13. Bottom View of the Thermal Test Pattern in Actual Scale

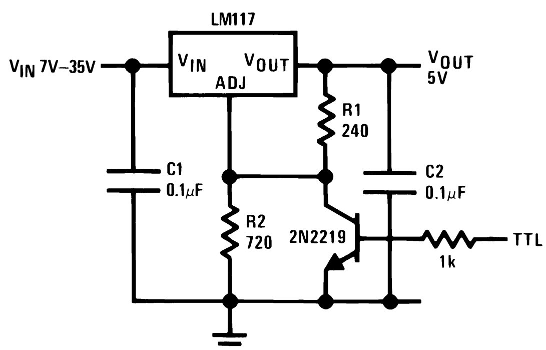
Schematic Diagram



00906308

Typical Applications

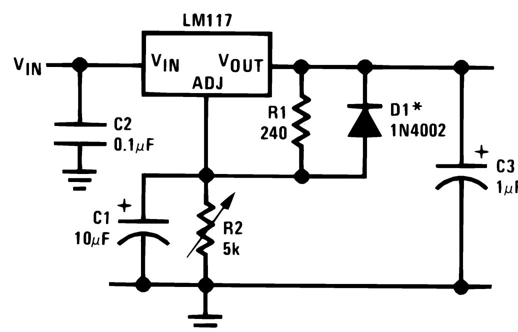
5V Logic Regulator with Electronic Shutdown*



00906303

*Min. output ≅ 1.2V

Adjustable Regulator with Improved Ripple Rejection

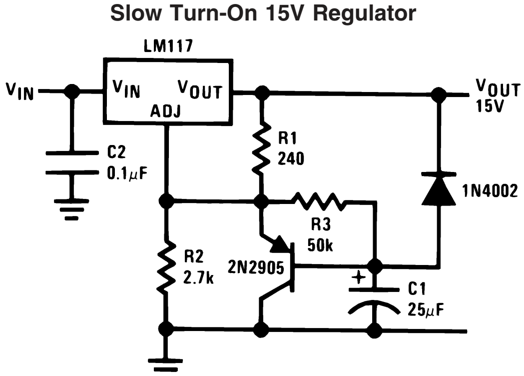


00906310

†Solid tantalum

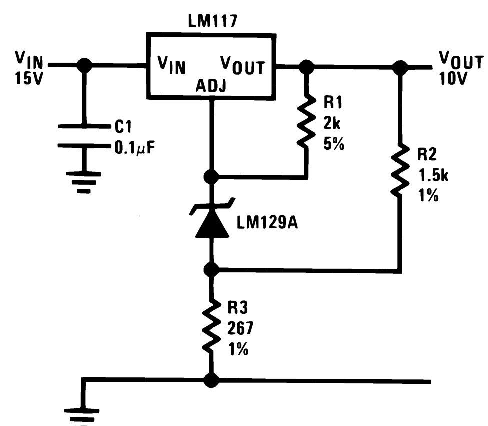
*Discharges C1 if output is shorted to ground

Slow Turn-On 15V Regulator



00906309

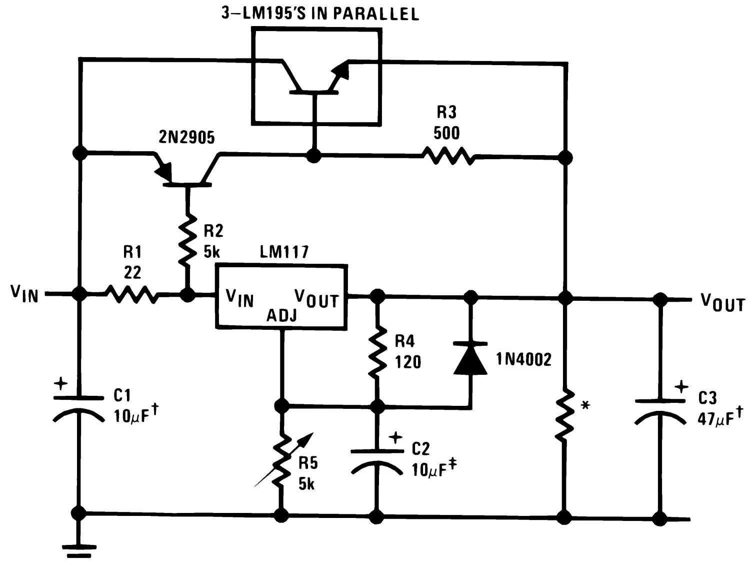
High Stability 10V Regulator



00906311

Typical Applications (Continued)

High Current Adjustable Regulator



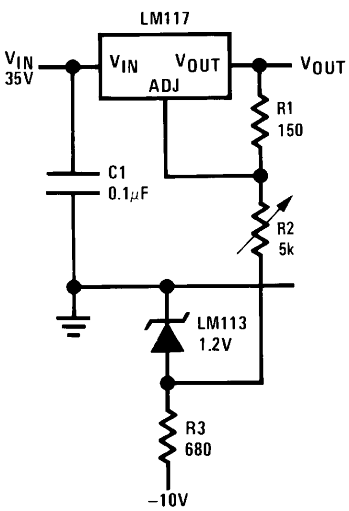
00906312

‡Optional — improves ripple rejection

†Solid tantalum

*Minimum load current = 30 mA

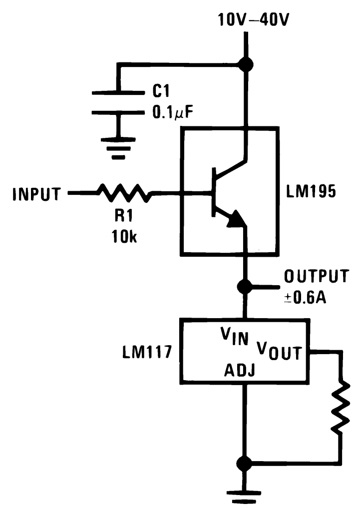
0 to 30V Regulator



00906313

Full output current not available at high input-output voltages

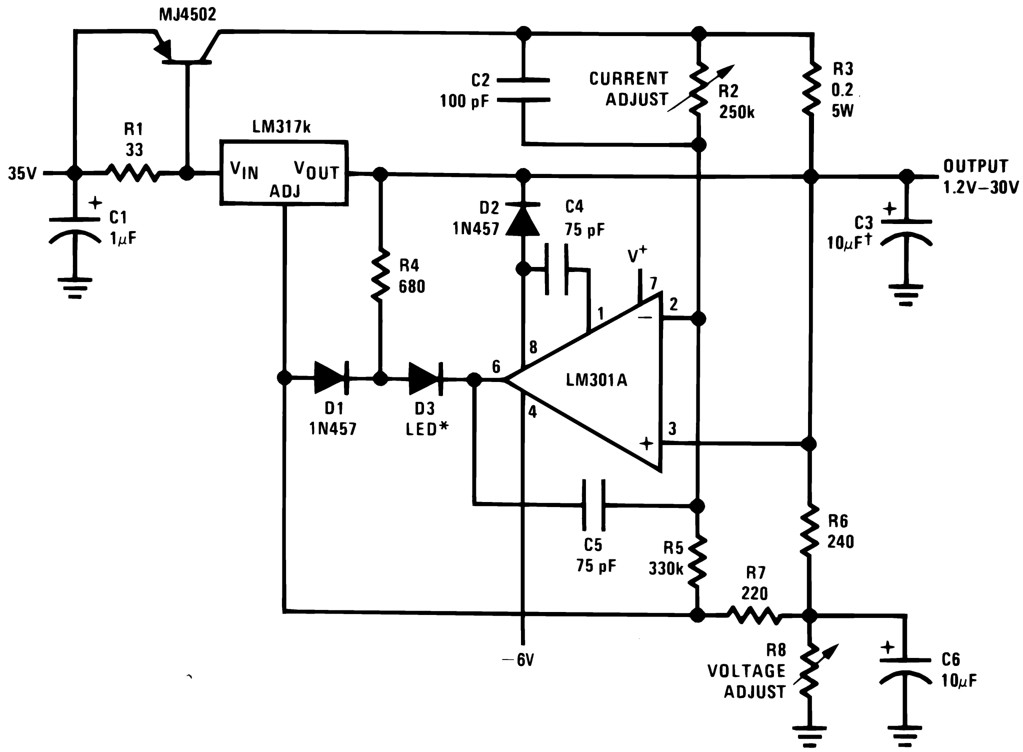
Power Follower



00906314

Typical Applications (Continued)

5A Constant Voltage/Constant Current Regulator

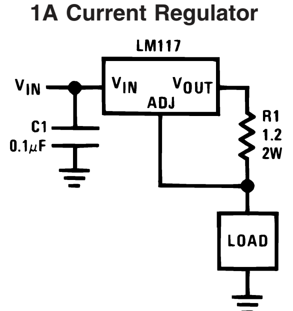


00906315

†Solid tantalum

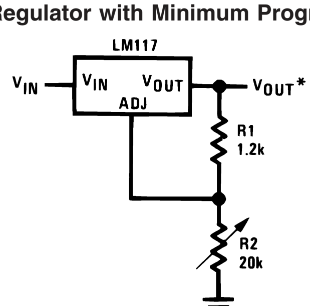
*Lights in constant current mode

1A Current Regulator



00906316

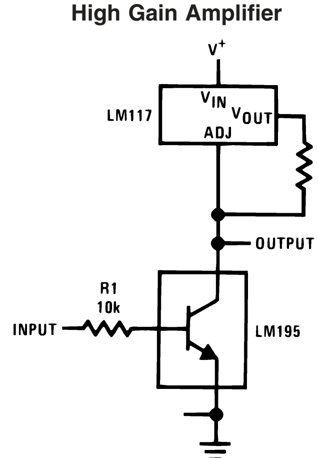
1.2V–20V Regulator with Minimum Program Current



00906317

*Minimum load current ≅ 4 mA

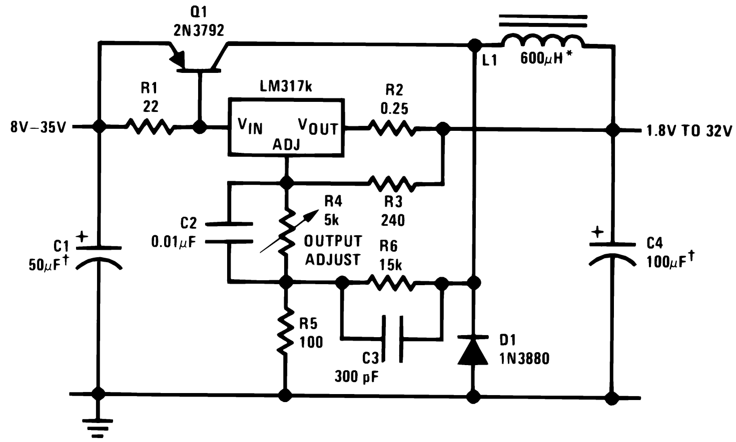
High Gain Amplifier



00906318

Typical Applications (Continued)

