Data Sheet / User Guide

PulsON® 440

TIME DOMAIN®
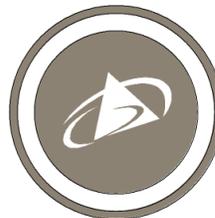
Cummings Research Park
4955 Corporate Drive Suite 101
Huntsville, AL 35805 USA
http://www.timedomain.com
Tel: +1 256.922.9229
        +1 888.826.8378
Fax: +1.256.922.0387

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Regulatory Approvals

The P440, as supplied by Time Domain, has been certified for general use in the United States. See Section 8, Regulatory Compliance for details.

The P440 is compliant with Europe's ETSI EN 302 065 standard. The user is free to buy the equipment for evaluation and demonstration purposes (but not for resale) in most countries. When in doubt, the user should confirm with the relevant authority governing radio emissions. Additional information is provided in Section 8.2, Compliance with the EU ETSI Standards.

All final products developed by the user which incorporate the P440 must be approved by the relevant authority governing radio emissions for the target market country(s). The User bears all responsibility for obtaining such approval(s).

Table of Contents

1 Summary

The PulsON® 440 (P440) module is an Ultra Wideband (UWB) radio transceiver operating between 3.1 and 4.8 GHz. It is a member of the P400 Series of UWB platforms. The P440 provides the following functions:

- It is based on Time Domain's FIFE UWB chip.
- It uses Two-Way Time-of-Flight (TW-TOF) ranging to measure the distance between two or more P440s. These measurements have an accuracy of <2 cm and are provided at rates up to 125 Hz.
- It communicates data between two or more P440s.
- It can operate as a monostatic, bistatic, or multistatic radar.
- It can provide all four functions (range determination, data transfer, monostatic radar, and multistatic radar) simultaneously.
- It operates with very low power transmissions (~50uW).
- It is provided with a network optimized for TW-TOF measurement. This network can be operated using either the ALOHA (randomized) or TDMA (Time Division Multiple Access) protocols.
- It supports 11 independent communications channels thus allowing operation as a CDMA (Code Division Multiple Access) network. Many more channels can be added.
- The network is provided with a location engine which can be used to determine the position of the unit in the X, Y, and Z dimensions.
- The user can specify whether the Location Engine reports position in 2D or 3D and whether it uses a Kalman Filter-based solver or a Geometric (Nonlinear Least Squares) solver.
- It is interoperable with Time Domain's earlier generation equipment (P400, P410, and P412).
- The hardware is designed to operate over the full industrial temperature range (-40°C to +85°C) as well as operate in high shock and high vibration environments.
- The P440 has been certified by the United States Federal Communications Commission (FCC) per Rule Part 15.519. The FCC Identifier is NUF-P440-A.
- The RF emissions are compliant with the European Union ETSI EN 302 065 standard mask.

The P440, like all of the members of the P400 family, is a coherent radio transceiver. This means that the energy in each transmitted pulse can be summed to increase the Signal-to-Noise Ratio (SNR) of received transmissions. Each time the number of pulses sent is doubled, the SNR of the received signal will double (increase by 3 dB). This comes at the cost of doubling the amount of time required to complete a full transmission. The transmission strength is not increased, rather more energy is summed to improve reception. This applies to all transmissions regardless of whether the transmission is intended for ranging, radar, or communications.

The user controls and monitors the P440 through an Application Programming Interface (API) over USB, Serial, SPI, Ethernet or CAN connections. USB driver support is provided for Windows 7 32/64, Windows 8 32/64, and Windows 10 operating systems. Unix and OS X systems do not need a special driver for USB. The P440 automatically appears as a serial device.

The API provides all the commands and capabilities required by a user to design a network tailored for operating multiple P440s as ranging radios or radar sensors.

To assist the user in demonstrating the performance of the P440, either as a ranging radio or as a radar sensor, Time Domain also provides PC-based Graphical User Interfaces (GUIs) which exercise all of the API commands and offer the following capabilities:

- They provide <u>programmers</u> with a visual example of a Host application which interfaces to the P440 through the API.
- They allow <u>users</u> to evaluate ranging, communications, networking, and localization performance.
- They allow <u>users</u> to evaluate the radar performance through use of a sample Motion Filter, sample Detection Processor, and a graphical display of raw and processed radar scans.
- They allow <u>system analysts</u> to visualize, collect, and log raw ranging and radar data such that it is possible to develop algorithms/strategies optimized for the chosen product application.
- They allow <u>users</u> to operate multiple P440s to form a network of self-localizing ranging radios.

Time Domain also provides sample C and MATLAB code for demonstrating the interface and performance of the hardware.

