Telos

## Ultra low power IEEE 802.15.4 compliant wireless sensor module

Revision A : Humidity, Light, and Temperature sensors with USB

Product Description

Telos is an ultra low power wireless module for use in sensor networks, monitoring applications, and rapid application prototyping. Telos leverages industry standards like USB and IEEE 802.15.4 to interoperate seamlessly with other devices.
By using industry standards, integrating humidity, temperature, and light sensors, and providing flexible interconnection with peripherals, Telos enables a wide range of mesh network applications. With TinyOS support out-of-the-box, Telos leverages emerging wireless protocols and the open source software movement. Telos is part of a line of modules featuring on-board sensors to increase robustness while decreasing cost and package size.
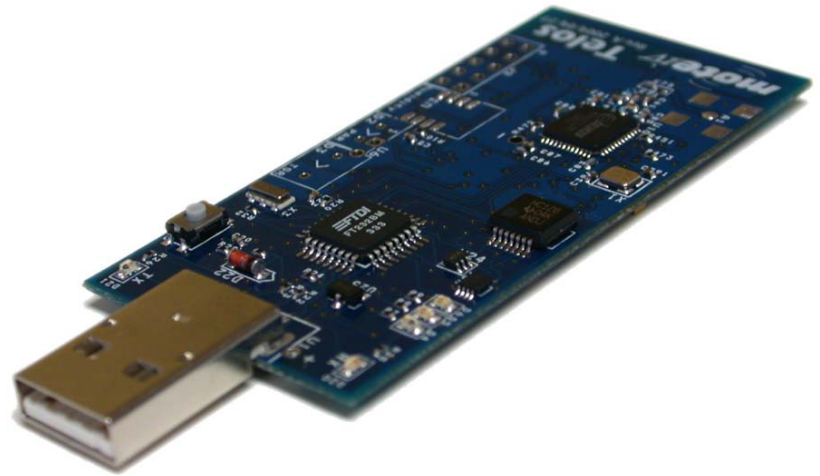
Key Features

- 250kbps 2.4GHz IEEE 802.15.4 Chipcon Wireless Transceiver
- Interoperability with other IEEE 802.15.4 devices
- 8MHz Texas Instruments MSP430 microcontroller (2k RAM, 60k ROM)
- Integrated onboard antenna with 50m range indoors / 125m range outdoors
- Integrated Humidity, Temperature, and Light sensors
- Ultra low current consumption
- Fast wakeup from sleep (<6μs)
- Hardware link-layer encryption and authentication
- Programming and data collection via USB
- 12-pin expansion support and optional SMA antenna connector
- TinyOS support : mesh networking and communication implementation

Table of Contents

Module Description

The Telos module is a low power "mote" with integrated sensors, radio, antenna, microcontroller, and programming capabilities.
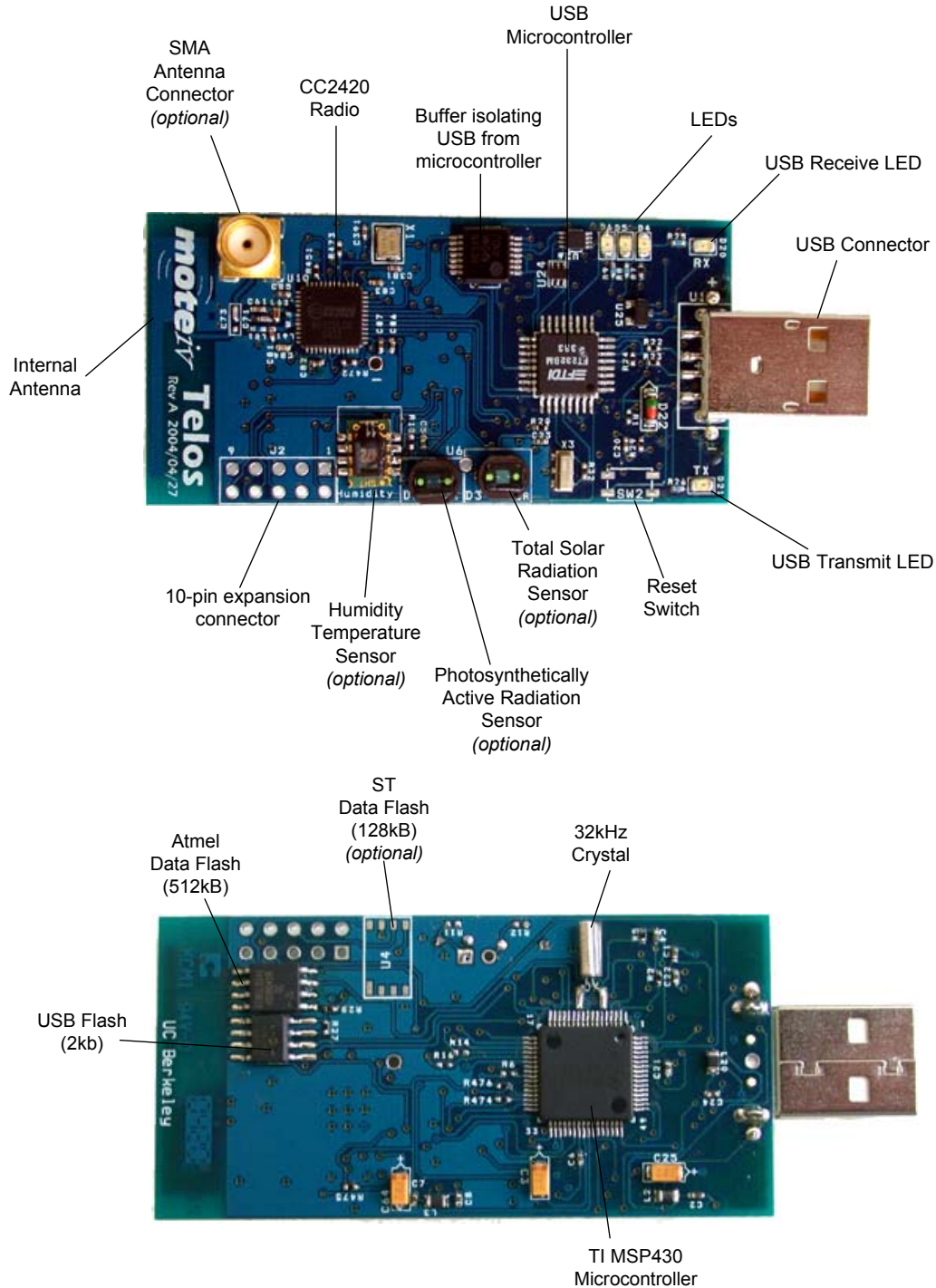

Figure 1 : Front and Back of the Telos module

Power

Telos may be powered by two AA batteries. The module was designed to fit the two AA battery form factor. AA cells may be used in the operating range of 2.1 to 3.6V DC, however the voltage must be at least 2.7V when programming the microcontroller's flash.

Telos may also be used with a 2/3A sized battery. The 2/3A battery holder may be soldered to the positive terminal directly under the USB connector and the negative terminal next to the radio. Part BH2/3A-2-ND from Digikey (www.digikey.com) is proven to work with the Telos module.

If the Telos module is plugged into the USB port for programming or communication, it will receive power from the host computer. The mote operating voltage when attached to USB is 3V. If Telos will always be attached to a USB port, no battery pack is necessary.

The 10-pin expansion connector (described in the Sensors Section on page 18) can provide power to the module. Any of the battery terminal connections may also provide power to the module. At no point should the input voltage exceed 3.6V—doing so may damage the microcontroller, radio, or other components.