Low Cost 3A Switching Regulator

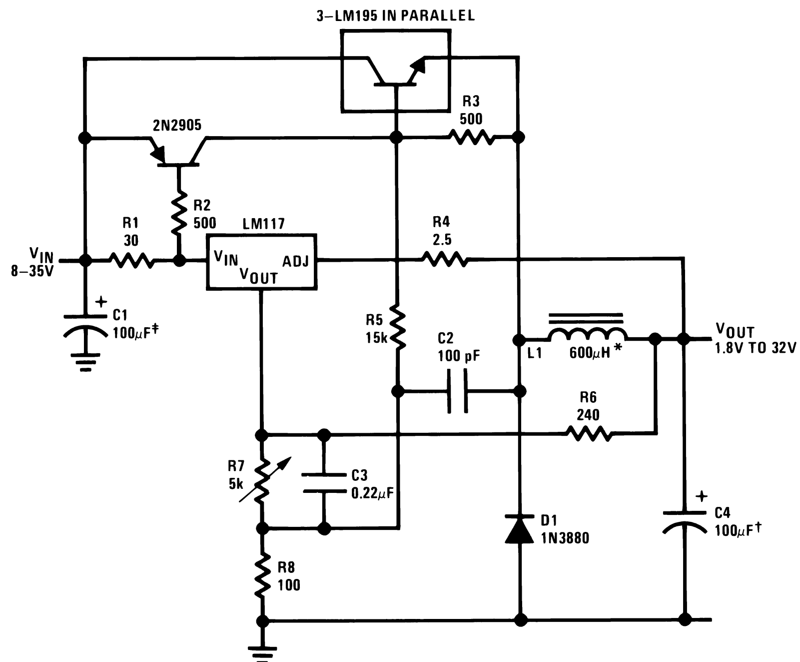


00906319

†Solid tantalum

*Core — Arnold A-254168-2 60 turns

4A Switching Regulator with Overload Protection

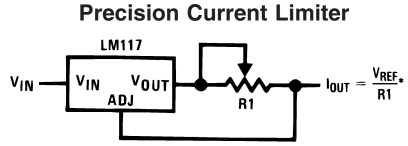


00906320

†Solid tantalum

*Core — Arnold A-254168-2 60 turns

Precision Current Limiter

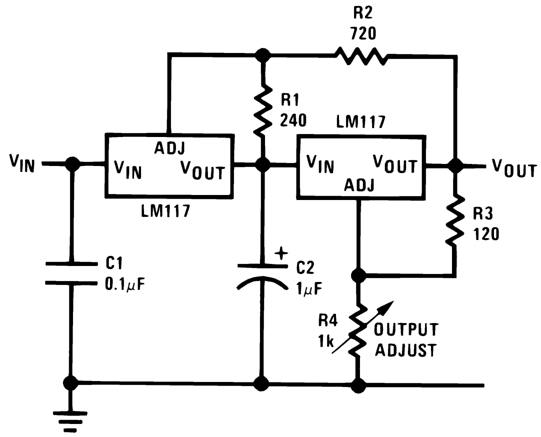


$*0.8\Omega \leq R1 \leq 120\Omega$

00906321

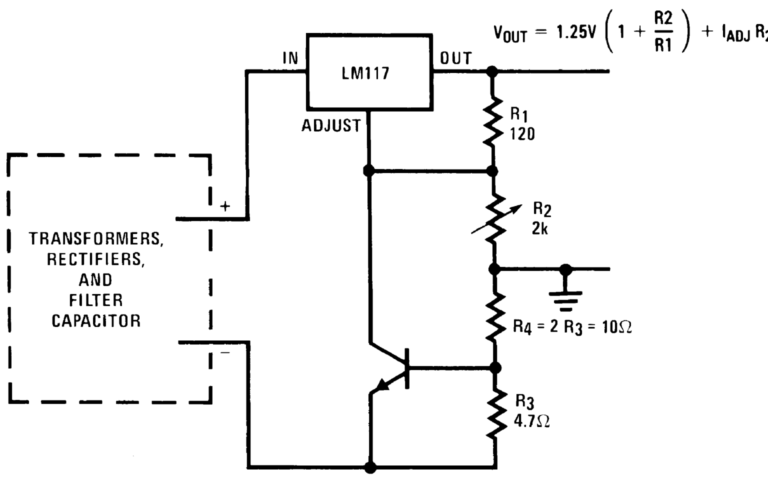
Typical Applications (Continued)

Tracking Preregulator



00906322

Current Limited Voltage Regulator



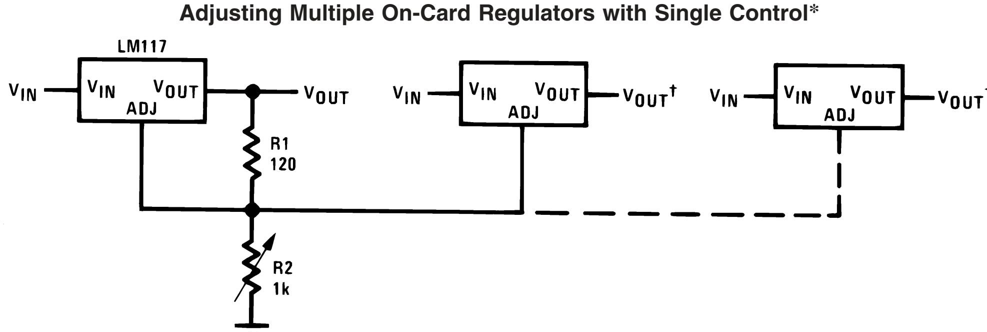
00906323

– Short circuit current is approximately $\frac{600\text{ mV}}{R3}$, or 120 mA

(Compared to LM117's higher current limit)

— At 50 mA output only ¾ volt of drop occurs in R_3 and R_4

Adjusting Multiple On-Card Regulators with Single Control*



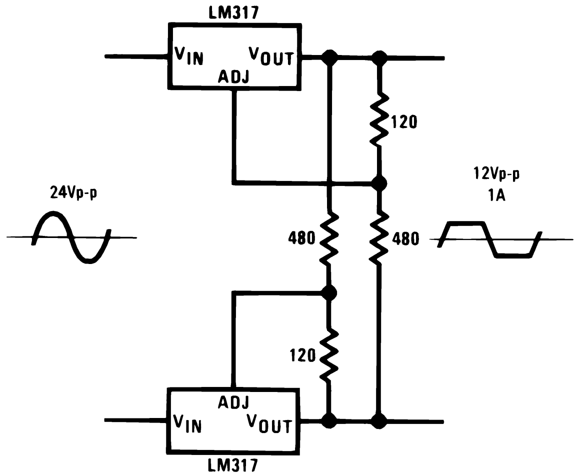
00906324

*All outputs within ±100 mV

†Minimum load — 10 mA

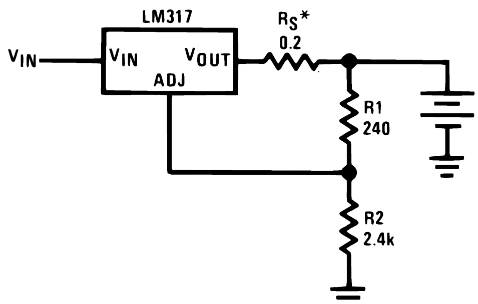
Typical Applications (Continued)

AC Voltage Regulator



00906325

12V Battery Charger

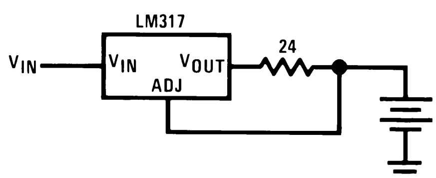


00906326

$$*R_S\text{—sets output impedance of charger: } Z_{OUT} = R_S \left(1 + \frac{R2}{R1}\right)$$

Use of R_S allows low charging rates with fully charged battery.

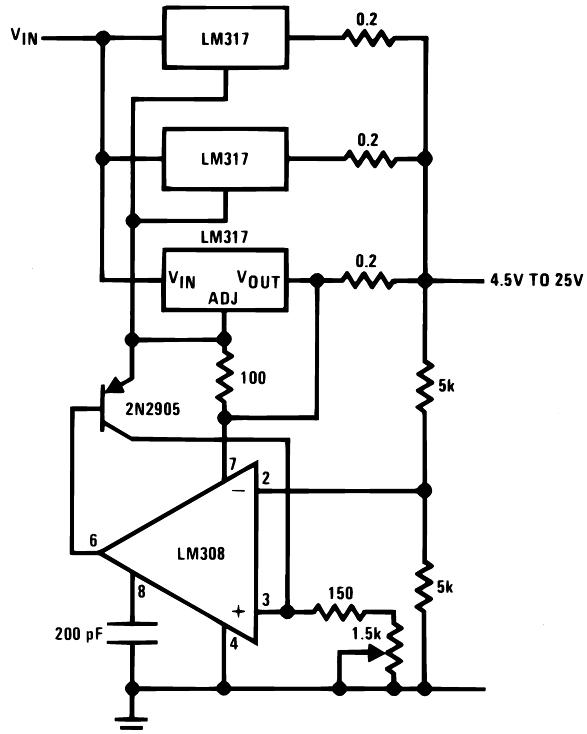
50mA Constant Current Battery Charger



00906327

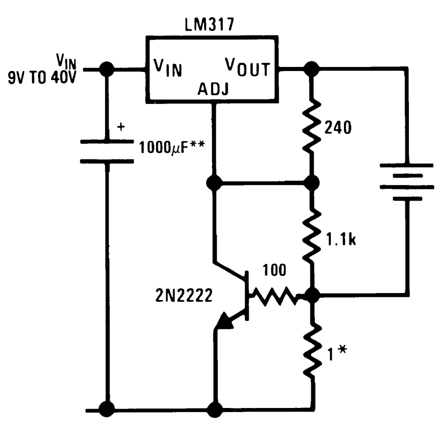
Typical Applications (Continued)

Adjustable 4A Regulator



00906328

Current Limited 6V Charger

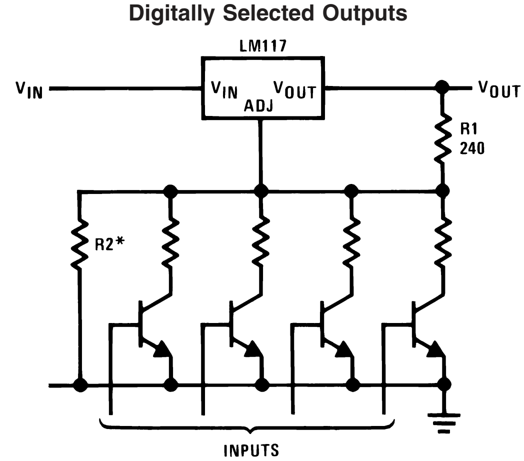


00906329

*Sets peak current (0.6A for 1Ω)