The objective of providing the GUIs, sample C and sample MATLAB code is to supply programmers with several example interfaces and implementations which the user may then replace or tailor with custom code optimized for their particular needs and applications.

This technology has been used in a wide variety of applications. For example, it has been used:

- To report safe distances between rail vehicles
- To allow robots to follow leaders at a safe distance
- To provide robots with location knowledge
- To guide drones as they fly
- To precisely locate vehicles in tunnels and mines
- To maintain safe distances between construction vehicles
- To measure the respiration rate of patients
- To locate and track people as they move through an area
- To precisely measure the length of long structures
- To precisely measure the location of specific features in buildings
- To track forklifts as they move through an area
- For various doctoral and post-doctoral research projects
- To teach university undergraduates about RF, radar, and signal processing

This document describes the P440 hardware and software. This discussion is subdivided into the following subsections.

> ***Section 2*** *P440 Software*
> ***Section 3*** *Hardware Block Diagram*
> ***Section 4*** *Electrical Interfaces*
> ***Section 5*** *Mechanical Interface*
> ***Section 6*** *Technical Specifications*
> ***Section 7*** *Broadspec Antenna*
> ***Section 8*** *Regulatory Compliance*
> ***Section 9*** *Import/Export Considerations*
> ***Section 10*** *Configuration and Ordering Information*

Additional information including all of the documents referenced in this section can be found on the web at www.timedomain.com. This includes: the API, software manuals, application notes, white papers, examples, published papers, sample C code, sample MATLAB code, and more.

2 P440 Software

The P440 software consists of six elements:

- Embedded software operating on the P440 module

- The Application Programming Interface (API) which defines the interface between the P440 and a Host processor

- GUIs provided to (1) illustrate operation of the P440 and (2) provide an analytical tool for characterizing performance

- Sample C and MATLAB code to assist the user in developing custom applications

- Network support to enable systems of P440s to range and communicate efficiently

- A Location Engine which calculates the position of the device

In addition, Time Domain is committed to periodically adding new features and capabilities through software upgrades.

2.1   P440 Embedded Software

The P440 is a microprocessor-based UWB platform. The onboard processor has three principal functions:

- It is responsible for providing supervisory control and monitoring of the UWB sub-system. The UWB sub-system consists of a digital baseband (implemented in an FPGA) and a custom mixed signal RF ASIC called FIFE (Fully Integrated Front End).

- It handles all communications with the user's Host processor (typically a PC or single-board computer). The format of these communications is defined by a set of three APIs, each tailored to a specific application. The user has a choice of communicating with the P440 over 5 different physical interfaces: Ethernet, USB, SPI, Serial, and CAN.

- When instructed to act as a network, the onboard processor:
    - o Assumes all responsibilities for scheduling communications and range requests
    - o Provides the Host with status update information
    - o Handles supervisory commands sent by the Host

  This increases the ranging update rate and significantly offloads the Host processor.

- When instructed to compute node locations, the onboard processor will monitor reported

ranges and use either a Kalman Filter-based algorithm or a Geometric solver to compute and report either the 2D or 3D location of the device. The location information includes not only the X, Y, and Z data but also the Variance (X, Y, Z) and Covariance (X, Y, Z) values. The onboard processor will automatically distribute this information (as well as configuration information) through the entire network. This behavior significantly offloads the Host processor.

For details on interfaces, refer to:

- *320-0287 Using the USB and Serial Interfaces*

2.2   Application Programming Interfaces (APIs)

There are three different APIs:

- Range measurement, network, location, and GPIO commands are defined in the document

  320-0313 P400 Series RangeNet API Specification

- Monostatic Radar commands are defined in the document

  320-0298 Monostatic Radar API Specification

- Bistatic radar and communications channel modeling commands are defined in the document

  330-0305 Channel Analysis Tool API Specification

While useful, this separation is artificial in that the embedded software in the P440 can handle all three APIs. If the embedded code in the P440 is updated, then all three APIs are updated as well. Furthermore, the user is free to develop applications that incorporate commands from any or all of these APIs. For example, this ability allows the user to create ranging measurement networks that incorporate bistatic and multistatic radar and also communicate data.

The high-level features of the APIs are discussed in **Section 2.4 – APIs and GUIs as Development Tools**.

2.3   Graphical User Interfaces (GUIs) and Sample Code

Mastering all of the commands in an API (or in this case, a set of three APIs) can be a time-consuming task, especially when the APIs have a rich command set. To accelerate this learning process, Time Domain provides three example Graphical User Interfaces (GUIs). These GUIs operate on a PC and exercise all of the API commands. They also display received data and allow the user to log all received data or API messages sent or received by the Host. Each GUI focuses on one particular API:

- **RangeNet** is used to demonstrate simple point-to-point ranging and communications under the control of a Host processor as well as operation as a fully self-localizing ranging network

under control of the P440. It also controls the GPIOs and configures the communications ports.