Typical Operating Conditions

	MIN	NOM	MAX	UNIT
Supply voltage	2.1		3.6	V
Supply voltage during flash memory programming	2.7		3.6	V
Operating free air temperature	-40		85	^{o}C
Current Consumption: MCU on, Radio on		20.2	23	mA
Current Consumption: MCU on, Radio off		420	1400	μA
Current Consumption: MCU asleep		2.4	6	μA

Mechanical Characteristics

	MIN	NOM	MAX	UNIT
Width	1.24	1.27	1.29	in
Length	2.55	2.58	2.60	in
Height (without battery pack)	0.49	0.50	0.55	in

Caution! ESD sensitive device. Precaution should be used when handling the device in order to prevent permanent damage.
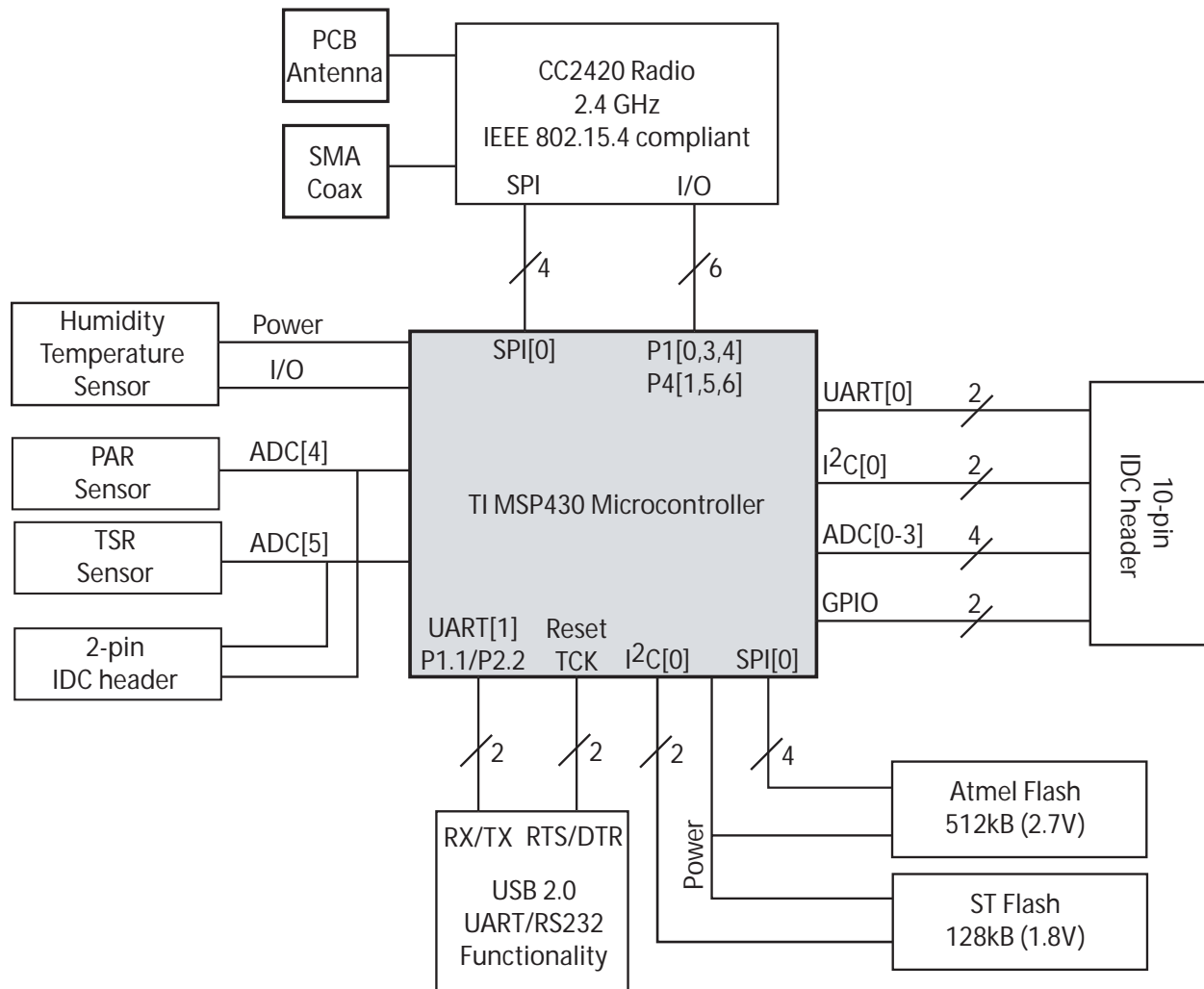
Block Diagram

Figure 2 : Functional Block Diagram of the Telos Module, its components, and buses

Schematic

Telos schematic Sheet 1 of 3 — MCU (TI_MSP430_F149), SENSORS, POWER, FLASH, LEDS sections. Title: Telos. (c) Copyright 2004: UC Berkeley. Size B. Rev 1. Date: Wednesday, April 28, 2004.