**The 1000μF is recommended to filter out input transients

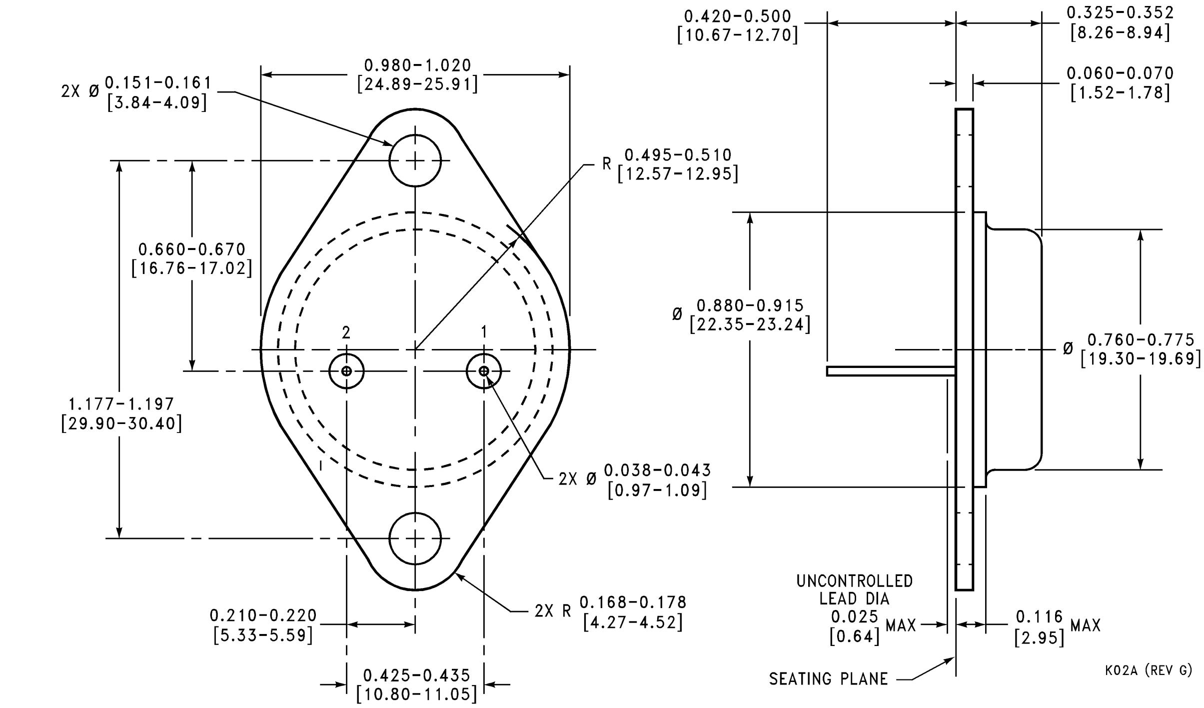
Digitally Selected Outputs



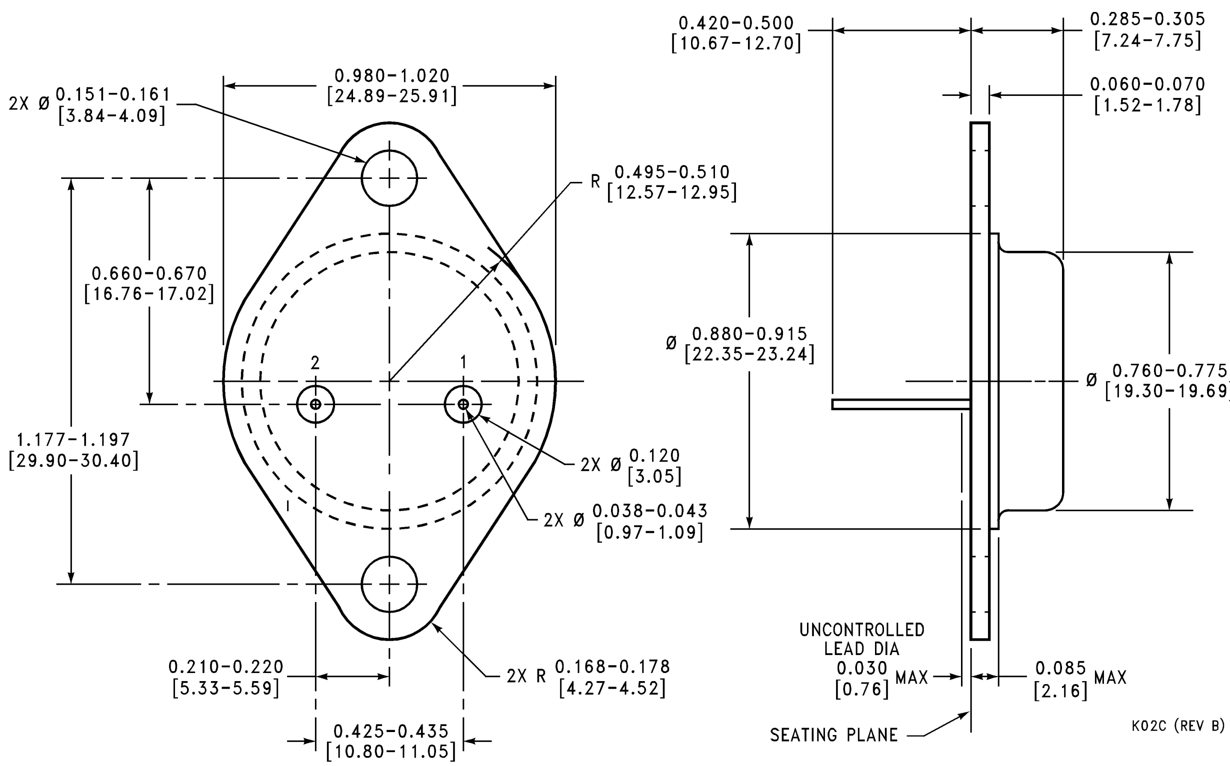
00906302

*Sets maximum V_{OUT}

Physical Dimensions inches (millimeters) unless otherwise noted

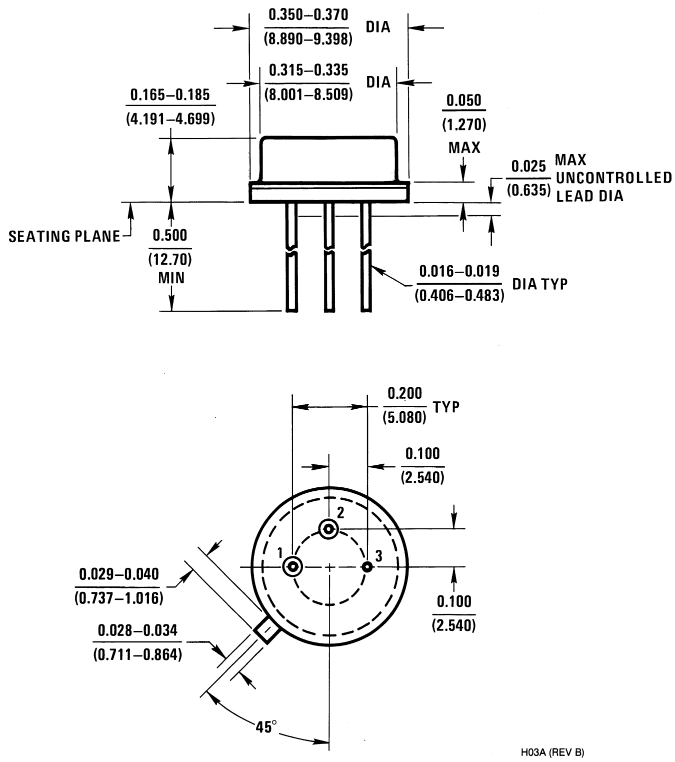


TO-3 Metal Can Package (K)
NS Package Number K02A

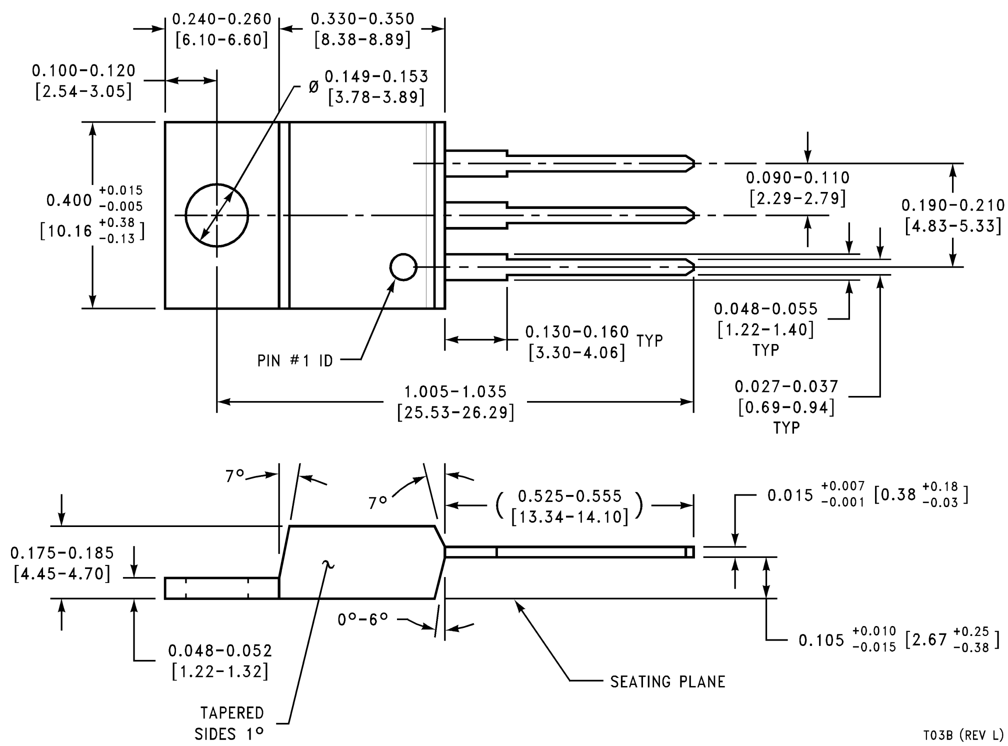


TO-3 Metal Can Package (K)
Mil-Aero Product
NS Package Number K02C

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)