- **MRM RET** is used to demonstrate monostatic radar.

- **Channel Analysis Tool (CAT)** is used to demonstrate either (a) bistatic and multistatic radar or (b) communications channel propagation analysis.

In addition, Time Domain also provides sample C and sample MATLAB code for each application area. The sample C code enables embedded programmers to quickly interface to the P440. The sample MATLAB code enables system analysts to quickly construct experiments to investigate and evaluate performance. The sample code also includes parsers for extracting information from the logfiles.

The sample code includes the following:

Ranging and Network (RangeNet)

- *150-0117 – P400 Series RangeNet Sample C Applications*

- *150-0118 – P400 Series RangeNet Sample MATLAB Applications*

- *150-0103 – P400 Series Ranging Sample C Applications*

- *150-0104 – P400 Series Ranging Sample MATLAB Applications*

Monostatic Radar

- *150-0107 MRM Sample C Application*

- *150-0108 MRM Sample MATLAB Applications*

Channel Propagation Analysis

- *CATCIR Delivery Files*

Each of the GUIs is provided with a Quick Start Guide and a User Guide that illustrate operation of the equipment. Within 30 minutes of receiving the equipment, the user will be able to measure range, operate a network, operate as a monostatic radar, or capture bistatic radar scans and RF communications channel waveforms. A list of the Quick Start Guide and User Guide documentation is provided below:

- **Ranging and Network (RangeNet):**
  - *320-0314 P400 Series RangeNet Quick Start Guide*
  - *320-0320 P400 Series RangeNet User Guide*

- **Monostatic Radar:**
  - *320-0301 MRM Quick Start Guide*
  - *320-0300 MRM User Guide*

- **Bistatic / Multistatic Radar and Channel Analysis:**
  - *320-0304 CAT Quick Start Guide*
  - *320-0303 CAT User Guide*

2.4   APIs and GUIs as Development Tools

This section provides a high level summary of the APIs and discusses how the GUIs can be used as a development tool.

In general, the GUIs perform as one would expect. They allow the user to configure the P440s, initiate range and radar requests, move in and out of a network, compute locations, control the GPIOs, move to and from different sleep states, measure the P440 temperature, display status, hardware and software version numbers as well as other useful information. In addition, they allow the user to display and log collected data as well as all communications between the Host and the P440. The radar GUI also bandpasses the received data and provides motion filter and detection filter processing.

2.4.1   Ranging Measurement with RangeNet

The RangeNet API allows the user to configure the P440 and take range measurements. In fact, it supports three different forms of range measurements, all of which will be described in this section.

But the types of range measurements taken are less important than the technique used to take the underlying data. The P440 uses a bank of receivers to digitize the received signal such that it is possible to produce an image of the received waveform. This image is produced with a resolution of 61 ps, which is twice the Nyquist rate. (An example is shown in **Figure 2-1**.)
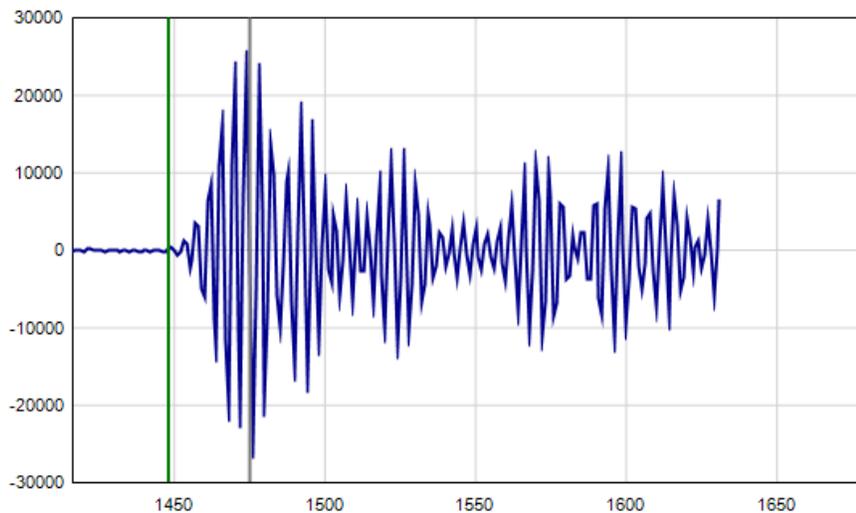
Fig. 2-1: A typical received waveform: signal magnitude (relative strength) vs time (increments of 61 ps)

This is a powerful capability for several reasons:

- Oversampling enables correlation processing, thereby producing reliable sub-centimeter range estimates.

