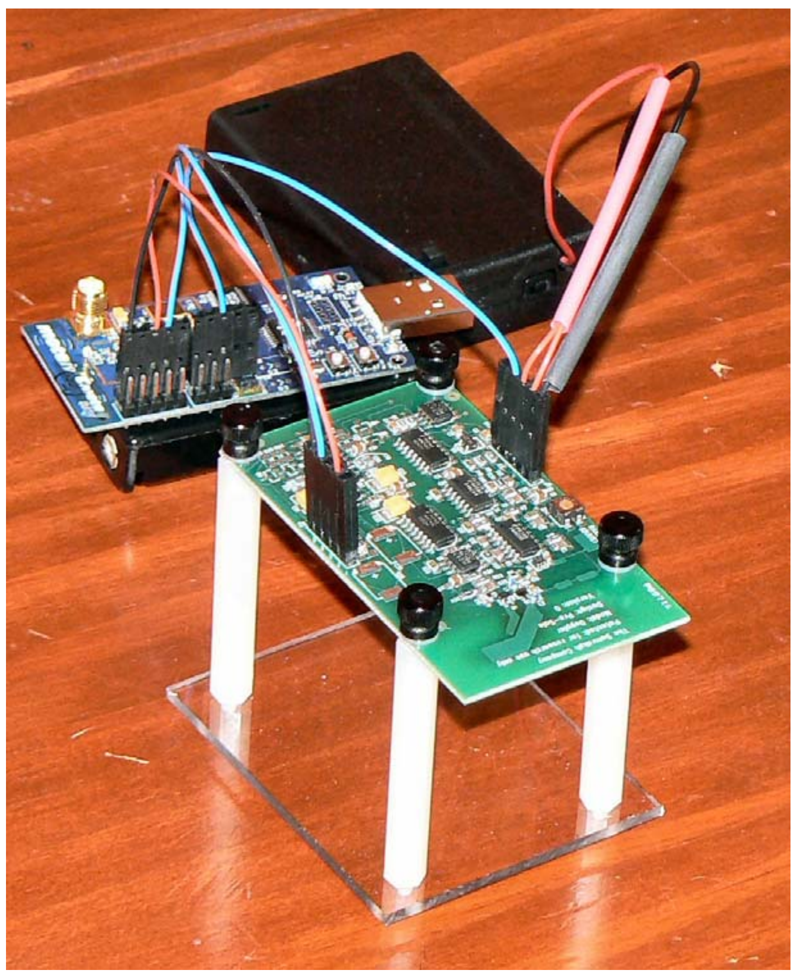
The Samraksh Company

समरक्ष

Ubiquitous Actualization

Users Manual
for the BumbleBee (Model 0)

A Mote-Scale Pulsed Doppler Radar for use in Wireless Sensor Networks



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(The latest version of this manual can be downloaded from www.samraksh.com/support.htm)

1. Introduction

The BumbleBee Radar is a low-power Pulsed Doppler Radar (PDR) that is designed for a variety of Wireless Sensor Network (WSN) applications. Unlike traditional radars, the BumbleBee is designed to be compatible at a systems level with small, battery powered nodes. In particular the BumbleBee is optimized for WSNs based on *motes*. Motes are significantly larger than “Smart-Dust”[1], but more like smart-dust than traditional network nodes. As a result the definition of a mote is not precise, but a mote roughly has the following quantitative property:

- Each mote has: 1) a built-in computing element, 2) a built-in peer-to-peer radio, and 3) at least one, but not more than a few, sensor(s).
- Motes are between 2 cm and 10 cm on a side, typically, 50 to 100 cc’s.
- Motes use between 100 J and 5 KJ of energy per day for the combination of computing, radio, and sensing.
- Motes can support networks with node-spacing between 5 m and 50 m.
- Motes cost between $20 and $200 each.

The BumbleBee is mote-scale in the sense that if used in a WSN system with motes, its costs, ranges, and other performance metrics will neither dominate nor be dominated by the corresponding metrics for the motes. Examples of system-level imbalance would be using a $1,000 sensor with a $20 mote, using a sensor with an effective range of 1 m with a mote that has a communication range of 100 m, or using a video camera that continuously uses 2 W of power with a mote that consumes 30 mW of power when running but only runs on a 3% duty cycle (for an average power draw of 0.9 mW). The BumbleBee attempts to avoid all of these mismatches.