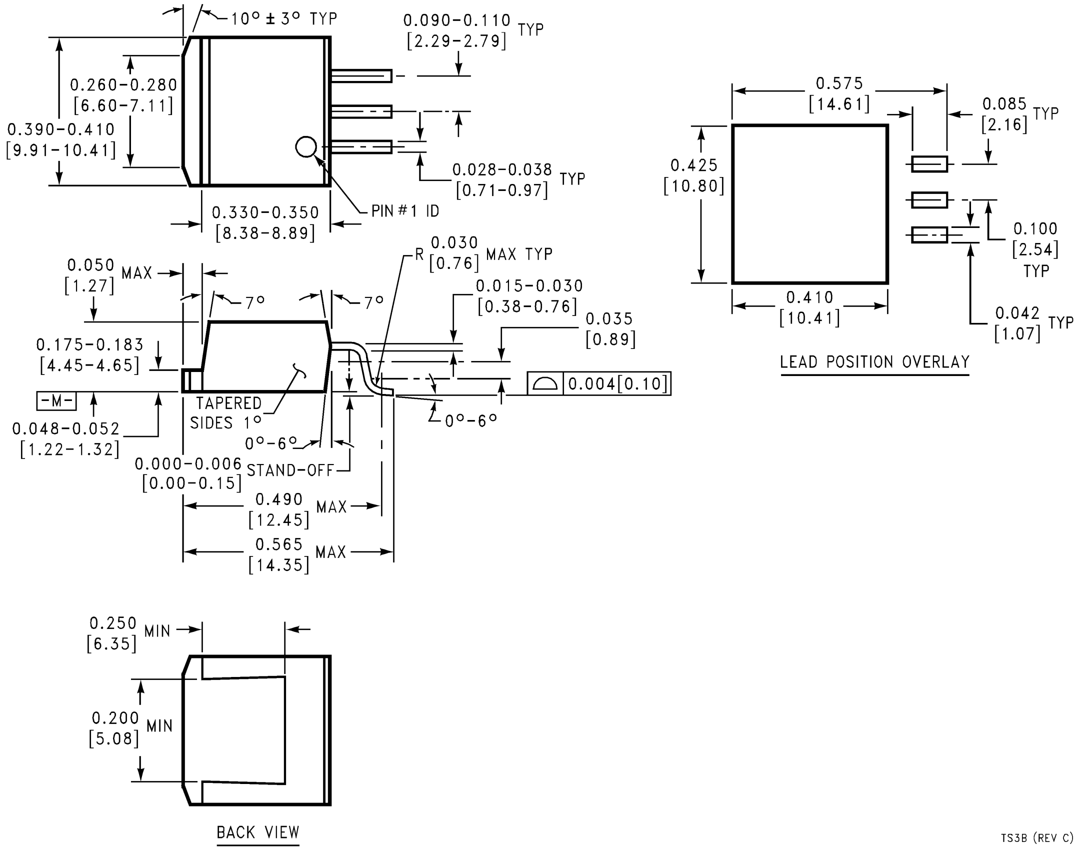


(TO-39) Metal Can Package
NS Package Number H03A



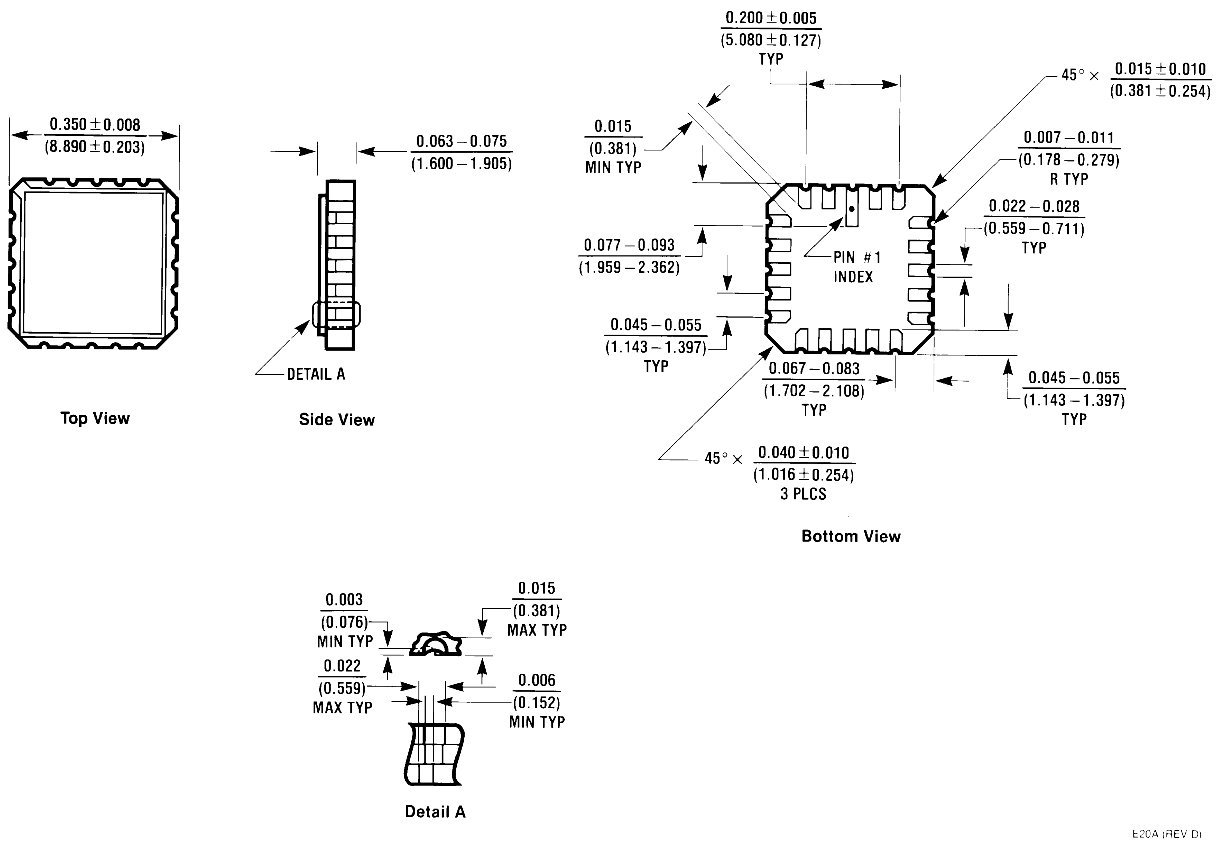
3-Lead TO-220
NS Package Number T03B

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)

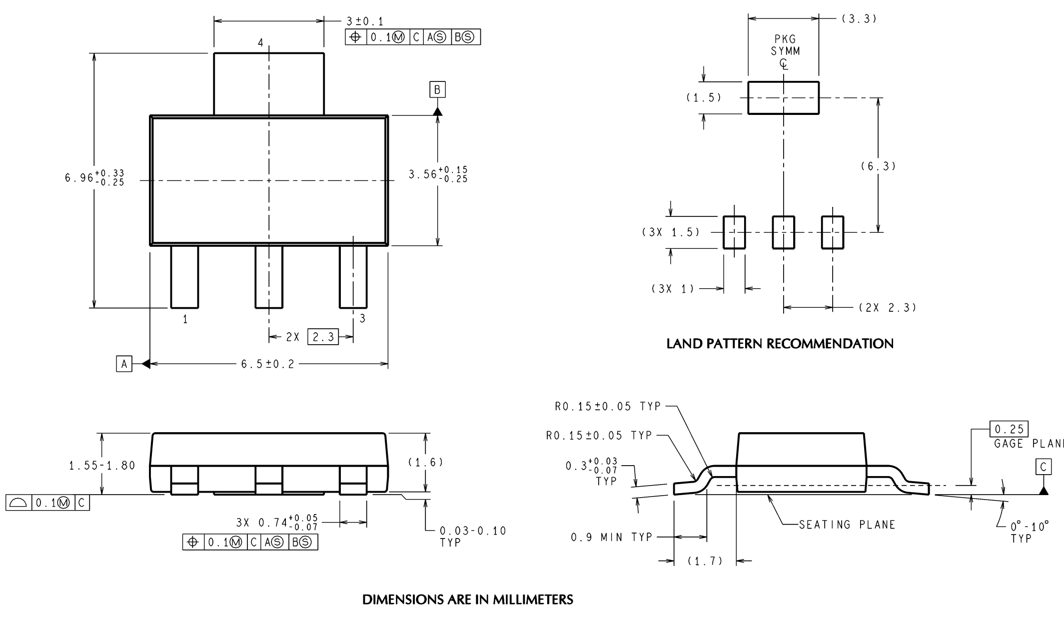


3-Lead TO-263
NS Package Number TS3B

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)

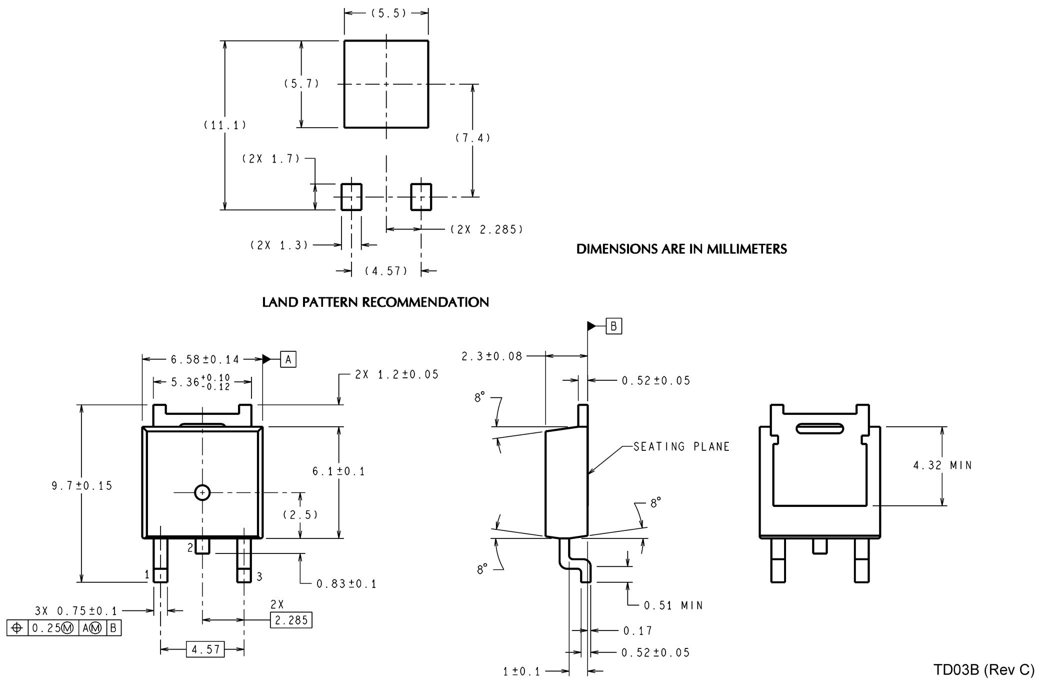


Ceramic Leadless Chip Carrier
NS Package Number E20A



4-Lead SOT-223
NS Package Number MP04A

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)



3-Lead D-Pack
NS Package Number TD03B

LIFE SUPPORT POLICY

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1. Life support devices or systems are devices or systems which, (a) are intended for surgical implant into the body, or (b) support or sustain life, and whose failure to perform when properly used in accordance with instructions for use provided in the labeling, can be reasonably expected to result in a significant injury to the user.
2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

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National Semiconductor certifies that the products and packing materials meet the provisions of the Customer Products Stewardship Specification (CSP-9-111C2) and the Banned Substances and Materials of Interest Specification (CSP-9-111S2) and contain no "Banned Substances" as defined in CSP-9-111S2.