- By analyzing the shape of the received waveform it is possible to determine importation characteristics of the channel such as (a) whether or not the signal is clear or non-line-of -

sight (NLOS), (b) determine if the signal is in compression, and (c) whether or not the signal is corrupted by multipath or Fresnel effects. This is illustrated in **Figure 2-2**.

- It is possible to measure the signal strength of the first arriving pulse as opposed to the strength of the largest multipath signal.

- It is possible to measure the background noise level. That, in conjunction with the signal strength measurement, allows the measurement of the received SNR.

- It is possible to characterize the received waveform and produce an error estimate of the range measurement estimate.
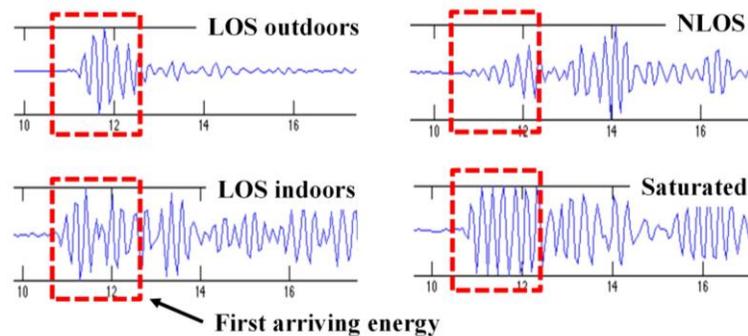

Fig. 2-2: Received waveforms captured at 61 ps intervals (2x Nyquist) in a variety of environments

This underlying capability allows the generation of the following three different types of range measurements:

Precision Range Measurements (PRM) are taken using the TW-TOF ranging technique. These readings typically have high accuracy and are provided with estimates of range error as well as flags that warn of possible errors. The user can use these range error estimates to drive a Kalman Filter. The flags can be used to disregard inaccurate readings.

Coarse Range Estimates (CRE) are analogous to RSSI (received signal strength indication) range estimates produced by continuous wave RF ranging systems in that they relate the strength of the received signal to range. They are different in two important ways. First, the signal strength reported is based on the strength of the first arriving energy and not on the strongest overall energy. This ensures that large signals produced by constructive multipath do not introduce false readings. Second, the signal strength reported is automatically calibrated based on the last successful Precision Range Measurement.

Echo Last Range (ELR) measurements are Precision Range Measurements which have been taken between two other radios in the system. In other words, any time a unit initiates a range request, it will broadcast the last range measurement it successfully completed. For example, if Unit A measures the distance between Unit A and Unit B, it will broadcast this range measurement to Units C, D, E, etc., whenever it next initiates a range measurement. This is an alternate way of automatically distributing range information through a system.

Finally, the P440 uses the API to make the range measurements, error flags, range error estimates, signal strength measurements, measurements of background noise, and waveform measurements available to the Host processor.

The RangeNet GUI exercises each of the API commands, thereby allowing the user to configure the unit and take range measurements. But the GUI adds an extra level of system software in that it will

allow the user to:

- Capture, display to the screen, and log waveforms to disk. **Figure 2-3** illustrates a representative waveform as displayed by the GUI.

- Request a single range measurement, a fixed number of measurements, or a continuous series of range measurements.

- Display the signal strength, noise, and SNR of the received signal.

- Display quality metrics that provide a warning if the reading is suspect.

- Calculate performance statistics. For example, if the user requests a finite number of ranges, the GUI will compute the range success rate, the average range, the standard deviation of the range measurements, the average SNR of the readings, and the standard deviation of the SNR. These statistics are valuable for determining the quality of service the user can expect. The system will also filter the received readings using the quality metrics and provide the same statistics.

- Determine if there are interference sources in the area.

- Recalibrate a given link such that the bias or offset inherent in a range measurement can be compensated.

- Allow the user to easily enter and transmit data.

- Allow the user to receive and display data.

- Log all messages exchanged between the Host and connected P440.

- Display range measurements taken between other units in the area for which the connected P440 is not a direct participant.