The BumbleBee board is shown in **Figure** 1. In this picture the antenna is formed by the covered lands on the right end of the board (as pictured). The radiation pattern of the antenna would be out the right end of the board, along the axis of the board.

Key features of the BumbleBee include:

- A detection range up to of 10 m.

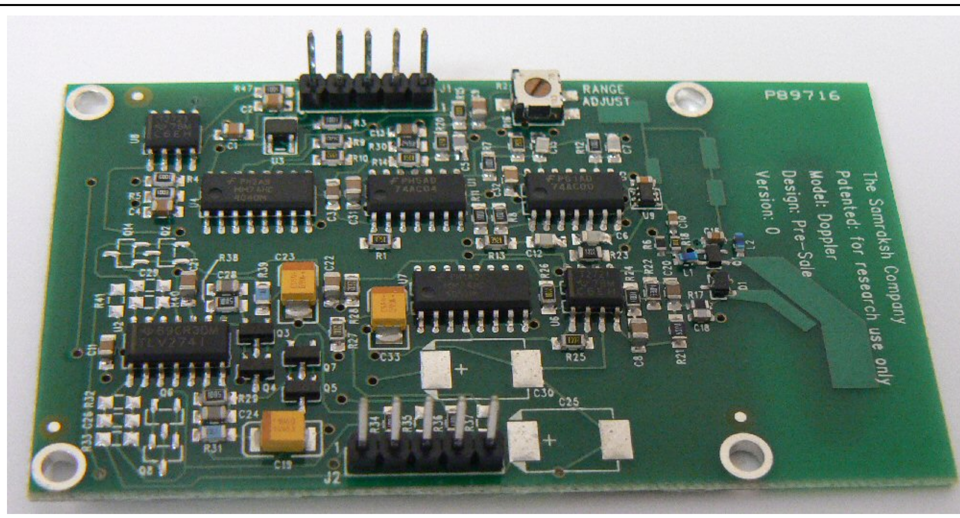

Figure 1. The bare board measures 3” by 1 ¾”.

[1] Smart Dust is a term popularized by Kris Pister (http://robotics.eecs.berkeley.edu/~pister) that refers to WSN nodes that are intended for use in vast scale networks and are as small as a few square millimeters.

- Coherent output (both I & Q channels).
- Maximum range controllable via software (between 1 m and 10 m).
- Range gate sharpness of 0.2 m, with both a minimum and a maximum range gate.
- On-board (i.e. internal) antenna.
- 60 degree conical coverage pattern.
- Responds to radial velocities between 2.6 cm/s and 2.6 m/s.

In addition to being system compatible with many motes, the BumbleBee works out-of-the-box with TelosB motes from Crossbow Inc. as well as TmoteSky motes from MoteIV Inc.

2. Contents of the Box

The contents of the box are shown in **Figure** 2. The box should contain:

- The BumbleBee bare board as shown in **Figure 1**. This is enclosed in an anti-static bag.

  The bare board is less sensitive to static electricity than some high impedance devices, like memory chips; in addition the board protects the most sensitive parts through resistive circuit elements that bleed off static build up. Nevertheless, like most electronics these boards can be reliably destroyed by exposing them to strong static electricity. Frequent handling or storage outside the electrostatic protective bag causes a noticeable failure rate.

Figure 2. The contents of the box.

- A battery pack that holds three AA alkaline batteries.
- A cable for connecting the BumbleBee Radar to a TelosB (or a TMote Sky).
- A clear plastic base for the stand.
- Four 2" posts for separating the board from the base of the stand.
- A tube of superglue.

If the contents of your box differ from this and you purchased your devices from our web site, please contact technical support at support@samarksh.com. Note that devices not-purchased on the web, typically larger orders, may contain other contents as negotiated at the time of purchase. If this is your case but your box doesn't contain what you expected, please contact sales@samraksh.com.

3. Radar Stand

A grounded object within one wavelength of an antenna will load the antenna in such a way as to dramatically diminish the effectiveness of the antenna. This is true rather the antenna is used for a radio or for a radar. We have witnessed as much as a 100-fold reduction in transmitted energy when a standard battery is placed next to the radio antenna of some popular motes. If you know in advance that an antenna will be loaded in a specific way it is possible to partially compensate for the loading, thus avoiding the most extreme losses in performance, but the typical result will still be a non-trivial degradation in performance.