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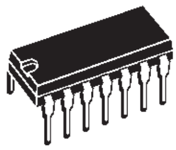
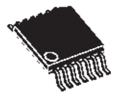
TL084
TL084A - TL084B

GENERAL PURPOSEJ-FET QUAD OPERATIONAL AMPLIFIERS

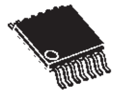
- WIDE COMMON-MODE (UP TO V_{CC}^{+}) AND DIFFERENTIAL VOLTAGE RANGE
- LOW INPUT BIAS AND OFFSET CURRENT
- OUTPUT SHORT-CIRCUIT PROTECTION
- HIGH INPUT IMPEDANCE J–FET INPUT STAGE
- INTERNAL FREQUENCY COMPENSATION
- LATCH UP FREE OPERATION
- HIGH SLEW RATE : 16V/µs (typ)



N
DIP14
(Plastic Package)



D
SO14
(Plastic Micropackage)



P
TSSOP14
(Thin Shrink Small Outline Package)

DESCRIPTION

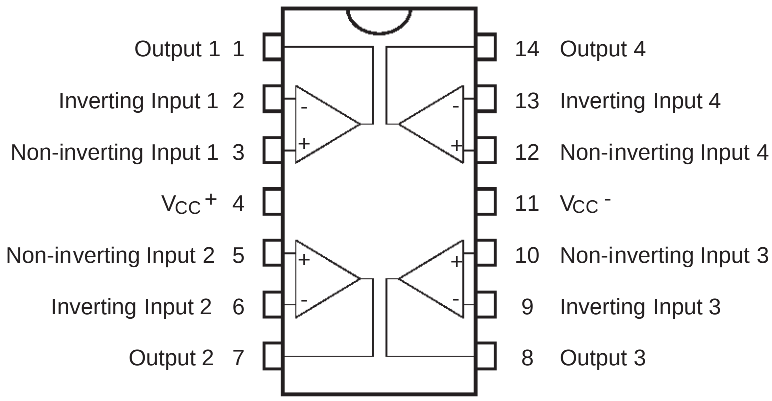
The TL084, TL084A and TL084B are high speed J–FET input quad operational amplifiers incorporating well matched, high voltage J–FET and bipolar transistors in a monolithic integrated circuit.

The devices feature high slew rates, low input bias and offset currents, and low offset voltage temperature coefficient.

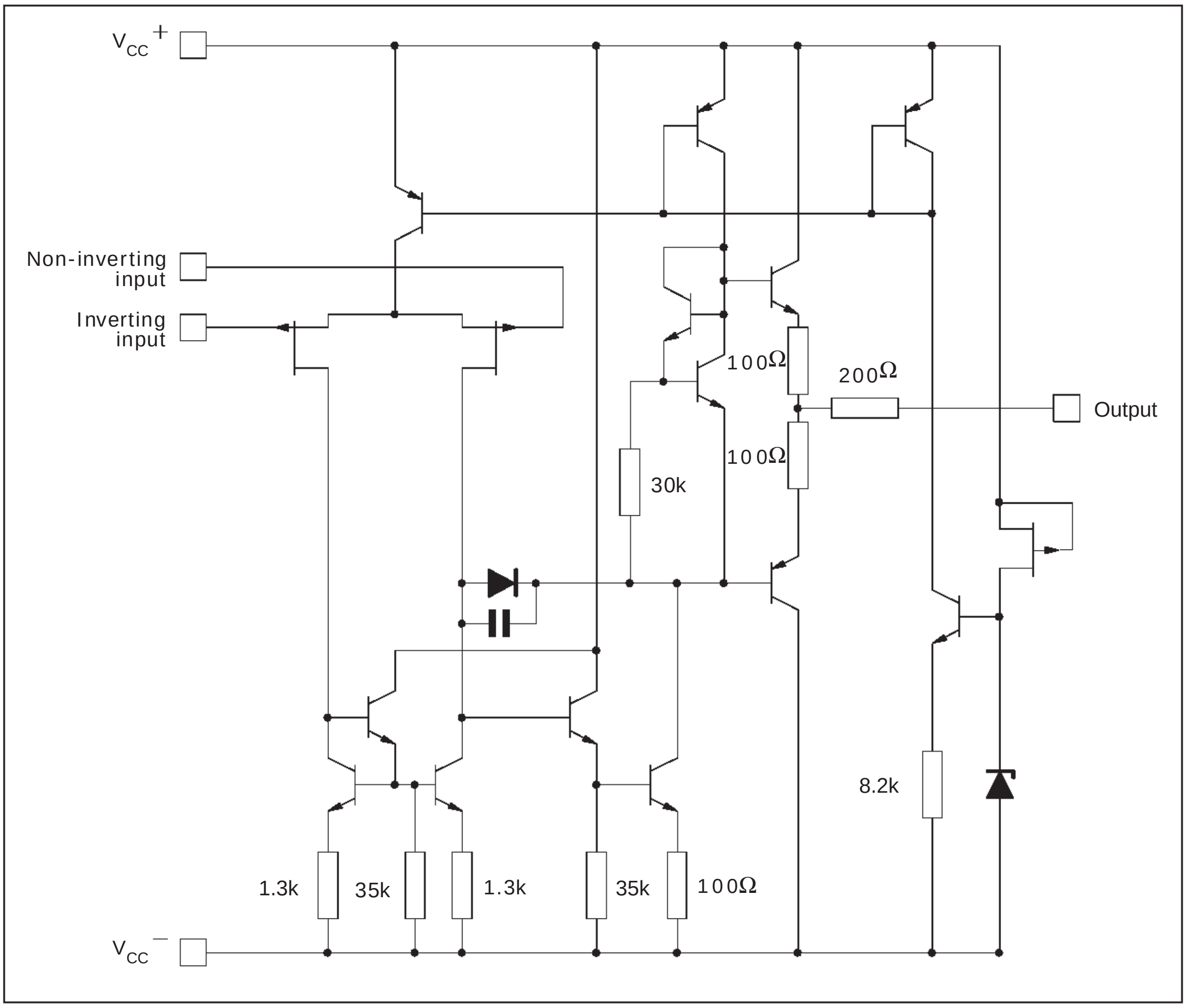
ORDER CODES

Part Number	Temperature Range	Package		
		N	D	P
TL084M/AM/BM	–55°C, +125°C	•	•	•
TL084I/AI/BI	–40°C, +105°C	•	•	•
TL084C/AC/BC	0°C, +70°C	•	•	•
Examples : TL084CN, TL084CD				

PIN CONNECTIONS (top view)



SCHEMATIC DIAGRAM (each amplifier)



ABSOLUTE MAXIMUM RATINGS

Symbol	Parameter		Value	Unit
V_{CC}	Supply Voltage - (note 1)		±18	V
V_i	Input Voltage - (note 3)		±15	V
V_{id}	Differential Input Voltage - (note 2)		±30	V
P_{tot}	Power Dissipation		680	mW
	Output Short-circuit Duration - (note 4)		Infinite	
T_{oper}	Operating Free Air Temperature Range	TL084C,AC,BC TL084I,AI,BI TL084M,AM,BM	0 to 70 –40 to 105 –55 to 125	°C
T_{stg}	Storage Temperature Range		–65 to 150	°C

Notes :
1. All voltage values, except differential voltage, are with respect to the zero reference level (ground) of the supply voltages where the zero reference level is the midpoint between V_{CC}^{+} and V_{CC}^{-}.
2. Differential voltages are at the non-inverting input terminal with respect to the inverting input terminal.
3. The magnitude of the input voltage must never exceed the magnitude of the supply voltage or 15 volts, whichever is less.
4. The output may be shorted to ground or to either supply. Temperature and /or supply voltages must be limited to ensure that the dissipation rating is not exceeded.

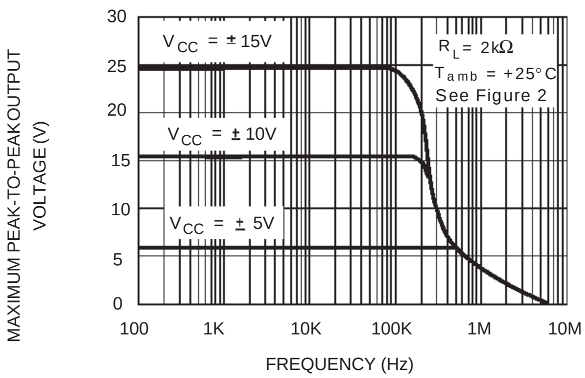
ELECTRICAL CHARACTERISTICS

V_{CC} = ±15V, T_{amb} = 25°C (unless otherwise specified)

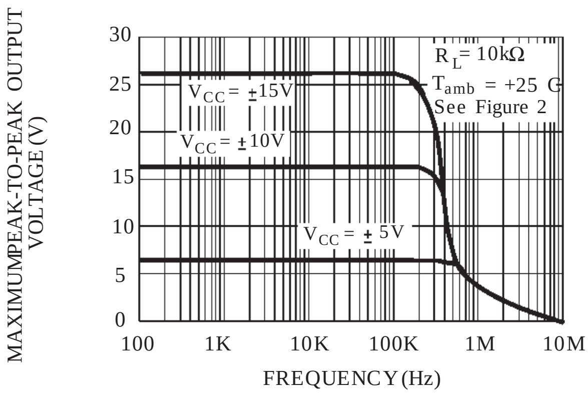
Symbol	Parameter	TL084I,M,AC,AI, AM,BC,BI,BM			TL084C			Unit
		Min.	Typ.	Max.	Min.	Typ.	Max.	
V_{io}	Input Offset Voltage (R_S = 50Ω) T_{amb} = 25°C TL084 TL084A TL084B $T_{min.} \le T_{amb} \le T_{max.}$ TL084 TL084A TL084B		 3 3 1	 10 6 3 13 7 5		 3	 10 13	mV
DV_{io}	Input Offset Voltage Drift		10			10		µV/°C
I_{io}	Input Offset Current * T_{amb} = 25°C $T_{min.} \le T_{amb} \le T_{max.}$		 5	 100 4		 5	 100 4	 pA nA
I_{ib}	Input Bias Current * T_{amb} = 25°C $T_{min.} \le T_{amb} \le T_{max.}$		 20	 200 20		 30	 400 20	 pA nA
A_{vd}	Large Signal Voltage Gain (R_L = 2kΩ, V_O = ±10V) T_{amb} = 25°C $T_{min.} \le T_{amb} \le T_{max.}$	 50 25	 200		 25 15	 200		V/mV
SVR	Supply Voltage Rejection Ratio (R_S = 50Ω) T_{amb} = 25°C $T_{min.} \le T_{amb} \le T_{max.}$	 80 80	 86		 70 70	 86		dB
I_{CC}	Supply Current, per Amp, no Load T_{amb} = 25°C $T_{min.} \le T_{amb} \le T_{max.}$		 1.4	 2.5 2.5		 1.4	 2.5 2.5	mA
V_{icm}	Input Common Mode Voltage Range	±11	+15 -12		±11	+15 -12		V
CMR	Common Mode Rejection Ratio (R_S = 50Ω) T_{amb} = 25°C $T_{min.} \le T_{amb} \le T_{max.}$	 80 80	 86		 70 70	 86		dB
Ios	Output Short-circuit Current T_{amb} = 25°C $T_{min.} \le T_{amb} \le T_{max.}$	 10 10	 40	 60 60	 10 10	 40	 60 60	mA
$\pm V_{OPP}$	Output Voltage Swing T_{amb} = 25°C R_L = 2kΩ R_L = 10kΩ $T_{min.} \le T_{amb} \le T_{max.}$ R_L = 2kΩ R_L = 10kΩ	 10 12 10 12	 12 13.5		 10 12 10 12	 12 13.5		V
SR	Slew Rate (V_{in} = 10V, R_L = 2kΩ, C_L = 100pF, T_{amb} = 25°C, unity gain)	 8	 16		 8	 16		V/µs
t_r	Rise Time (V_{in} = 20mV, R_L = 2kΩ, C_L = 100pF, T_{amb} = 25°C, unity gain)		 0.1			 0.1		µs
K_{OV}	Overshoot (V_{in} = 20mV, R_L = 2kΩ, C_L = 100pF, T_{amb} = 25°C, unity gain)		 10			 10		%
GBP	Gain Bandwidth Product (f = 100kHz, T_{amb} = 25°C, V_{in} = 10mV, R_L = 2kΩ, C_L = 100pF)	 2.5	 4		 2.5	 4		MHz
R_i	Input Resistance		10^{12}			10^{12}		Ω
THD	Total Harmonic Distortion (f = 1kHz, A_V = 20dB, R_L = 2kΩ, C_L = 100pF, T_{amb} = 25°C, V_O = $2V_{PP}$)		 0.01			 0.01		%
e_n	Equivalent Input Noise Voltage (f = 1kHz, R_s = 100Ω)		 15			15		$\frac{nV}{\sqrt{Hz}}$
∅m	Phase Margin		45			45		Degrees
V_{O1}/V_{O2}	Channel Separation (A_v = 100)		120			120		dB