Telos schematic Sheet 2 of 3 — CC2420 802.15.4 Wireless Radio. Title: Telos CC2420 802.15.4 Wireless Radio. (c) Copyright 2004: UC Berkeley. Size B. Rev 1. Date: Tuesday, April 13, 2004.
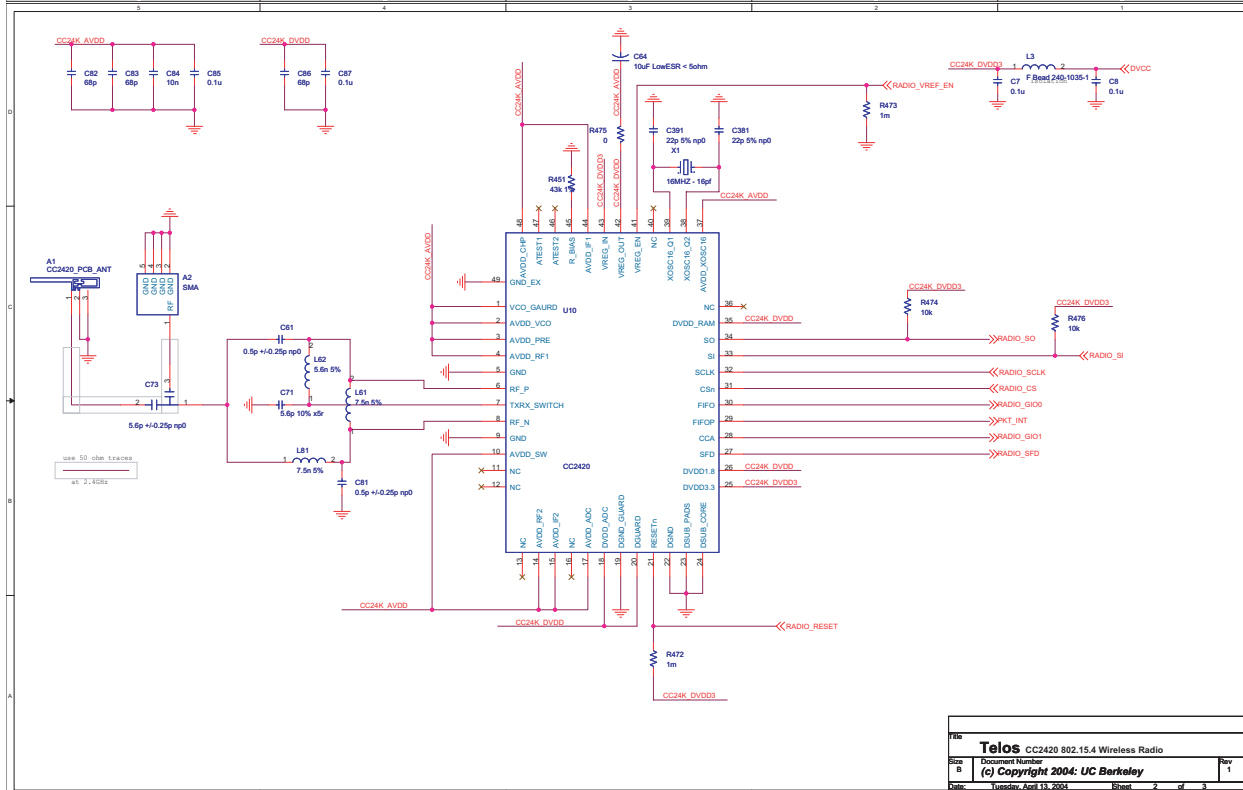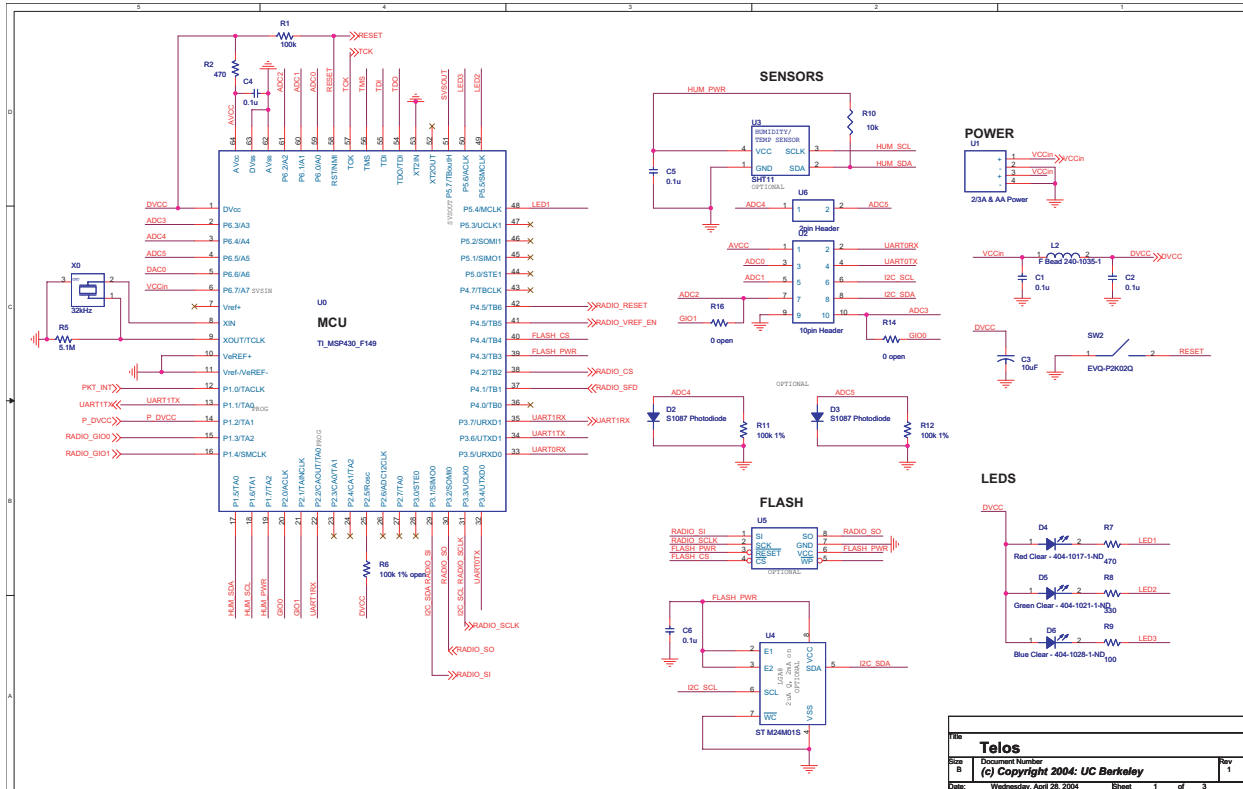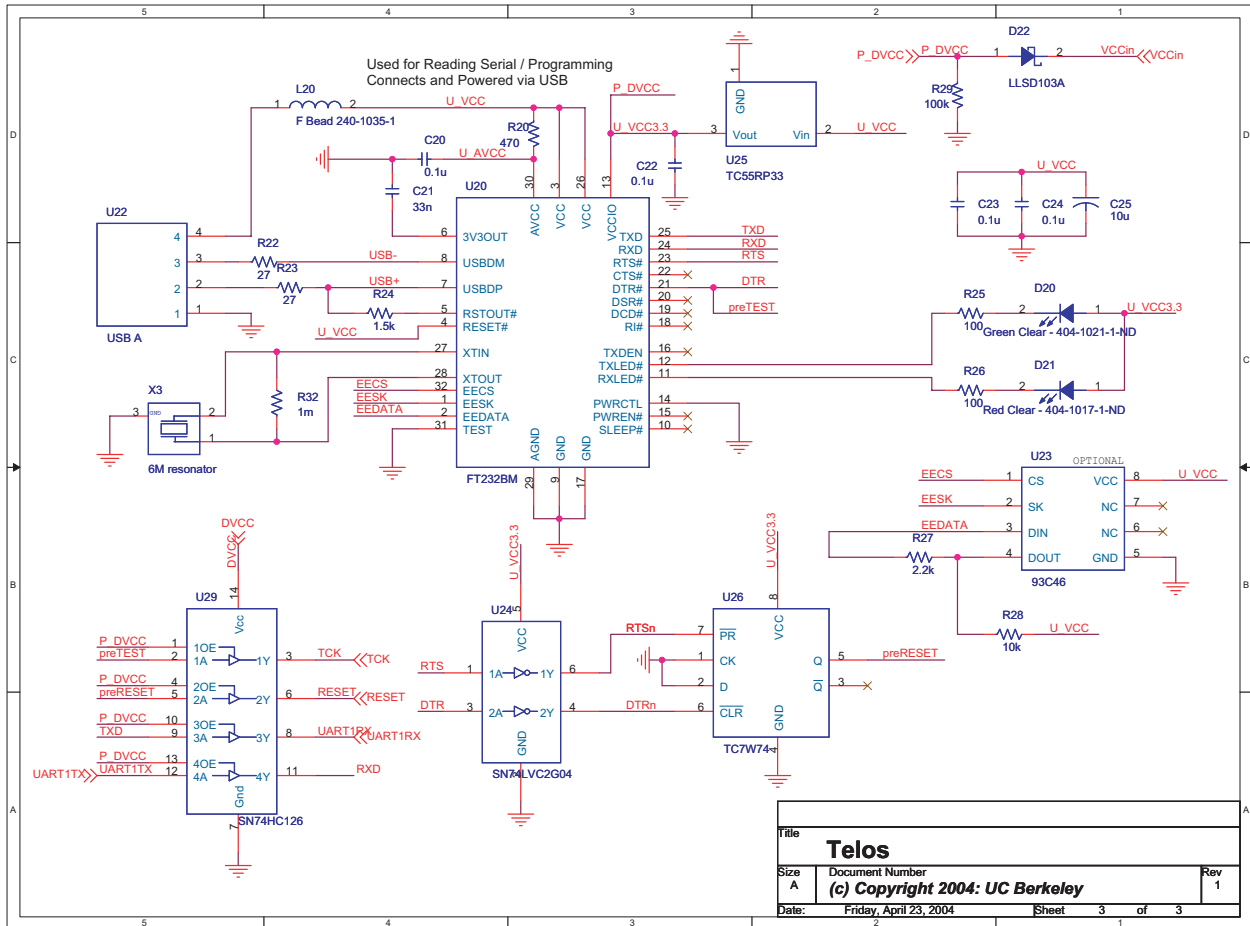
Figure 3 : Schematics for the Telos module (Rev A)

Schematic modifications:

- P4.3 on the TI MSP430 is tied to DVcc through a board rework. P4.3 should never be set as output and low, otherwise a short is created in the circuit.
- On the Atmel flash (part U5), pins 5 and 6 are connected together through a board rework.
- ADC3 is not physically connected to U2.10. Instead, GIO0 is connected to R14 and R14 is connected directly to U2.10.

Microprocessor

Description

The low power operation of the Telos module is due to the ultra low power Texas Instruments MSP430 microcontroller. This 16-bit RISC processor features extremely low active and sleep current consumption that permits Telos to run for years on a single pair of AA batteries. The MSP430 has an internal digitally controlled oscillator (DCO) that may operate up to 8MHz. The DCO may be turned on from sleep mode in 6μs, however 292ns is typical at room temperature. When the DCO is off, the MSP430 operates off an eternal 32768Hz watch crystal. Although the DCO frequency changes with voltage and temperature, it may be calibrated by using the 32kHz oscillator.

In addition to the DCO, the MSP430 has 8 external ADC ports and 8 internal ports. The internal ports may be used to read the internal thermistor or monitor the battery voltage.   A variety of peripherals are available including SPI, UART, digital I/O ports, Watchdog timer, and Timers with capture and compare functionality.

The features of the MSP430 F149 are presented in detail in the Texas Instruments MSP430x1xx Family User's Guide available at http://ti.com/msp430.

Typical Operating Conditions

	MIN	NOM	MAX	UNIT
Supply voltage during program execution	1.8		3.6	V
Supply voltage during flash memory programming	2.7		3.6	V
Operating free air temperature	-40		85	^{o}C
Low frequency crystal frequency		32.768		kHz
Active current at Vcc = 3V, 4MHz		420	560	μA
Sleep current in LPM3 Vcc = 3V, 32.768kHz active		1.6	1.9	μA
Wake up from LPM3 (low power mode)			6	μs

PC Communication

Telos uses a USB controller from FTDI to communicate with the host computer. In order to communicate with the mote, the FTDI drivers must be installed on the host. FTDI provides drivers for Windows, Linux, BSD, Macintosh, and Windows CE. These drivers are included on the Moteiv CD shipped with your order. Windows users will need the Virtual Com Port (VCP) drivers. They may also be downloaded from FTDI's website at: http://www.ftdichip.com/

After installing the driver, Telos appears as a COM port in Windows' device manager (or as a device in /dev in Linux, OSX, and BSD). Multiple Telos motes may be connected to a single computer's USB ports at the same time. Each mote will receive a different COM port identifier. In the example below, one Telos is connected and assigned COM6 "USB Serial Port".