The BumbleBee's center frequency is 5.8 GHz, which corresponds to a wavelength of about 5.2 cm. As a result it is ideal to position the radar so that its antenna is at least 5 cm away from any large metal objects, especially the batteries. To make this easier to do we've included a plastic stand. The stand is assembled by screwing the four plastic posts into the base as shown in **Figure 3**. The plastic thread can easily be striped with excess force. In addition avoiding cross threading requires a steady downward force and carful perpendicular alignment.

Figure 3. Assembling the stand.

Once all 4 posts are secured, remove the black thumb screw and washers on the top of each post. Place the board on top of the posts and refasten each of the thumb screws, making sure that the washers are on top of the board. The result is shown in **Figure 4.**

The threaded posts allow you to assemble and disassemble the stand many times. However the plastic threads are striped more easily than metal threads. Once your setup is finalized you can improve the strength by gluing the posts into the base.

You can also glue the base of the stand to the battery pack in order to provide greater stability. We suggest aligning the base of the stand perpendicular to the battery pack, so that the ends of the posts extending through the base do not

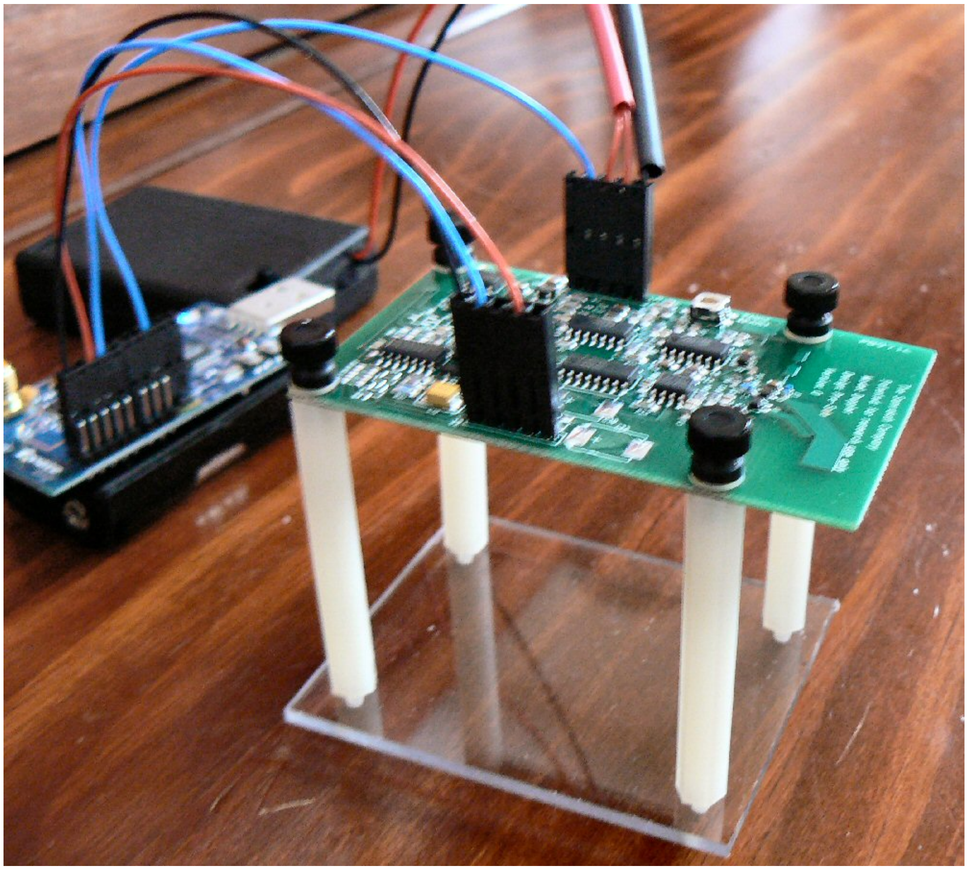

Figure 4. The fully assembled stand.

touch the battery pack. Also we caution you to be sure that you can still open the battery pack, in order to change batteries.

If the radar moves, stationary objects will produce returns that are not removed by the Doppler filter. As a result most applications will fail, if the radar rocks in the wind or vibrates due to the rumble of nearby traffic. So in outdoor settings it is usually necessary to attach the battery pack to an even more stable support. The battery pack can be glued to fence posts, trees, wall-mounts, even rocks. The enclosed superglue works best for smooth surfaces. Silicon glue or Polyurethane glue (not included but readily available from most home improvement stores) works much better on rough surfaces.