* The input bias currents are junction leakage currents which approximately double for every 10°C increase in the junction temperature.

MAXIMUM PEAK-TO-PEAK OUTPUT VOLTAGE VERSUS FREQUENCY



MAXIMUM PEAK-TO-PEAK OUTPUT VOLTAGE VERSUS FREQUENCY



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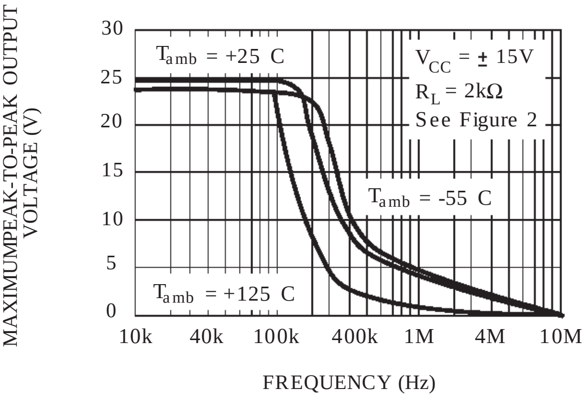
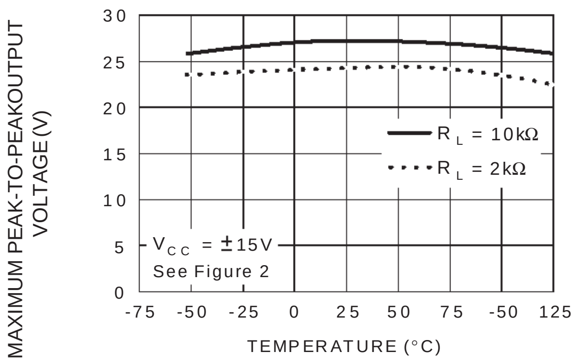
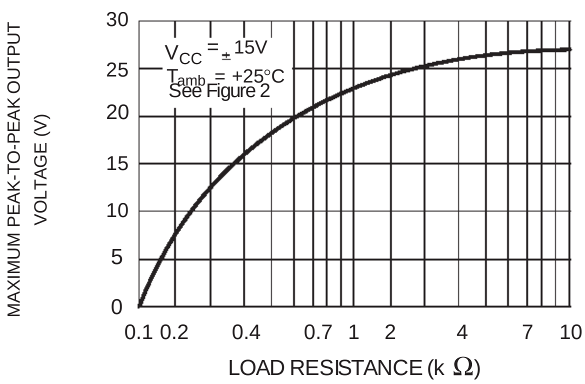


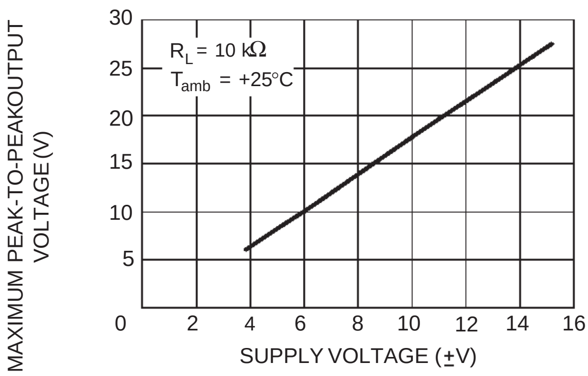
MAXIMUM PEAK-TO-PEAK OUTPUT VOLTAGE VERSUS FREE AIR TEMP.



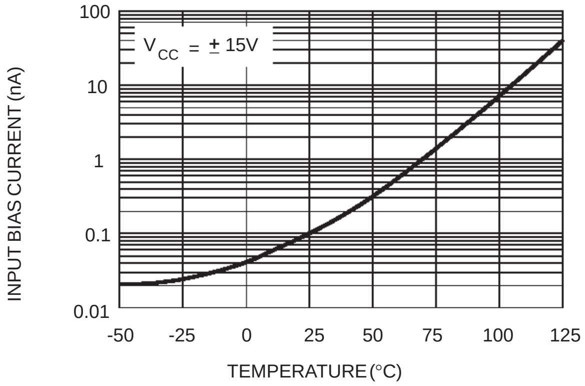
MAXIMUM PEAK-TO-PEAK OUTPUT VOLTAGE VERSUS LOAD RESISTANCE



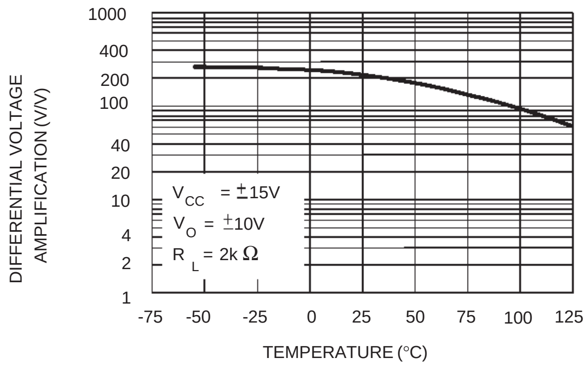
MAXIMUM PEAK-TO-PEAK OUTPUT VOLTAGE VERSUS SUPPLY VOLTAGE



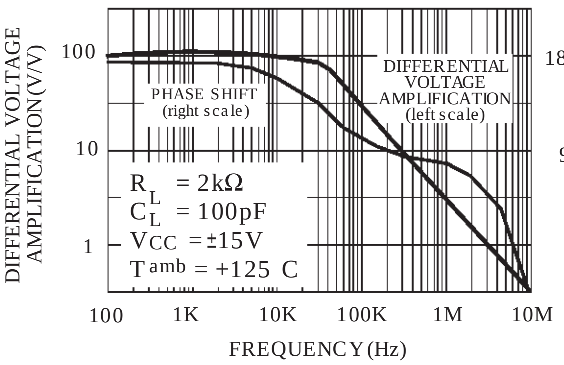
INPUT BIAS CURRENT VERSUS FREE AIR TEMPERATURE



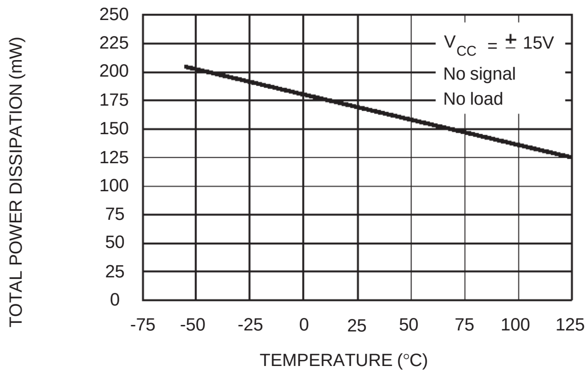
LARGE SIGNAL DIFFERENTIAL VOLTAGE AMPLIFICATION VERSUS FREE AIR TEMPERATURE



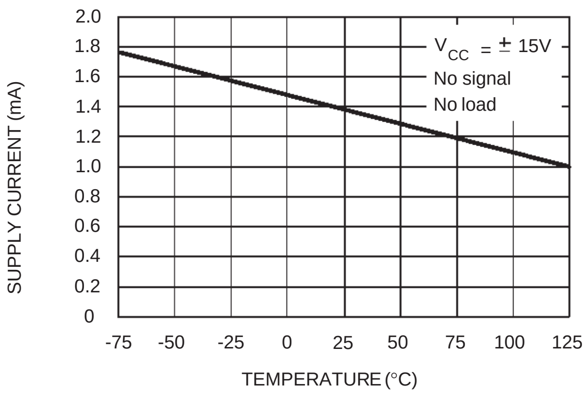
LARGE SIGNAL DIFFERENTIAL VOLTAGE AMPLIFICATION AND PHASE SHIFT VERSUS FREQUENCY