An application may read from Telos by opening the COM port assigned to the Telos mote. Telos communicates with the host PC through USART1 on the TI MSP430.
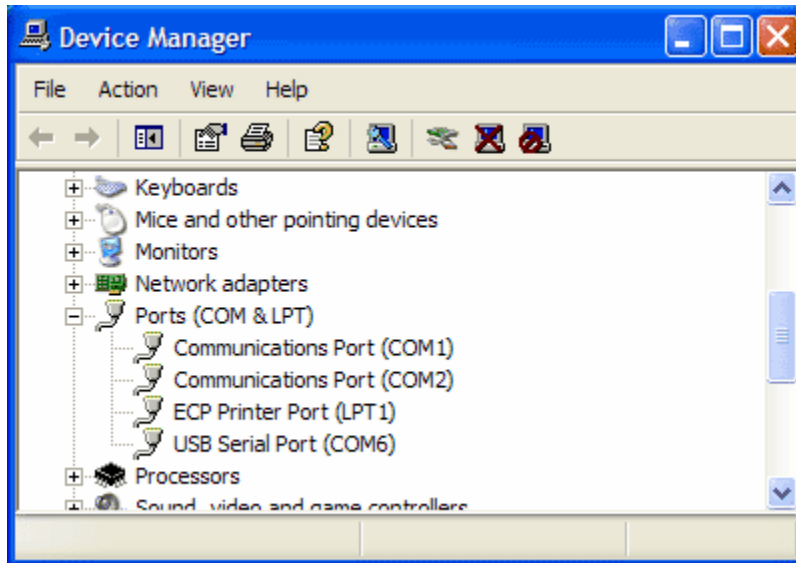
Figure 4 : Device Manager showing Telos installed as COM6

The motelist command line utility lists all of the Telos motes currently connected to a computer. This utility optionally lists previously connected motes that the system has cached. Invoke motelist with the -h option for more information.

```
> motelist
Reference   CommPort   Description
----------  ---------- ---------------------------------------
M4BR4Z37    COM6       Telos (Rev A 2004-04-27)
```

> ⚠️ **NOTE:** Since Telos uses the USB interface for both programming and communication, spurious signals on the RTS or DTR lines of the COM port may cause the mote to reset. To prevent accidentally resetting the module, ensure that your communications application does not send RTS or DTR signals when opening and closing COM ports.

Programming

The Telos module is programmed through the onboard USB connector. A modified version of the MSP430 Bootstrap Loader, msp430-bsl, programs the microcontroller's flash. Telos has a unique hardware circuit that prevents the mote from spuriously resetting. This hardware circuit makes it necessary to have a special sequence sent to the module in order to program it.

By invoking msp430-bsl, verify you have the patched BSL by looking for the "telos" keyword.

```
> msp430-bsl
MSP430 Bootstrap Loader Version: 1.39-telos-3
Use -h for help
```

To communicate with Telos, the MSP430 Bootstrap Loader requires a set of options to provide the proper signals to the microcontroller to initiate programming. For convenience, the options have been folded into a single Telos flag:

```
--telos
```

The Telos flag (--telos) simply expands the following options, which are functionally equivalent to using --telos:

```
--invert-test --invert-reset --swap-reset-test --telos-latch
```

To program a Telos module on COM3 (or /dev/ttyUSB2 in Linux) with an application image named app.ihex, invoke the MSP430 Bootstrap loader with the following options.

```
> msp430-bsl --telos -c 2 -r -e -I -p app.ihex
MSP430 Bootstrap Loader Version: 1.39-telos-1
Mass Erase...
Transmit default password ...
Invoking BSL...
Transmit default password ...
Current bootstrap loader version: 1.10 (Device ID: f149)
Adjust SP. Load PC with 0x0C22 ...
Transmit default password ...
Patch for flash programming required!
Load and verify patch ...
Program ...
8374 bytes programmed.
Reset device ...
```

If you are using TinyOS, it has support for programming Telos. After compiling your application, you may install it with the following command

```
> make telos install.x bsl,n
```

Where x is the 16-bit address assigned to the mote and n is the COM port that Telos is currently using. Note that not including "bsl" or "bsl,n" will program automatically using the bsl to the first Telos mote found on the USB bus.

For more information about the options in the MSP430 Bootstrap loader, invoke msp430-bsl with the -h option to display the help information.

> **NOTE:** msp430-bsl starts counting from 0, but COM ports in Windows start counting at 1. If Telos is connected to COM3 in Windows, you must program it using "-c 2" or "bsl,2" when invoking msp430-bsl. In Linux, Telos will appear as /dev/ttyUSB2 and may be programmed using "-c 2" or "bsl,2".
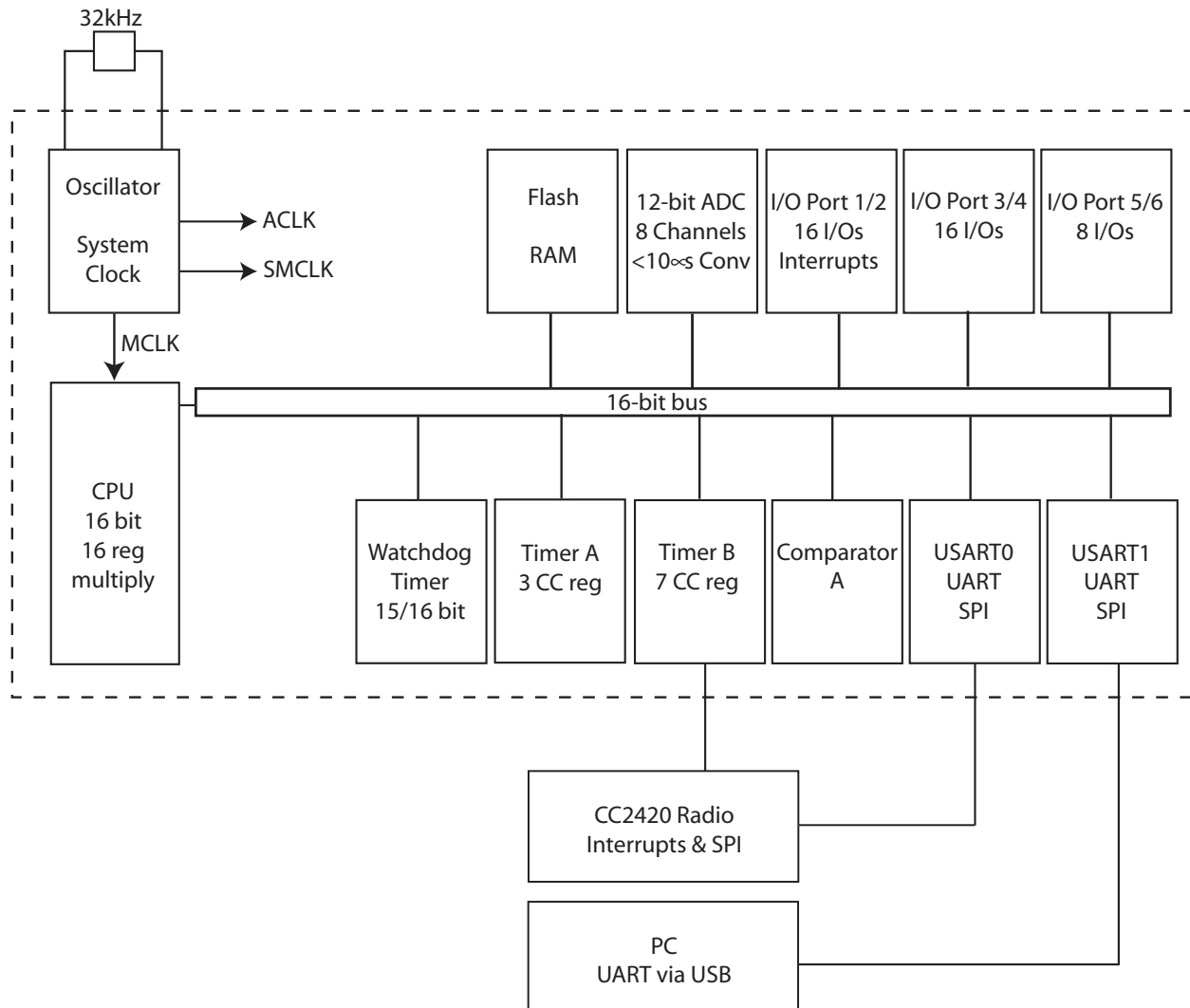
Block Diagram

Figure 5 : Block diagram of the TI MSP430 microcontroller and its connection to other peripherals in the Telos module

Radio

Description

Telos features the Chipcon CC2420 radio for wireless communications. The CC2420 is an IEEE 802.15.4 compliant radio providing the PHY and some MAC functions. With sensitivity exceeding the IEEE 802.15.4 specification and low power operation, the CC2420 provides reliable wireless communication. The CC2420 is highly configurable for many applications with the default radio settings providing IEEE 802.15.4 compliance. Features and usage of the CC2420 is available in Chipcon's datasheet at http://www.chipcon.com

The CC2420 is controlled by the TI MSP430 microcontroller through the SPI port and a series of digital I/O lines and interrupts (see the Schematics on page 6 for more information). The radio may be shut off by the microcontroller for low power duty cycled operation.

The CC2420 has programmable output power. Common CC2420 register values and their corresponding current consumption and output power are shown in Figure 6.