Before committing to any glue it is a good idea to experiment with removal. Superglue dissolves readily in acetone which is available in the paint section of most home improvement stores. In addition, for many surfaces the battery pack can be cutoff with the use of a razor blade or similar tools. A primary advantage of silicon glue is that it's less permanent and can often be pealed off with the fingers.

4. Basic Hookup

The BumbleBee has two 5-pin square-pin headers on either side of the board. These headers use the common 0.1 inch spacing with a pin depth of 0.261 inches (although 0.25" connectors appear to work), so cabling is readily available. Such cables can be bought from on-line electronics

Table 1. Parts for making custom cable available from Mouser Electronics.

Description	**Part Number**	**Cost Jan. '08**
5-pin Housing	538-50-57-9005	73 cents
Pins for Housing	538-16-02-0096	8 cents
Hookup Wire 26 Gage	566-83002-100-** ** spec. color	$29 100 feet.

stores such as Newark[2], Mouser Electronics[3], or Digi-Key[4]. In addition you can make custom cables using hookup wire, hoods, and pin. For your convenience **Table 1** lists part number for suitable parts from Mouser Electronics. These exact same parts are typically available from Digi-Key and Newark. In addition similar parts from other manufacturers are typically available through Mouser and Digi-Key. Hookup wire is generally available from many other sources including RadioShack. However, if buying form a retailer, care must be taken that the wire is not too thick for the specific pins; the pins specified in **Table 1**, for example, will not work well with wire thicker than 24 gauge and most speaker hookup wire sold through retailers is 18 to 22 gauge.

The BumbleBee's connectors are described in **Table** 2.

Notice that the power source voltage may span a large range. This is provided for greater experimental convenience. The on-board voltage regulator produces a stable internal 3.3 volts, even if the voltage source drifts with time (or under load). However, it is a shunt style regulator; as a result, the use of higher voltage power sources becomes progressively less efficient.

Also, the DC reference output is provided for convenience when building interface circuits. However, the signal outputs are not differential. That is, the noise when considering J2-2 or J2-4 vs J1-5 is no less than when considering J2-4 and J1-5 individually.

If J1-4 is allowed to float (i.e., left unconnected) the range is controlled by the potentiometer. In fact, a more exact reading of the potentiometer setting can be computed from the voltage on this pin (i.e., when it's allowed to float). The potentiometer setting (i.e., between 0 and 1) is

$$\alpha = \frac{V_{J1-4}}{3.2}.$$

But the BumbleBee Radar is designed so that by setting the potentiometer to midrange (i.e., $\alpha = 0.5$) and then controlling the value of V_{J1-4} the range can be changed under software control through a Digital-to-Analog Converter (DAC).

To understand this method of range control, let α' be defined as the potentiometer setting that would yield the same range setting if the range were controlled

Table 2. Description of **BumbleBee**'s pin-outs.

Pin	Name	Use	Description
J1-1	Ground	In	
J1-2	Power	In	From 3.65 to 16 V.
J1-3	Shutdown	In	Hold high to turn on.
J1-4	Range Control	In Out	0 V is maximum range 3.3 V is minimum range
J1-5	DC Ref	Out	Nominally 1.65 V
J2-1	Ground	Out	
J2-2	In Phase	Out	This is the real part of the complex signal.
J2-3		Open	
J2-4	Quadrature	Out	This is the imaginary part of the complex signal.
J2-5		Open	

2 www.newark.com
3 www.mouser.com
4 www.digikey.com

through the potentiometer, i.e., if J1-4 were unconnected. Then

$$\alpha' \approx \frac{V_{J1-4}}{3.2}.$$

More details on software range control are provided in **Section 9**.

5. Oscilloscope Test

Perhaps one of the best initial tests that your radar is working is to examine its output using an oscilloscope. A very slow oscilloscope will work fine, but a digital storage oscilloscope that allows playback and zooming can be useful. The Tektronix TDS 1000B, is an inexpensive scope that works well for this purpose.

Connect power to pins J1-1, J1-2, and J1-3. Ground pin J1-4 for maximum range or if working in a cluttered indoor environment leave it open and set the potentiometer to about midrange. Connect high-impedance scope probes to the analog outputs J2-2 and J2-4. Set the scope to abut 1 sec/div and about 1V/div (on both channels), and select DC coupling. The radar's analog outputs have a 1.65V DC offset, so set the vertical position control to center the traces once the power has been applied and the outputs have stabilized. If the scope has a bandwidth reduction feature, enable it in order to reduce noise pickup through the probes. Finally, set the trigger to free-running (often labeled "auto").