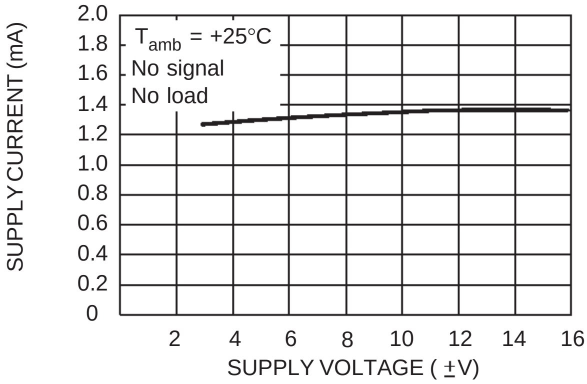
TOTAL POWER DISSIPATION VERSUS FREE AIR TEMPERATURE



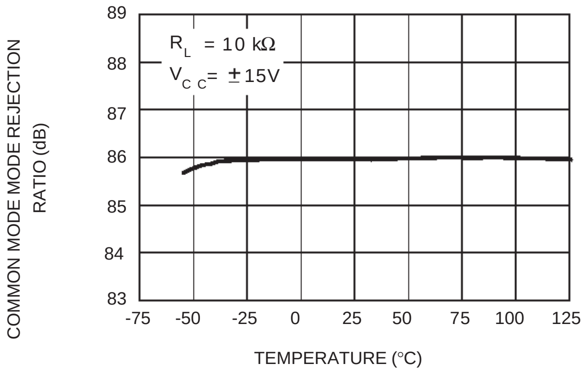
SUPPLY CURRENT PER AMPLIFIER VERSUS FREE AIR TEMPERATURE



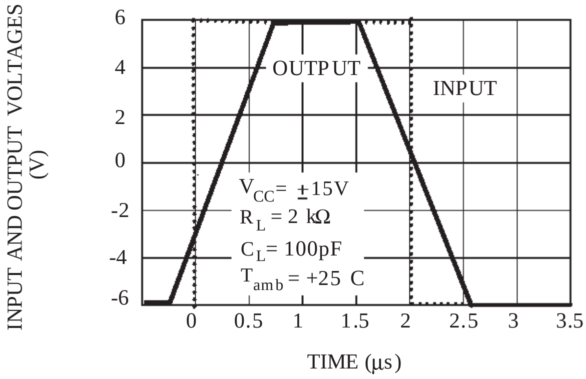
SUPPLY CURRENT PER AMPLIFIER VERSUS SUPPLY VOLTAGE



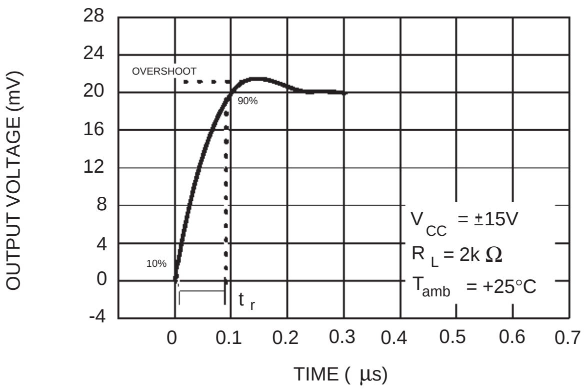
COMMON MODE REJECTION RATIO VERSUS FREE AIR TEMPERATURE



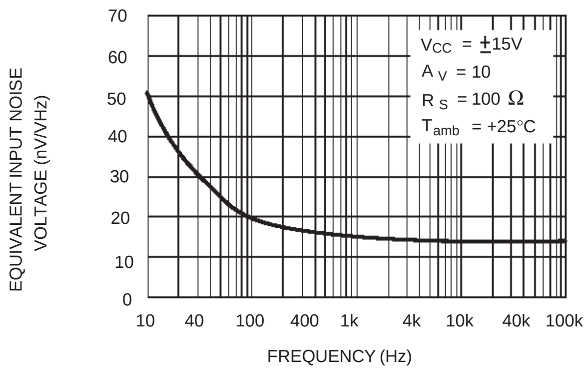
VOLTAGE FOLLOWER LARGE SIGNAL PULSE RESPONSE



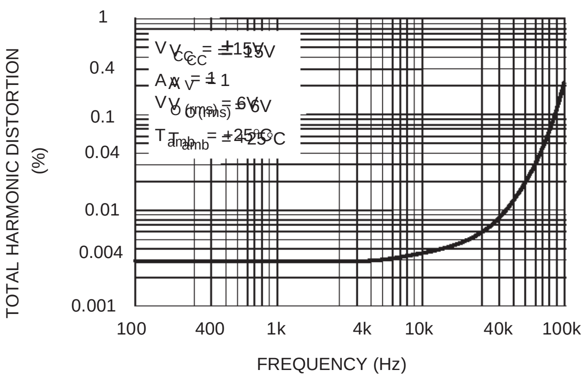
OUTPUT VOLTAGE VERSUS ELAPSED TIME



EQUIVALENT INPUT NOISE VOLTAGE VERSUS FREQUENCY



TOTAL HARMONIC DISTORTION VERSUS FREQUENCY



PARAMETER MEASUREMENT INFORMATION

Figure 1 : Voltage Follower

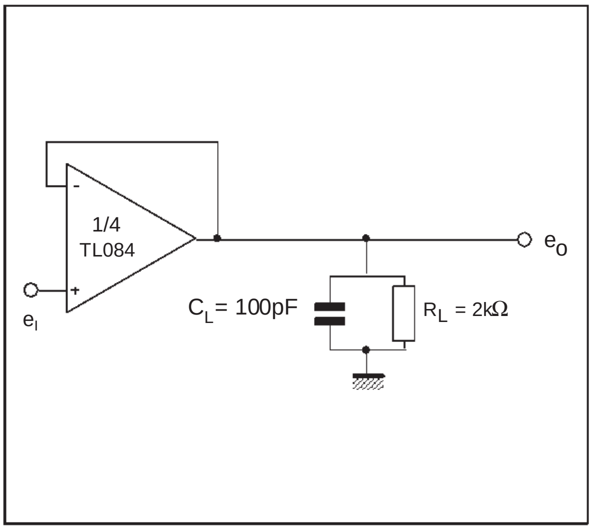
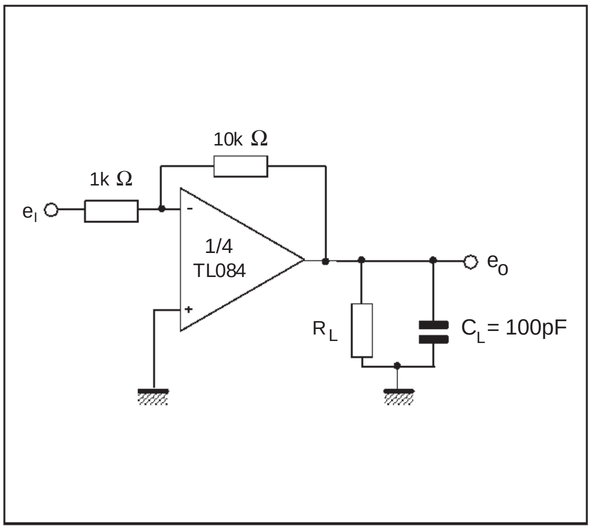
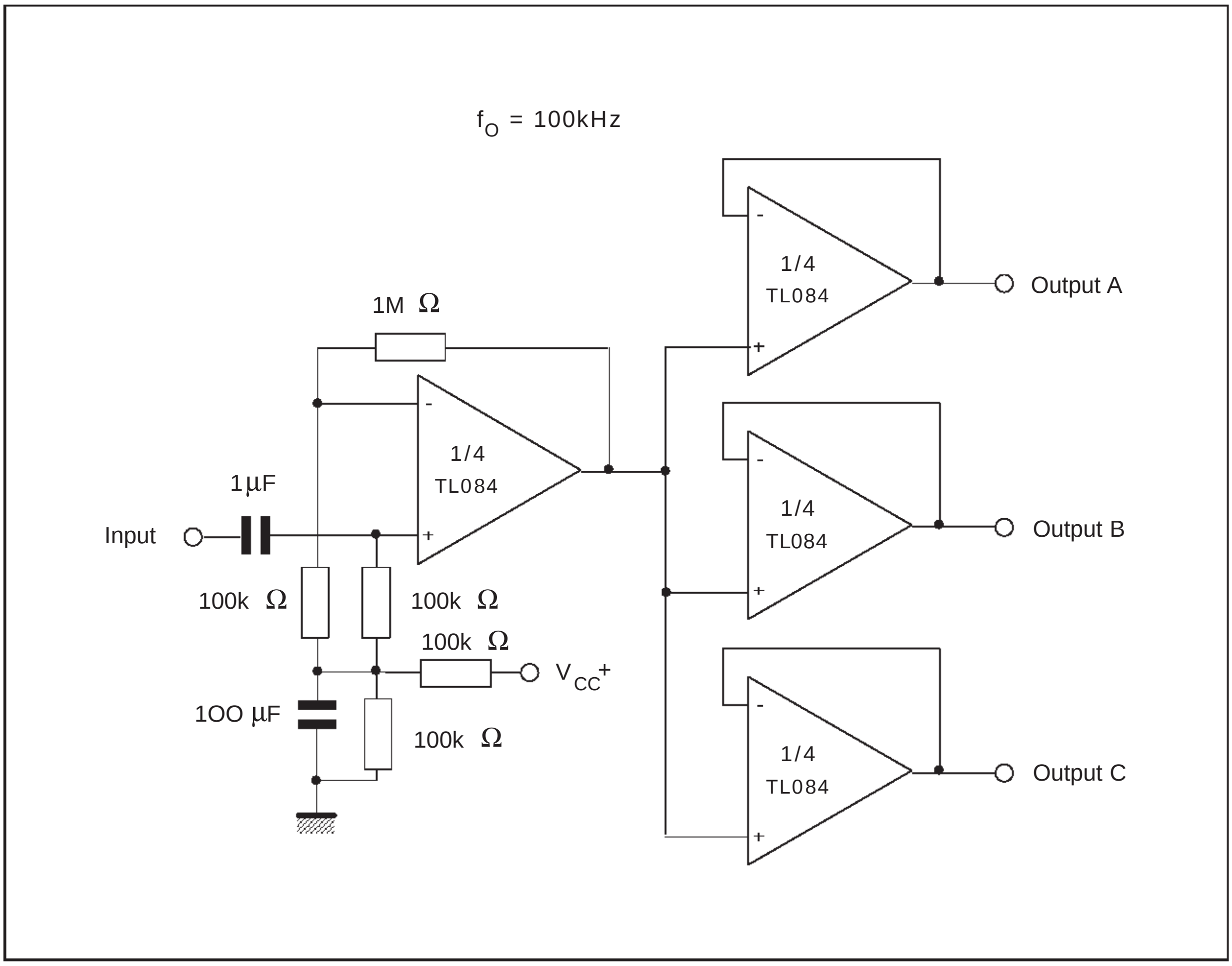


Figure 2 : Gain-of-10 Inverting Amplifier



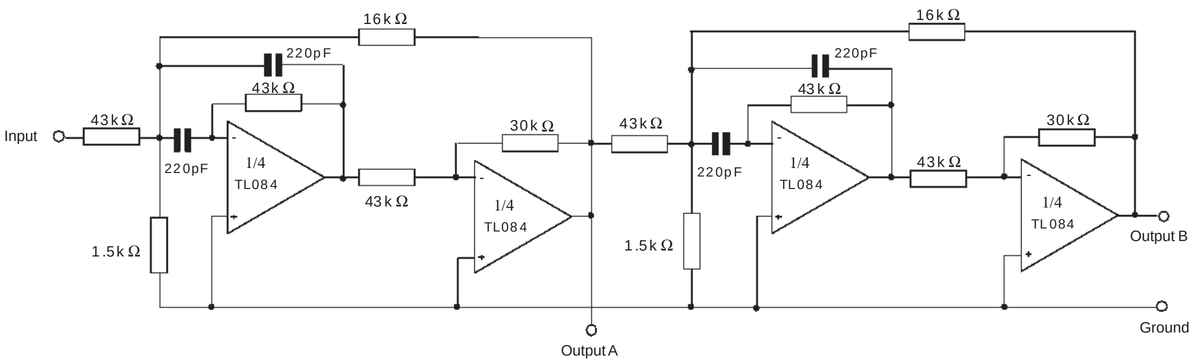
TYPICAL APPLICATIONS

AUDIO DISTRIBUTION AMPLIFIER

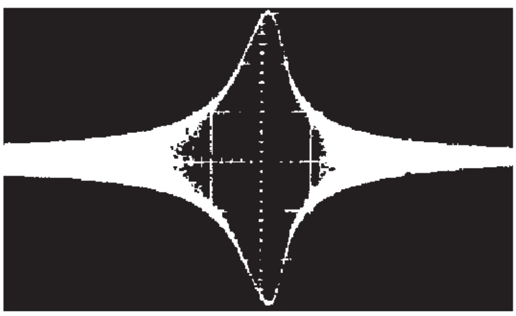


TYPICAL APPLICATIONS (continued)