PA_LEVEL	TXCTRL register	Output Power [dBm]	Current Consumption [mA]
31	0xA0FF	0	17.4
27	0xA0FB	-1	16.5
23	0xA0F7	-3	15.2
19	0xA0F3	-5	13.9
15	0xA0EF	-7	12.5
11	0xA0EB	-10	11.2
7	0xA0E7	-15	9.9
3	0xA0E3	-25	8.5

Figure 6 : Output power configuration for the CC2420

The CC2420 provides a digital received signal strength indicator (RSSI) that may be read any time. Additionally, on each packet reception, the CC2420 samples the first eight chips, calculates the error rate, and produces a link quality indication (LQI) value with each received packet. A mapping from RSSI to the RF level in dBm is shown in Figure 7.
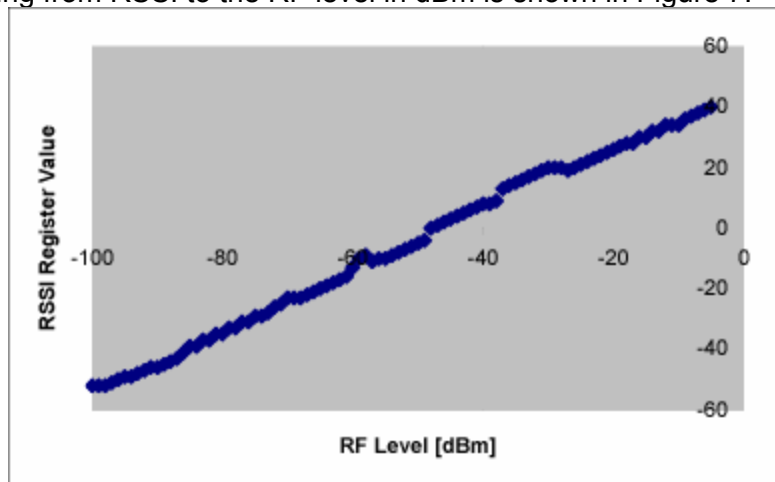

Figure 7 : Received Signal Strength Indicator mapping to RF Power [dBm]

Typical Operating Conditions

	MIN	NOM	MAX	UNIT
Supply voltage during radio operation (Vreg on)	2.1		3.6	V
Operating free air temperature	-40		85	^{o}C
RF frequency range	2400		2483.5	MHz
Transmit bit rate	250		250	kbps
Nominal output power	-3	0		dBm
Programmable output power range		40		dBm
Receiver sensitivity	-90	-94		dBm
Current consumption: Radio transmitting at 0 dBm		17.4		mA
Current consumption: Radio receiving		19.7		mA
Current consumption: Radio on, Oscillator on		365		μA
Current consumption: Idle mode, Oscillator off		20		μA
Current consumption: Power Down mode, Vreg off			1	μA
Voltage regulator current draw	13	20	29	μA

Measured Output Power

The RF output power of the Telos module from the CC2420 radio is shown in Figure 8. For this test, the Telos module is transmitting at 2.405GHz (IEEE 802.15.4 channel 11) using the O-QPSK modulation with DSSS. The CC2420 programmed output power is set to 0 dBm. The measured output power of the entire modulated spectrum is 1.67 dBm.
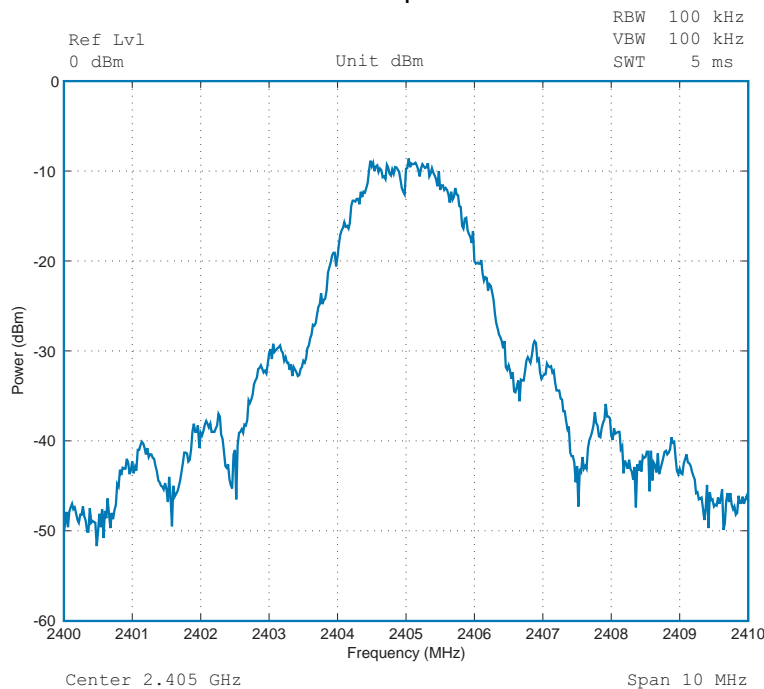

Figure 8 : Measured RF output power over the modulated spectrum from the Telos module

Antenna

Telos has two antenna options—and internal antenna built into the module and an external SMA connector for connecting to external antennas. By default, Telos is shipped with the internal antenna enabled. If an application requires an external antenna or a different directional pattern than the internal antenna, an SMA connector may be installed and an antenna may be connected directly to Telos' SMA female connector.

In order to switch between the internal antenna and the SMA connector, the capacitor at C73 must be moved from the two left pads to the two right pads connecting the radio to the SMA connector. This process may be completed quickly with a heat gun and tweezers by sliding the capacitor over to the adjacent pad once the solder begins to melt.
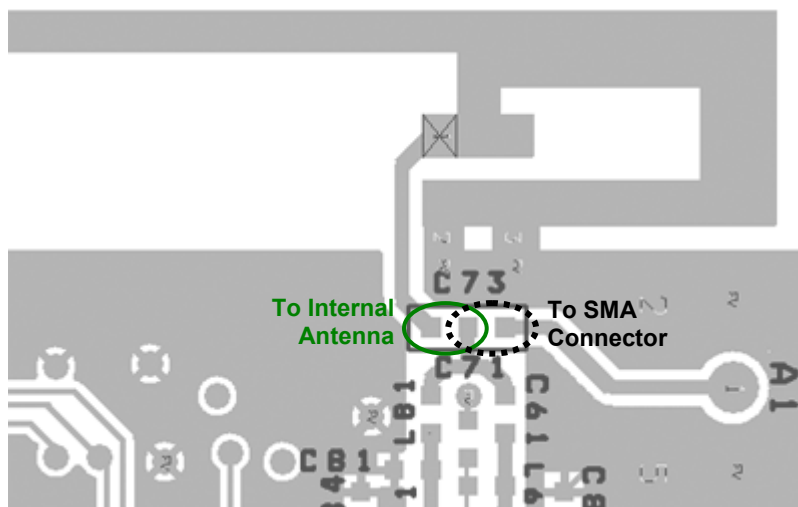

Figure 9 : Moving C73 to select between the internal antenna and the SMA connector

Internal Antenna

Telos' internal antenna is an Inverted-F microstrip design protruding from the end of the board away from the battery pack. The Inverted-F antenna is a wire monopole where the top section is folded down to be parallel with the ground plane. Although not a perfect omnidirectional pattern, the antenna may attain 50-meter range indoors and upwards of 125-meter range outdoors. Measurements of the internal antenna's performance with and without a battery pack are show in Figure 10 and Figure 11. Approximate radiation patterns for the Inverted-F antenna as provided by Chipcon AS are shown in Figure 12 and Figure 13.
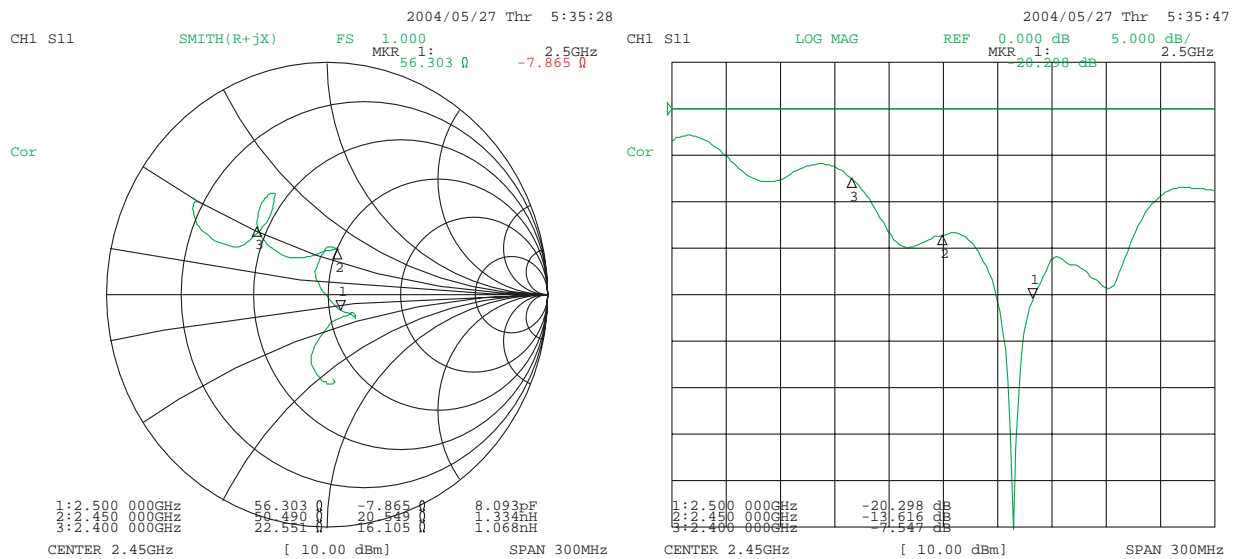
Internal Antenna without Battery Pack