When there is no motion within the radar's field of view, the result should be a relatively stable signal with about 30 mV of white noise over the frequency range from 1 Hz to 100 Hz. If you see a large 60 Hz signal it may be caused by a broken wire or by an induction motor driven fan within the radar's field of view. Older style florescent lights can also cause smaller 60 Hz vibrations within the field of view that are sensed by the radar.

When a human walks into to the radar's field of view, which depends on the range setting, at a normal speed the signal should swing very nearly to full scale (i.e., from 0 V to 3.2 V). Careful analysis of this signal would reveal a cluster of energy around the frequency that corresponds to the person's radial velocity. The relation between radial velocity and Doppler frequency is

$$F_d = 2\frac{V_r}{\lambda},$$

where F_d is the Doppler frequency (i.e., the frequency of the BumbleBee's output), V_r is the radial component of the "target's" velocity, and λ is the wavelength at the center frequency. All of the returns within the range gate and within the Doppler filter's radial velocity window (i.e., from ~2.5 cm/s to 2.5 m/s) are coherently combined to produce the output. When a human walks the radial velocities of the legs and arms (and perhaps the head) are instantaneously different than the radial velocity of the torso. The result is a complex mixture of signals that typically can't be analyzed visually. In indoor settings, multipath may significantly exacerbates this affect.

However, if a strong point reflector moves through the radar's field of view it will tend to dominate the returns from smaller moving objects (remember that the Doppler filter removes the large returns from stationary objects). In this case, the radar's output will be a relatively purer phase spiral that can be visually analyzed on an oscilloscope without computational aids. This is best done by setting the scope so that one channel corresponds to the X-dimension and the other channel corresponds to the Y-dimension of the display. Then a smoothly approaching corner reflector should trace out an approximate circle.

Figure 5. Example of a corner reflector. The one on the left is homemade; the one on the right is a fairly common commercial design for marine and boating safety.

Corner reflectors can be made or purchased from many marine and boating safety suppliers. **Figure 5** shows examples of corner reflectors. If you wish to purchase a corner reflector, we suggest searching the internet for “Marine Radar Reflector”. In early 2008 we found many reflectors for under $50, including shipping and handling.

If you do not test with a corner reflector it is still a good idea to check that both the *I* and *Q* outputs are responding to the target and that the responses are not the same.

6. TelosB (or TMote Sky) Cabling

The BumbleBee Radar ships with a battery pack and connectors that enable easy hookup to a TelosB (or equivalently to a TmoteSky mote). The hookup diagram is shown in **Figure 6**. Note that the TelosB headers U2 and U2B are 2 rows of 5 pins and 2 rows of 3 pins, respectively; whereas the headers on the BumbleBee are each 1 row of 5 pins. Both ends of the provided cabling have connectors that contain 1 row of 5 pins. These connectors are to be plugged into the