POSITIVE FEEDBACK BANDPASS FILTER

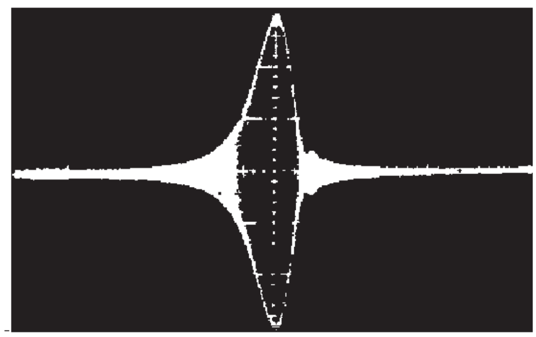


OUTPUT A



SECOND ORDER BANDPASS FILTER
fo = 100kHz ; Q = 30 ; Gain = 4

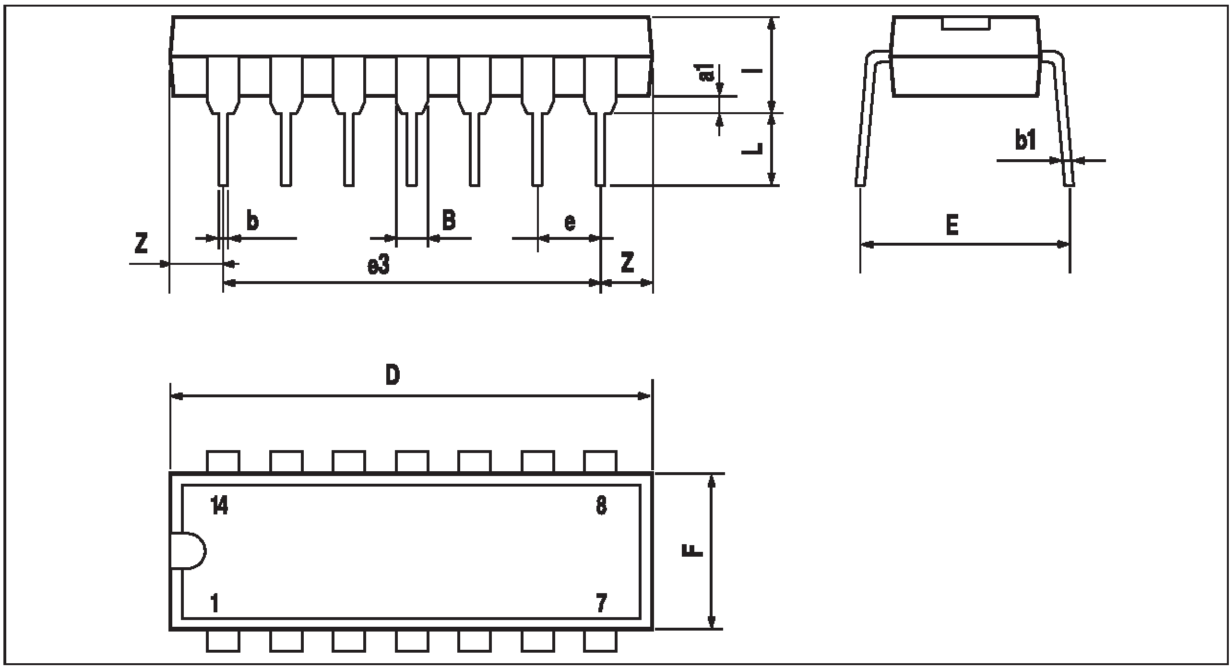
OUTPUT B



CASCADED BANDPASS FILTER
fo = 100kHz ; Q = 69 ; Gain = 16

PACKAGE MECHANICAL DATA

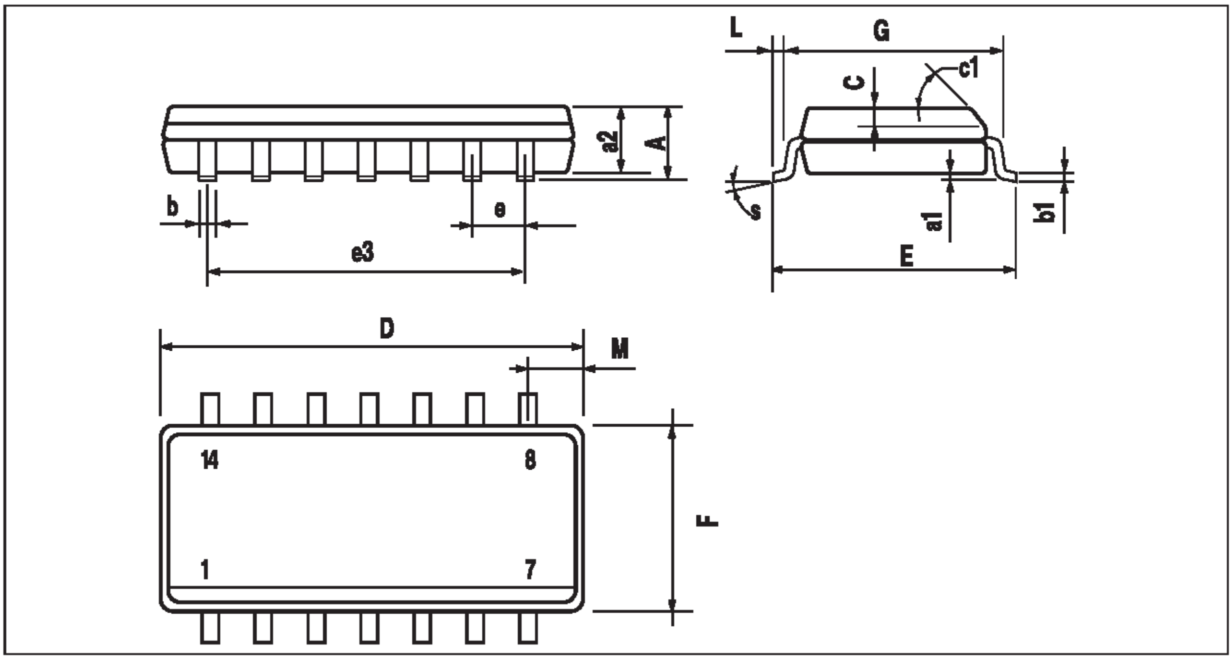
14 PINS - PLASTIC DIP



Dimensions	Millimeters			Inches		
	Min.	Typ.	Max.	Min.	Typ.	Max.
a1	0.51			0.020		
B	1.39		1.65	0.055		0.065
b		0.5			0.020	
b1		0.25			0.010	
D			20			0.787
E		8.5			0.335	
e		2.54			0.100	
e3		15.24			0.600	
F			7.1			0.280
i			5.1			0.201
L		3.3			0.130	
Z	1.27		2.54	0.050		0.100

PACKAGE MECHANICAL DATA

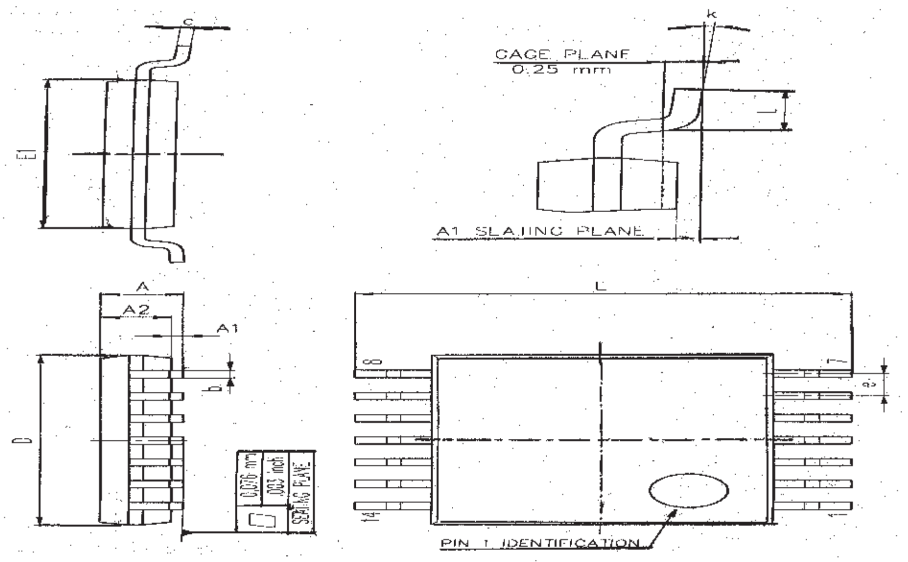
14 PINS - PLASTIC MICROPACKAGE (SO)



Dimensions	Millimeters			Inches		
	Min.	Typ.	Max.	Min.	Typ.	Max.
A			1.75			0.069
a1	0.1		0.2	0.004		0.008
a2			1.6			0.063
b	0.35		0.46	0.014		0.018
b1	0.19		0.25	0.007		0.010
C		0.5			0.020	
c1	45^{o} (typ.)					
D	8.55		8.75	0.336		0.334
E	5.8		6.2	0.228		0.244
e		1.27			0.050	
e3		7.62			0.300	
F	3.8		4.0	0.150		0.157
G	4.6		5.3	0.181		0.208
L	0.5		1.27	0.020		0.050
M			0.68			0.027
S	8^{o} (max.)					

PACKAGE MECHANICAL DATA

14 PINS - THIN SHRINK SMALL OUTLINE PACKAGE



Dim.	Millimeters			Inches		
	Min.	Typ.	Max.	Min.	Typ.	Max.
A			1.20			0.05
A1	0.05		0.15	0.01		0.006
A2	0.80	1.00	1.05	0.031	0.039	0.041
b	0.19		0.30	0.007		0.15
c	0.09		0.20	0.003		0.012
D	4.90	5.00	5.10	0.192	0.196	0.20
E		6.40			0.252	
E1	4.30	4.40	4.50	0.169	0.173	0.177
e		0.65			0.025	
k	0^o		8^o	0^o		8^o
l	0.50	0.60	0.75	0.09	0.0236	0.030