Figure 10 : S11 measurements for the internal inverted-F antenna when no battery pack is present
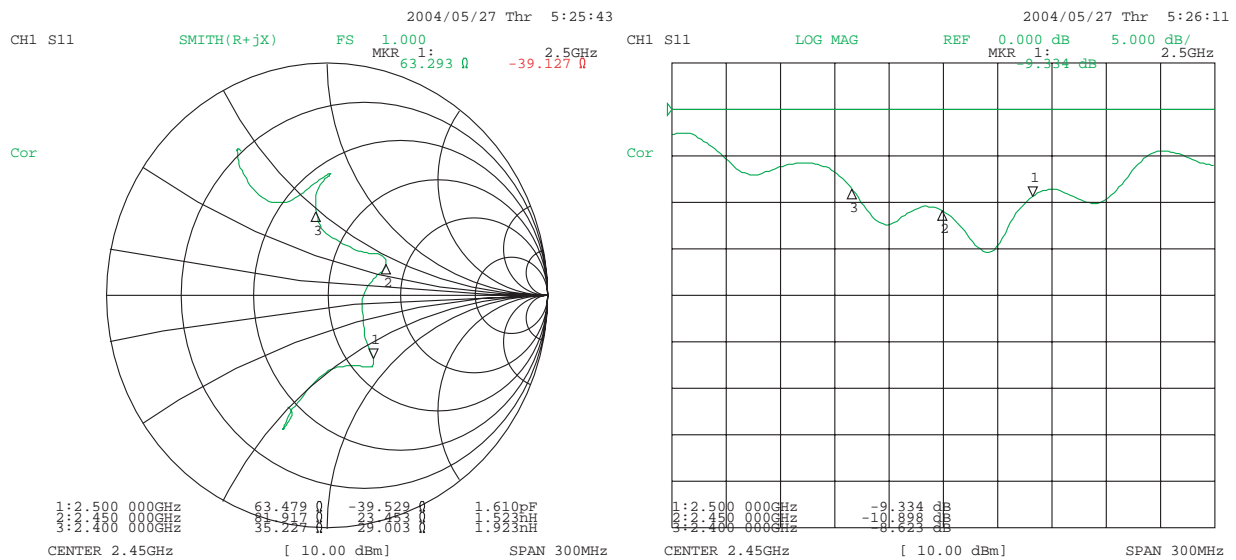
Internal Antenna with Battery Pack

Figure 11 : S11 measurements for the internal inverted-F antenna with battery pack underneath

Radiation Pattern

Ref.no: 18-12-03

CF 2442.000 MHz
4 dB/ div
Ref Lev: .... dBm

Horisontal Polarization
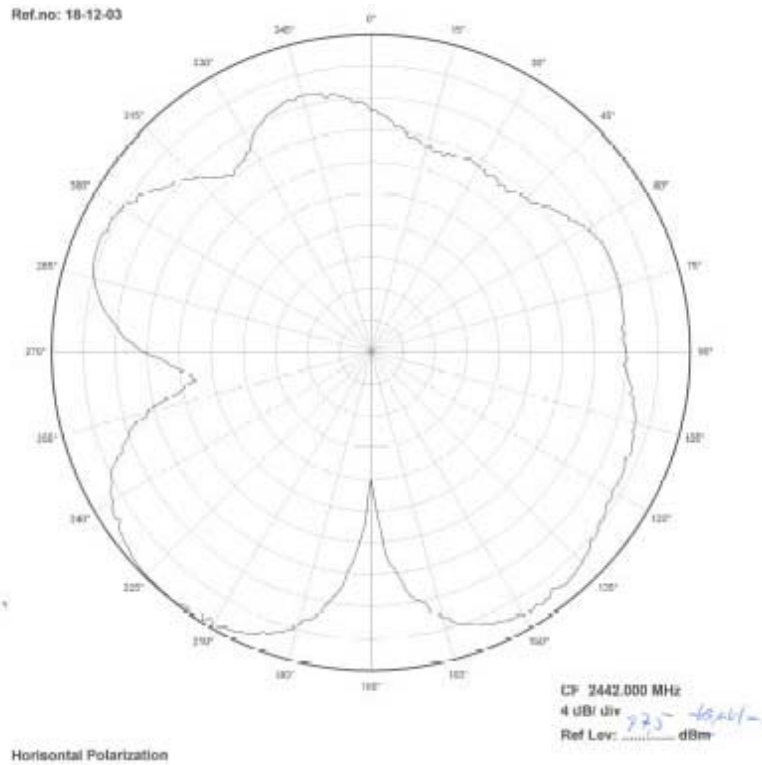
Figure 12 : Radiated pattern of the Inverted-F antenna with horizontal mounting (from Chipcon AS)

Ref.no: 18_12_03

CF 2442.000 MHz
5 dB/ div
Ref Lev: .... dBm
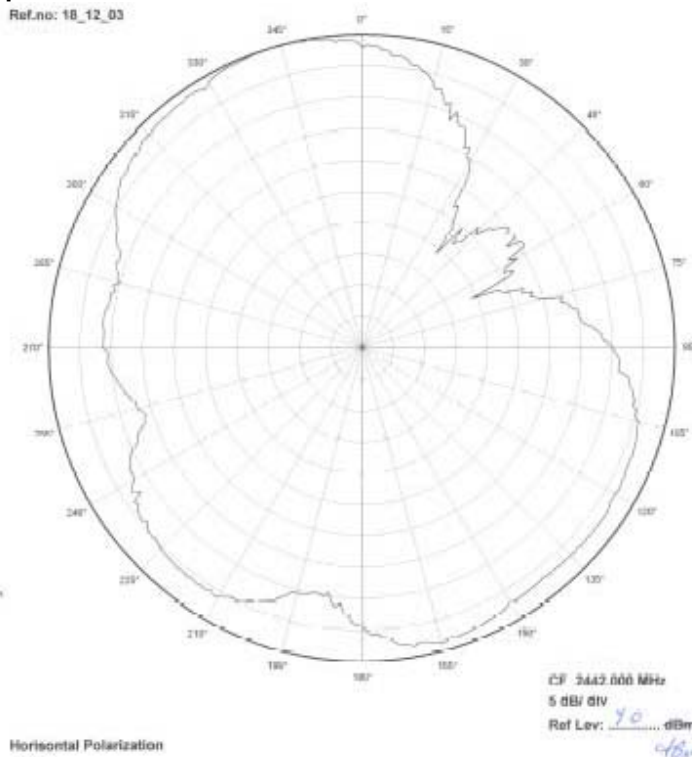
Horisontal Polarization

Figure 13 : Radiated pattern of the Inverted-F antenna with vertical mounting (from Chipcon AS)

SMA Connector

The SMA connector is a surface mount female coax connector for attaching an external antenna. The default Telos configuration does not include the surface mount SMA connector. The connector may be purchased separately from Allied Electronics (http://www.alliedelec.com). The manufacturer's part number is 142-0711-201 from Johnson Components.