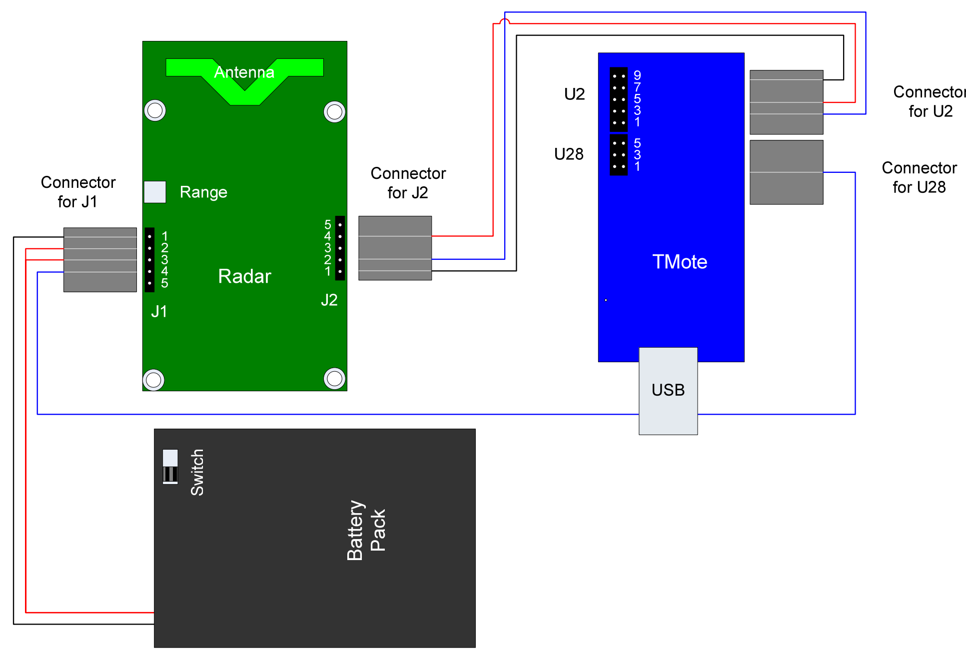

Figure 6. Hook-up diagram for the TelosB and the TMote Sky.

right-hand half of the TelosB headers when the TelosB is oriented as in **Figure** 6. It is OK if the connector for U2B extends off the end of the header.

Table 3. Part numbers for compatible headers from Mouser Electronics.

Description	Part Number	Cost Jan. '08
U2	538-90131-0125	33 cents
U2B	538-90131-0123	85 cents

Many TelosB's were sold with these headers unpopulated, so you may need to add theses headers. Because these headers are through hole components, manually soldering them requires only modest skill, provided you have at least a mid-level soldering iron. Note that because the pins dissipate the head rapidly, soldering them may be easier with a higher wattage soldiering iron than would typically be used for delicate electronics (e.g., 30 watts). Headers can be purchased from the same on-line electronics vendors suggested in **Section 4**.

Part numbers for suitable parts from Mouser Electronics are provided in **Table 3**.

7. Software

The BumbleBee is bundled with a software suite that consists of 3 modules:

1. A device driver.
2. A data acquisition application.
3. A simple detector application.

This software is written in TinyOS 2.x for the TelosB. The latest version of TinyOS can be downloaded from

http://www.tinyos.net/tinyos-2.x/doc/html/install-tinyos.html;

although, a version of TinyOS is often provided with the TelosB's. The latest versions of our software can be downloaded from

www.samraksh.com/support.htm

Device Drivers

The *I* and *Q* outputs are connected to TelosB inputs ADC0 and ADC1, respectively. The radar's output is the complex signal formed by these two real quantities. As a result, in order to sample the radar's output it is necessary to sample both of these channels simultaneously. The TMote only has one Analog to Digital Converter (ADC) and can not do this. However, if the two real valued channels are sampled in rapid succession the result is an adequate approximation to the ideal sample. The core purpose of our device driver is to performs this operation.

The sensor driver, developed for use with TinyOS 2.x, uses the `Msp430Adc12MultiChannel` interface to exploit the "Sequence-of-Channels" conversion mode available through the Telos ADC hardware. Our measurements show that the time difference between sampling the *I* and *Q* channels is less than 15 µs, which is about what is required, to approximate the ideal sample.

Although there is no DAC module released in TinyOS 2.x, we provide a DAC module based on a DAC implementations from earlier versions of TinyOS. To avoid sharing conflicts over the reference voltage, the driver assumes that the reference voltage is already initialized to 2.5V by an ADC client; that is this driver does not control the reference voltage from the DAC module.

The range control logic in the BumbleBee driver accepts a 12-bit DAC, that we'll denote as v. The resulting output voltage is:

$$V_{J1-4} = \frac{2.5 \cdot v}{4096}$$

Data Acquisition Applications

For data acquisition we provide two simple applications named, `RadarDataCollect` and `WirelessRadarDataCollect`, which illustrate the wiring and control of the BumbleBee device driver. In both these applications, the radar is sampled at the sampling period specified in the header file `DataCollect.h` and the resulting complex value is sent out as a message. Each message contains a sequence number that is incremented with every reading. The only difference between the two applications is that in `RadarDataCollect` the sampled values are sent out over the USB Serial port, whereas in `WirelessRadarDataCollect` they are broadcast as a radio message.

Simple Detector Application

The `SimpleRadarDetector` application uses a threshold-based decision logic to detect motion within the range of the radar. The nominal DC value of the radar output is 1.65V. The software subtracts a value corresponding to 1.65 V from each component of the radar samples in order to produce signed samples. The detector then computes the amplitude of the sample, i.e., $I^2 + Q^2$. The sample amplitudes are then compared to a static threshold and any anomaly detections are passed through a simple *M*-out-of-*N* filter and a hysteresis filter in order to produce the final detection decision.