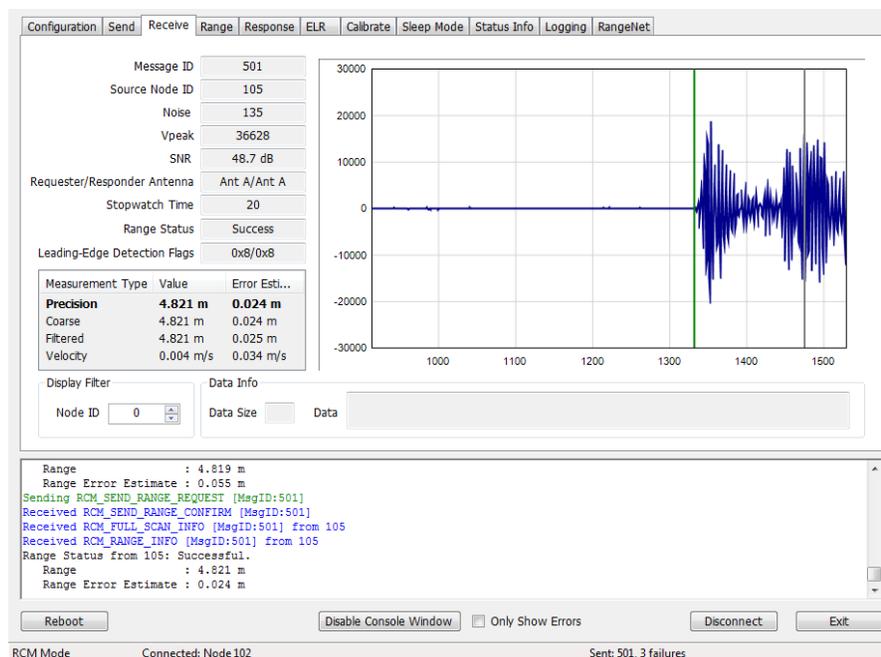- Produce a real time plot of range measurements in strip chart form.

Fig. 2-3: Typical waveform as displayed by the GUI

The ability to log data also allows the user to plot performance as a function of range. This is an excellent tool for evaluating signal propagation in a given area. For example, the information shown in **Figure 2-4** was collected as the distance between two units was increased. Basically, one unit was stationary while the second unit was slowly driven away. **Figure 2-4** shows a plot of the Signal, Noise, and SNR as a function of separation distance. In this figure one can observe several items of note:

- There is a Fresnel cancellation at 40, 60, and 100 meters.

- There is a Fresnel enhancement at ranges greater than 120 meters.

- The noise floor is constant; therefore there are no significant interference sources in the vicinity.
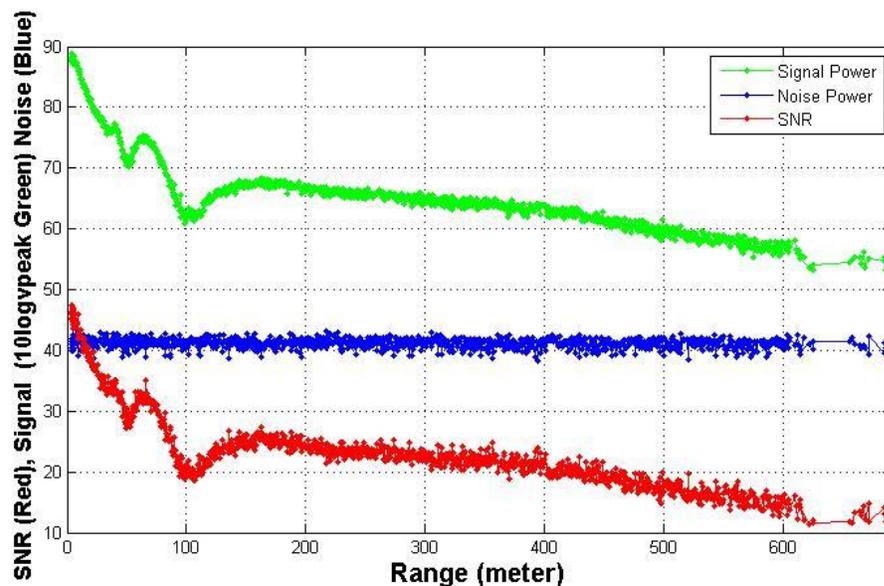
Fig. 2-4: Signal (green), Noise (blue), and SNR (red) of a link as function of separation distance. (Note the Fresnel cancellation and enhancement.)

2.4.2   Networking with RangeNet

Operating a system that consists of only two units is very simple. Operating with more than two units starts to introduce significant complexity. For example:

- The number of radios in the system may vary with time. Units that enter the system need to be discovered. Units that exit the system need to be removed from the network.

- There needs to be a way to prevent units from interfering with each other.

- Not all units need to behave the same way. Some units might initiate and respond to range measurement requests. Some might only initiate requests. Some might only respond. Some units might only communicate with a subset of the system.