The performance of the SMA connector is independent of the presence of the battery pack. The S11 network analyzer measurements for the SMA connector performance are shown in Figure 14.
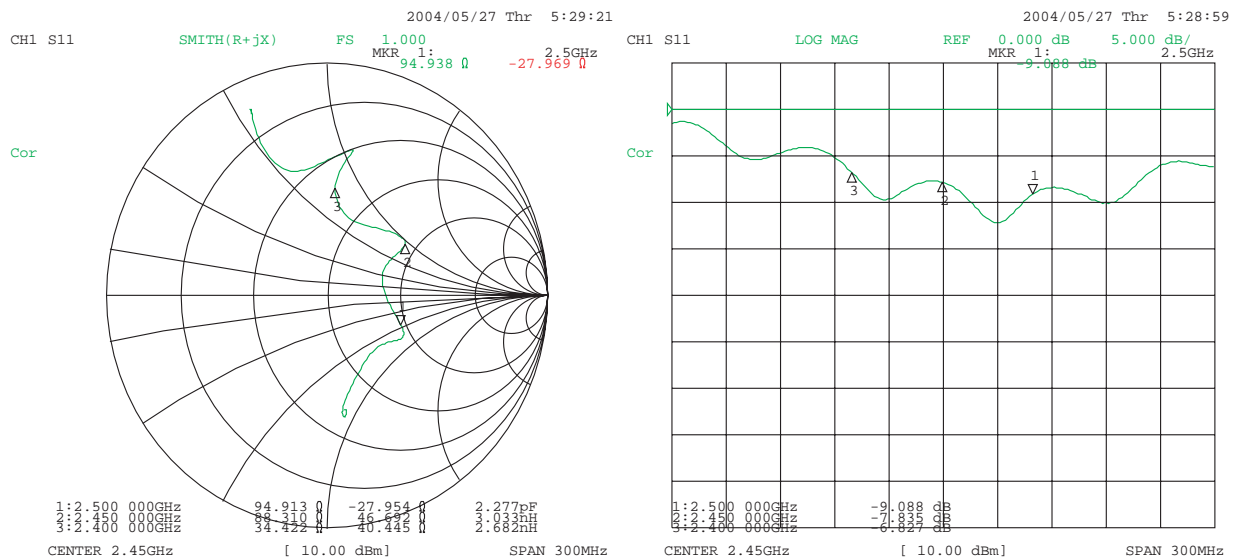

Figure 14 : S11 measurements of the SMA connector (minimal variance with/without battery pack)

Sensors

Humidity/Temperature Sensor

The optional humidity/temperature sensor is manufactured by Sensirion AG. The SHT11 and SHT15 models may be directly mounted on the Telos module in the `U3` component position.

The SHT11/SHT15 sensors are calibrated and produce a digital output. The calibration coefficients are stored in the sensor's onboard EEPROM. The difference between the SHT11 and SHT15 model is that the SHT15 produces higher accuracy readings as shown in Figure 16. The sensor is produced using a CMOS process and is coupled with a 14-bit A/D converter. The low power relative humidity sensor is small in size and may be used for a variety of environmental monitoring applications.

More information can be found in the SHT1x datasheet available at http://www.sensirion.com

Parameter	MIN	TYP	MAX	Units
Humidity				
Resolution	0.5	0.03	0.03	%RH
	8	12	12	Bit
Repeatability		±0.1		%RH
Range	0		100	%RH
Temperature				
Resolution	0.04	0.01	0.01	^{o}C
	0.07	0.02	0.02	^{o}F
	12	14	14	bit
Repeatability		±0.1		^{o}C
		±0.2		^{o}F
Range	-40		123.8	^{o}C
	-40		254.9	^{o}F

Figure 15 : Sensirion relative humidity and temperature performance specifications
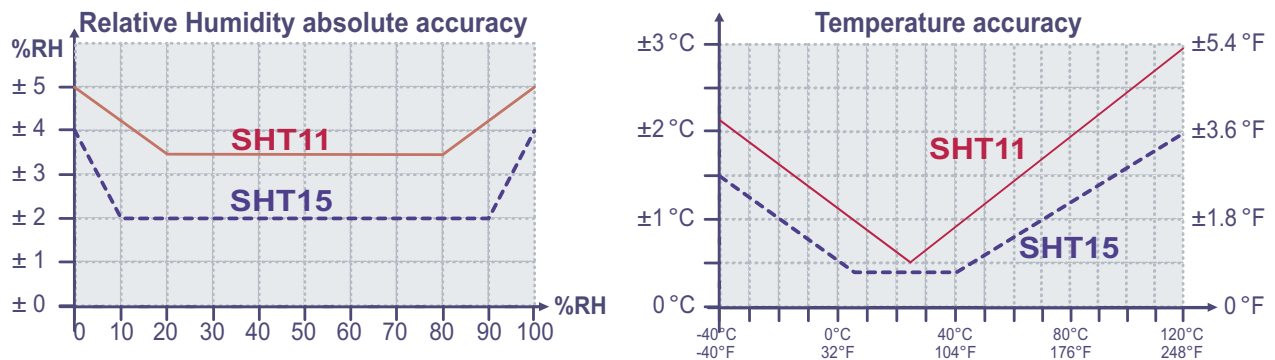

Figure 16 : Accuracy of Sensirion relative humidity and temperature sensors (courtesy Sensirion)

Light Sensors

A variety of light sensors may be used with Telos. Telos (rev A) has connections for two photodiodes. Moteiv currently uses photodiodes from Hamamatsu Corporation (http://www.hamamatsu.com)

If your mote is populated with light photodiodes, the default diodes are the S1087 for sensing photosynthetically active radiation and the S1087-01 for sensing the entire visible spectrum including infrared. The S1337 high precision photodiode may be substituted for the S1087-01.

Although these photodiodes from Hamamatsu have been tested with Telos, any photodiode with similar physical dimensions may be used with Telos.
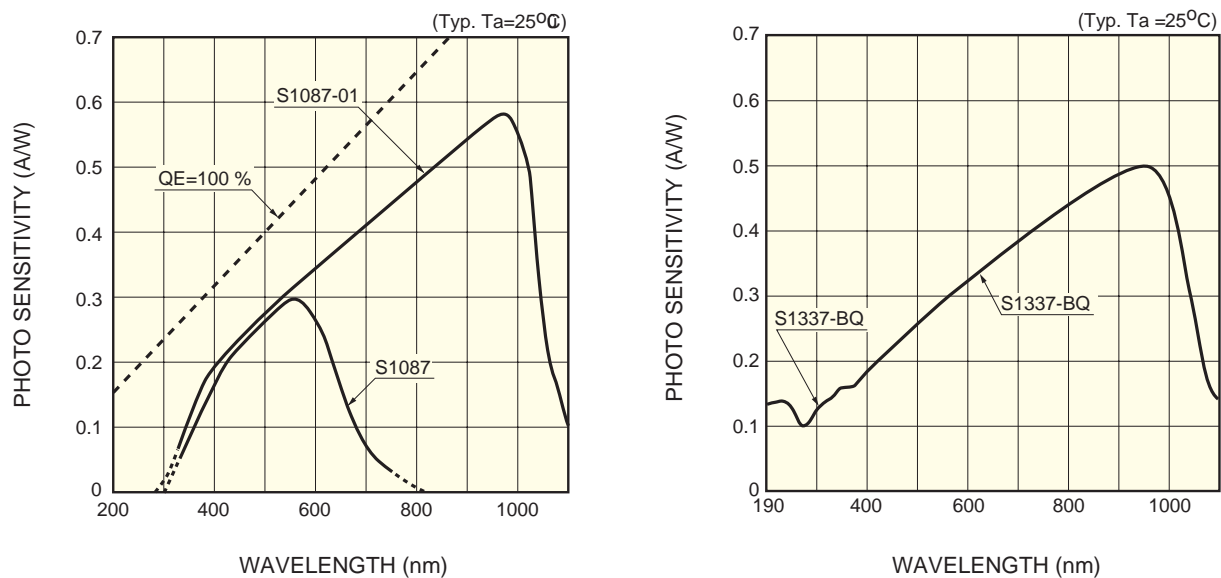
Figure 17 : Photo Sensitivity of the Light sensors on Telos (from Hamamatsu)