The result is a remarkably good motion detector. In indoor environments where the environment typically does not move unless a target is present this detector may suffice for fully operational applications. In more complex environments, like many outdoor environments, where the background moves, it is usually necessary to employ more sophisticated signal processing to distinguish the motion of a target from the motion of the background. We will provide examples of such detectors, in the form of application notes, as they become available.

When a detection occurs, a message is sent over the serial port containing a one word payload with the value 1 and LED0 is turned on. When a detection ends, a similar message, except with a payload of 0 is sent and LED0 is turned off. The formats of these messages are shown in Table 4.

We also provide a application called `WirelessSimpleRadarDetector`, which broadcasts detection messages over the radio.

8. How to Collect Raw Data Using Motes

We also provide the `RadarDataCollect` application for collecting raw data, perhaps for analysis in other environments such as MatLab.

Install the BumbleBee Radar software suite by extracting its tar file to the `tinyos-2.x/apps` folder in the TinyOS hierarchy. In the command window (i.e., either the Linux shell or cygwin on windows), navigate to the `RadarDataCollect` folder and then compile and install the

Table 4. Detailed message formats for the simple detector application, as displayed by the TinyOS Listen tool.

Message	Header	Type	Seq Num	Payload	Reserved
Start Detect	00 FF FF 00 00 06 00	EE	00 0F	00 01	00 00
Stop Detect	00 FF FF 00 00 06 00	EE	00 0F	00 00	00 00

application with the command

```
make telosb install.
```

Connect the TelosB with the installed program to the radar, remembering to turn on the battery pack switch. The application will sample the ADC0 and ADC1 ports at the specified sampling period and send the readings as a message over the serial port. These messages can be received using the standard Listen tool from the TinyOS installation. The usual command is

```
java net.tinyos.tools.Listen -comm serial@COM6:telos
```

The message formats are shown in **Table 5.**

A similar procedure can be used to run the simple detector applicaiton.

9. Range Control

In actual practice the $0 < \alpha'$ when $V_{J1-4} = 0$ and $\alpha' < 1$ when $V_{J1-4} = 3.2$. In fact the value of α' various linearly between a minimum value, $\alpha_{\min}$, and a maximum value, $\alpha_{\max}$, as V_{J1-4} varies from 0 to 3.2 volts. The values of $\alpha_{\min}$ and $\alpha_{\max}$ depend on the pot setting, i.e., α :

$$\alpha_{\min} = \frac{1}{1+100\alpha-100\alpha^2}$$

$$\alpha_{\max} = \frac{(101+100\alpha)\alpha}{1+100\alpha-100\alpha^2}.$$

Notice that for the preferred case when $\alpha = 0.5$, $\alpha_{\min} = 1/52$ and $\alpha_{\max} = 51/52$.

When the range is changed, it perturbs the Doppler Filter, which takes nearly a second to stabilize. Readings during the first second after startup and during the first second after the range has been changed will be nearly impossible to interpret. The signal is shifted high or low at the moment the range changes, depending on whether the range was increased or decreased and then the signal decays exponentially back toward the DC value. With significant experimentation, it is probably possible to model and to account for the distortion that occurs when the range is changed. However, this is not our intent. The BumbleBee is a Doppler radar with controllable range gates; it was not intended to be used as a ranging radar, for example by rapidly scaning through a series of range gate settings in order to do some sort of ranging.

There are many subtle software bugs, and few hardware flaws, that can cause the DAC value to flicker during operation. If this happens it will corrupt the radar value. For example it is easy for another service to turn off the DAC converter periodically. If the radar centric service

Table 5. Example output from the data collection application as displayed by the TinyOS Listen tool.

Header	Type	Seq Num	I	Q	CRC
00 FF FF 00 00 06 00	EE	01 4A	0A 7D	0B 17	00 00
00 FF FF 00 00 06 00	EE	01 4B	0A 6F	0B 13	00 00
00 FF FF 00 00 06 00	EE	01 4C	0A 5F	0B 0F	00 00
00 FF FF 00 00 06 00	EE	01 4D	0A 53	0B 0D	00 00
00 FF FF 00 00 06 00	EE	01 4E	0A 4B	0B 07	00 00
00 FF FF 00 00 06 00	EE	01 4F	0A 43	0A FD	00 00

automatically turns the DAC back on the problem may not be obvious, but the radar will perform poorly, because its range gate is being dithered.