The RangeNet API allows the user to define a network and to define the behavior of the radios in the system. Operation of the network is controlled by the P440. In particular, the P440 is responsible for scheduling range requests, maintaining all of the neighbors in a database, and passing data between the Host and the network. The Host computer function is thereby limited to monitoring and

supervision, thus significantly offloading its responsibilities.

The RangeNet API provides the user with tools to define and monitor the network. For example:

- A network can be defined using two different time-sharing protocols: ALOHA (randomized) or TDMA (Time Division Multiple Access).

- If the ALOHA protocol is used, then the average interval and the random variation of that interval can both be defined. The average interval can be manually or automatically throttled based on the number of units in the system. Radio behavior can be limited on a per unit basis such that some units initiate and respond to range requests, while others initiate-only or respond-only. In addition, some units can be instructed to limit their interactions to a subset of the network members. While most ALOHA networks have an efficiency of 18%, the efficiency of this ALOHA network is approximately 35%, making it equivalent to the performance of a Slotted ALOHA system.

- If the TDMA protocol is used, then the user can define a slot map that provides each radio with an indication of when and to whom and with what parameters it should communicate. An example slot map is shown below in **Figure 2-5**. The slot map shown is for a system of 4 nodes (100, 101, 102, and 103) in which 100 and 101 range to each of the other three and 102 ranges to 100 and 101.

Fig. 2-5: Representative RangeNet slot map

Maintaining system synchronization is the responsibility of the P440 processor and it does so with an accuracy of 1 μs.

- Because the P440 supports multiple communications channels, it is possible to operate either the ALOHA or TDMA protocol with a CDMA overlay.

- Because the P440 network schedules range requests, it avoids the overhead of Host to P440 communications and can therefore run at a higher ranging rate.

- The P440 network maintains a neighbor database. Besides noting all of the members of the network and their ranges, this database also contains a large body of statistics and other useful information. For example, the database includes SNR, approach velocity, effective ranging rate, and signal quality.

- The network also takes advantage of two features available with simple ranging applications, Echo Last Range (ELR) and Coarse Range Estimate (CRE), but which find special utility when used in a network. ELR takes advantage of the fact that all units can receive any transmission. Whenever a unit requests a range from a particular unit, it also transmits the last successful range measurement and node number of the corresponding unit. This information is effectively broadcast to all units in the area. This mechanism therefore distributes network range information throughout the units in the system.

  CREs take similar advantage of the broadcast nature of transmission. When a unit receives a transmission it will automatically generate a waveform scan and measure the strength of the first arriving energy. This yields a number similar to RSSI, but which is different in two ways. First, the strength measured is proportional to the strength of the first arriving energy and not, as in the case of RSSI, the peak strength of any signal. Second, while RSSI is rarely if ever calibrated, the CREs are calibrated based on the last time the unit successfully completed a TW-TOF range measurement with the target unit. While the accuracy of a CRE does not compare with the accuracy of the TW-TOF measurement, its level of accuracy is frequently good enough to be useful and it has the added benefit of expanding the network knowledge without incurring any cost.

While these are all powerful network tools, the complexity inherent in this richness can make it difficult to visualize and operate through just the API. The RangeNet GUI fills this gap. Not only does it allow the user to configure the system, but it also provides a means for easily maintaining different configurations, monitoring results, evaluating the performance of individual links in the network, and monitoring the neighbor database. For example, the RangeNet GUI allows the user to:

- Define all types of configuration information (including TDMA slot map, ranging configuration details, ALOHA setup information, neighbor database characteristics), download it to the P440, store that configuration to disk, and recover from disk any given configuration.

- Monitor the database at whatever update rate the user finds useful. **Figure 2-6** illustrates the database from a 4-node system. Note the extent and volume of statistics maintained in the database. (For details on the meaning of specific fields, refer to the RangeNet User Guide.)

- Send, receive, and display data.