Expansion Connector

Telos has two expansion connectors and a pair of onboard jumpers that may configured so that additional devices (analog sensors, LCD displays, and digital peripherals) may be controlled by the Telos module. On the opposite side of the board from the USB connector is a 10-pin IDC header at position U2. This is the primary connector and provides digital and analog input and output lines. Peripherals may be connected to the 10-pin connector using an IDC header, an IDC ribbon cable, or by designing a printed circuit board that solders directly on to the IDC header providing a robust connection to the module.
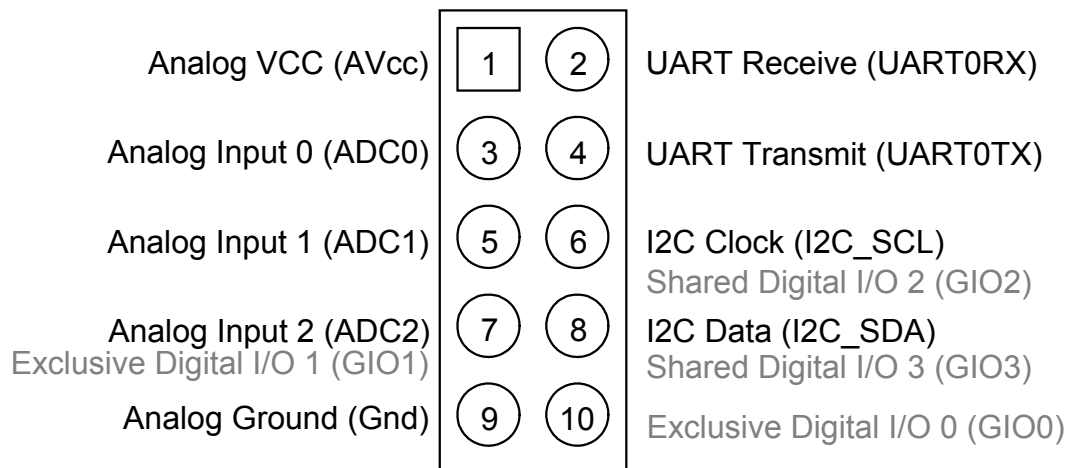
Analog VCC (AVcc)	1	2	UART Receive (UART0RX)
Analog Input 0 (ADC0)	3	4	UART Transmit (UART0TX)
Analog Input 1 (ADC1)	5	6	I2C Clock (I2C_SCL) Shared Digital I/O 2 (GIO2)
Analog Input 2 (ADC2) Exclusive Digital I/O 1 (GIO1)	7	8	I2C Data (I2C_SDA) Shared Digital I/O 3 (GIO3)
Analog Ground (Gnd)	9	10	Exclusive Digital I/O 0 (GIO0)

**Figure 18 : Functionality of the 10-pin expansion connector (U2).
Alternative pin uses are shown in gray.**

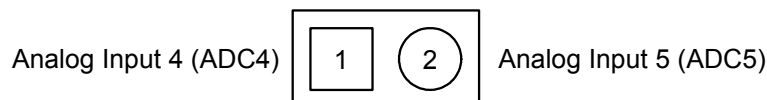| Analog Input 4 (ADC4)	1	2	Analog Input 5 (ADC5)

Figure 19 : Functionality of the 2-pin expansion connector (U6).

The analog voltage port is intended for use as output and should not be used to power the mote. AVcc is conditioned with an RC-filter and a pi-filter to remove noise in the sourced signal. As a result of the filters, there is a 470 ohm current limiting resistor. Currents larger than 10mA should not be sourced through this connector. If larger currents are required, replace R2 (located on the bottom of the module) with a 0 ohm resistor or an appropriately calculated value to source the required current.

If the UART is not used, the UART pins on the microcontroller may be used as general purpose digital I/O pins instead.

> **NOTE:** The I^2C pins are shared with the radio's data input pin and the radio clock. Care must be taken by application developers to multiplex operations on the I^2C bus and the radio.

If expansion pin 10 (ADC3) is used for digital I/O instead of analog inputs, `R14` must be populated with a 0 ohm resistor to enable the pin for digital I/O (GIO0) on the microcontroller. R16 must be populated with a 0 ohm resistor to enable GIO1. `R14` and `R16` are located on the bottom side of Telos directly next to the microcontroller.

> **NOTE:** When `R14`/`R16` is populated (GIO0/GIO1 enabled), ADC3/ADC2 will not provide reliable readings if an application reverts to using the ADC input instead of the digital I/O port input on the microcontroller. `R14`/`R16` should be removed when using ADC3/ADC2 for analog input.

The second expansion connector labeled `U6` is located directly next to the photodiodes. This connector may only be used if the photodiodes are not installed; otherwise the ADC readings will be unpredictable and tied to the photodiode output. U6 simply exports two additional ADC channels for applications required the full ADC functionality of the Telos module.

Internal Temperature and Voltage Monitoring

The MSP430 microcontroller has internal temperature and voltage sensors that may be used through the microcontroller's ADC interface.

The voltage port (input 11) on the 12-bit ADC monitors the output from a voltage divider. For Telos motes with serial numbers prior to M4BR6CR6 (serial numbers can be found by running the `motelist` utility while Telos is connected), there is an external 470 ohm resistor on the input to AVcc. As a result, the voltage port is not an exact voltage divider. The error on the input readings for motes prior to M4BR6CR6 is +/- 8 ADC counts. The schematic and formula to calculate the voltage are shown below. For Telos Rev A motes with serial numbers after M4BR6CR6, there is no 470 ohm resistor prior to AVcc input and ADC port 11 reads exactly 1/2 DVcc.
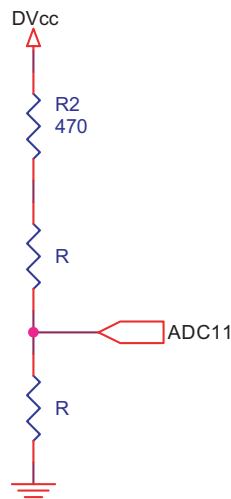
Voltage monitoring for Telos motes prior to serial number M4BR6CR6.
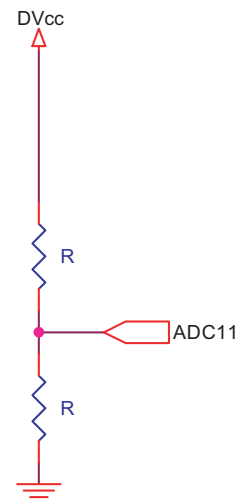
Voltage monitoring for Telos motes including and subsequent to serial number M4BR6CR6.

Converting the ADC units to a voltage reading can be done with the following formulas:

For motes with serial numbers prior to M4BR6CR6:

$$DVcc = \frac{ADCCounts}{4096} \times V_{ref} \times \frac{R + R + 470}{R}$$

$$R \approx 1175\Omega$$

For motes with serial numbers including and subsequent to M4BR6CR6:

$$DVcc = \frac{ADCCounts}{4096} \times V_{ref} \times \frac{2R}{R}$$

The temperature input is internal ADC port 10. It consists of an uncalibrated diode. When using the temperature sensor, the sample period must be greater than 30 µs. The temperature sensor offset error can be large, and may need to be calibrated for most applications. The typical response of the temperature sensor is shown in Figure 20.

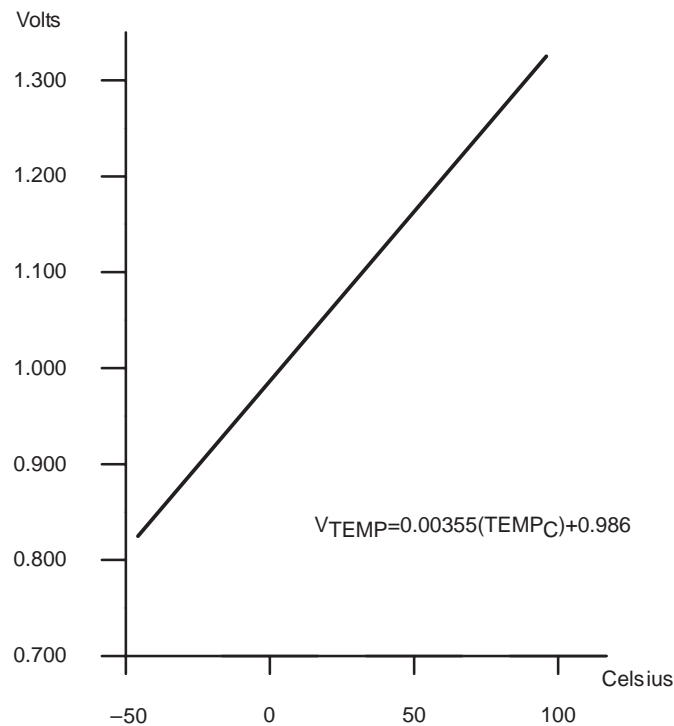$$V_{TEMP}=0.00355(TEMP_C)+0.986$$

Figure 20 : Typical response of the internal temperature sensor. Results vary and the sensor should be calibrated for most applications. Response curve from Texas Instruments.

General Information

Document History

Revision	Date	Notes
1.0	2004/05/31	Initial Release
1.01	2004/06/16	Included information about calculating voltages from the internal ADC voltage port and temperature from the internal temperature port on the MSP430 microcontroller. Fix: Schematic modifications from product assembly rework. Fix: S1337-BQ may be substituted for the S1087-01.
1.02	2004/07/14	Error: ADC3 is not connected to U2.10 as the schematic depicts Updated Address and Phone information
1.03	2004/08/14	Added mechanical characteristics

Product Status Definitions

Data Sheet Identification	Product Status	Definition
Advance Information	Planned or under development	This data sheet contains the design specifications for product development. Specifications may change in any manner without notice.
Preliminary	Engineering samples or first production	This data sheet contains preliminary data, and supplementary data will be published at a later date. Moteiv reserves the right to make changes at any time without notice in order to improve design and supply the best possible product.
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