- Display waveform scans associated with a particular link.
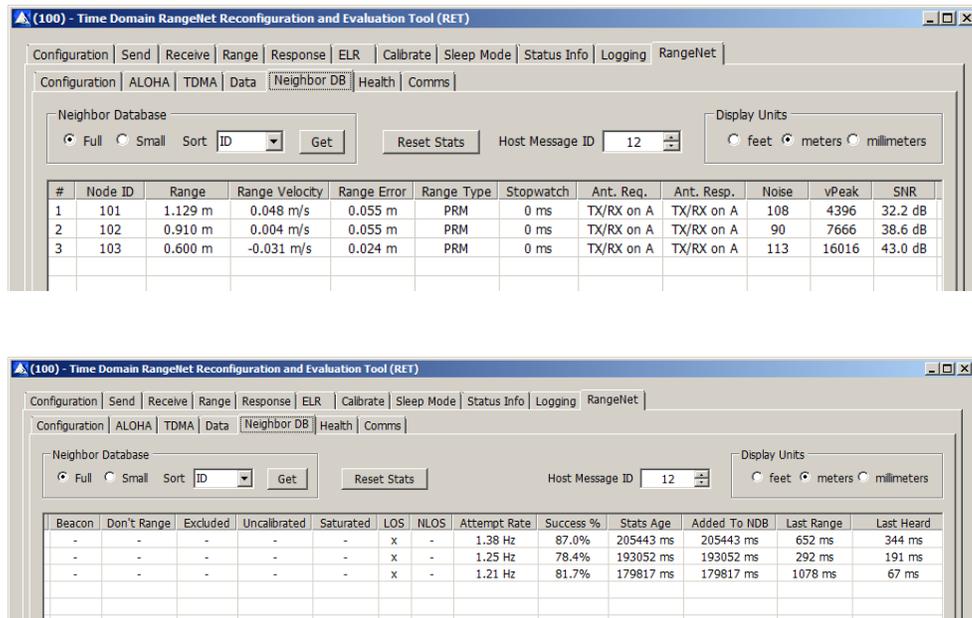
Fig. 2-6: Representative neighbor database of a 4-node system

2.4.3   Localization with RangeNet

The localization capability has been added as an upper layer to the RangeNet network.   The Location layer (or Location Engine) has the following characteristics:

- It operates on the P440 processor, thereby offloading the Host computer.
- It runs in conjunction with either the ALOHA or TDMA network.
- The location computation method is user-definable as either a 2D (XY) value or as a full 3D (XYZ) value.
- In 2D mode, the user can place the units at any Z elevation of interest, but the units are assumed to remain at these elevations.
- The user can select one of two methods for computing location. Option 1 uses a Kalman filter and a motion model. Option 2 uses a Geometric solver.   The Kalman option is best for applications where mobile units move quickly relative to the measurement rate and the Geometric option is better for cases where the mobiles are semi-stationary or moving slowly relative to the measurement rate. Both systems use Two-Way Time-of-Flight (TW-TOF) range measurements, Geometric Dilution of Precision (GDOP) calculations, and the user-measured Z elevation in the computation of location.
- The various tuning constants controlling the Location Engine and Kalman filter are user adjustable.
- (X, Y, Z) location Variance and Covariance values are also computed and reported.
- It takes advantage of the UWB network to transfer the location information throughout the network.   Because of this, the user can connect to any node and collect location information from every unit in the system.
- The RangeNet GUI incorporates an Autosurvey capability which uses TW-TOF measurements between Reference or Anchor nodes to automatically compute the location of References. Alternatively, the user can manually survey the Reference locations and enter that information into the system.

- The RangeNet GUI provides additional tools for configuring, controlling, monitoring, logging, and displaying results. See **Figures 2-7** and **2-8** for examples.
- The RangeNet GUI supports the addition of Waypoints, thereby simplifying the task of validating performance.
- Users are free to use the localizer or develop their own Host-based localization engine.

For details on how to interface with a P440 operating the Location Engine see the document *320-0313 P400 Series RangeNet API Specification*. For details on how to setup a system and calibrate units, or how to initialize, monitor, control, and display RangeNet operating as a localizer, see the document *320-0320 P400 Series RangeNet User Guide*.
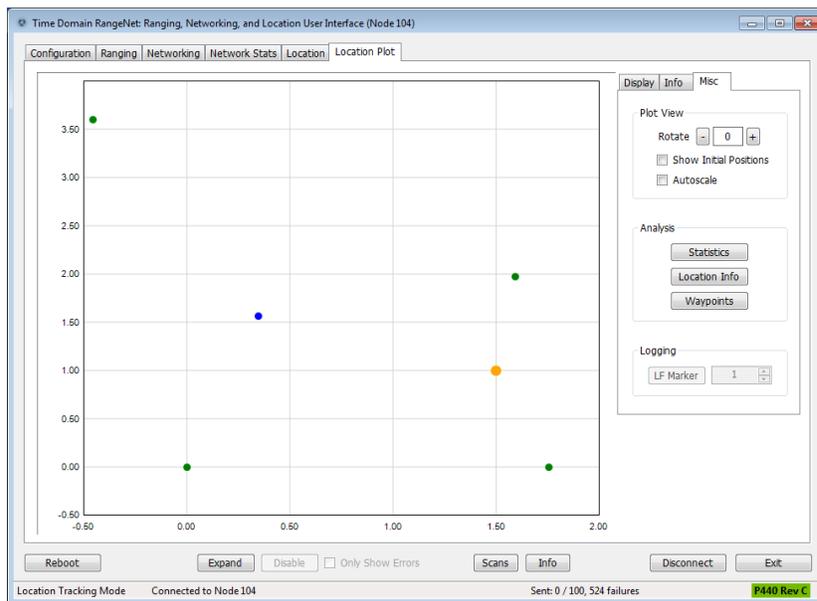
Fig. 2-7: RangeNet GUI display of P440 location as a function of time. Anchor (Reference) nodes shown in green, Mobile position in blue, and Waypoint(s) in orange.
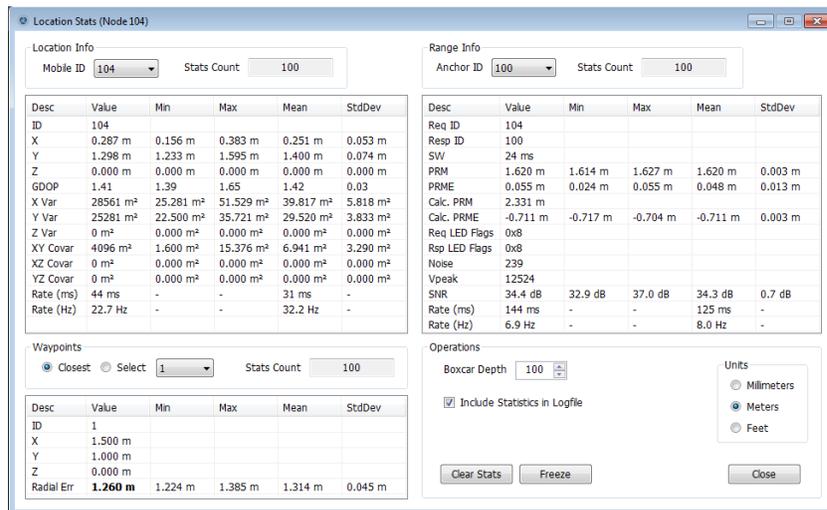
Fig. 2-8: Display of representative data computed and reported by the Location engine to RangeNet GUI

The overall objective of the Location Engine is to enable the user to quickly demonstrate the ability of UWB technology to provide location-based information for proof-of-concept projects, end products, or services. The Location Engine can be viewed either as a standalone capability or as a means to jumpstart the development of independent localization techniques.

If set-up properly, calibrated exactly, and operated in a benign environment, the system will locate Mobiles within 1 or 2 millimeters.

2.4.4   Monostatic Radar with MRM RET

The Monostatic Radar API allows the user to configure the radar parameters, transmit pulses, and measure radar returns. Configuration parameters include the following:

- Communication channel

- Transmit antenna configuration

- Transmit power

- The number of pulses that will be integrated to form a measurement

- The desired duration of the received RF scan

This final parameter warrants discussion. The user can define what portion of the radar return should be measured and reported. Furthermore, that portion does not need to be continuous or taken at the same integration. For example, it is possible to measure the radar return corresponding to the distance:

- From the antenna to 10 meters

- From 10 to 20 meters from the antenna

- From 10 to 20 meters, from 30 to 40 meters, and from 50 to 55 meters

- From 10 to 20 meters with integration of 256:1 and 40 to 50 meters with integration of 2048:1

The API also allows the user to define a rate at which the radar returns are generated. Furthermore, these scans are coherent both in radar fast time and in radar slow time. With the use of a Hilbert transform the radar returns can be post-processed to generate I and Q data streams.

The MRM RET GUI allows the user to:

- Define all of the configuration parameters, download them to the P440, and save and retrieve configurations from disk

- Initiate radar transmissions

- Collect, display, and log received data to disk

Furthermore, the MRM RET GUI has an associated Host-based task which will:

- Bandpass the received data

- Motion filter the data

- Detection filter the data

- Report detections as well as the first arriving detection

This filtering task provides basic motion filter functionality and allows the user to tune the filter constants. If desired, the user can also log all of this information with the raw data.

It should be noted that these filters are very general in nature and are not optimized for any particular application.   They are offered to the system developer as an example and the source code for the filters can be found in the MRM RET User Guide.

The MRM RET GUI and associated sample code allow the user to exercise the P440 in a number of important ways.   Consider the following three examples:

Example 1 - I/Q Doppler processing: MATLAB Sample Application #3 allows the user to exercise several radar modes. One mode of operation involves measuring the radar return from a moving target and then using I/Q Doppler processing to produce a plot of a Range vs. Doppler shift.   An example plot is shown in **Figure 2-9**.
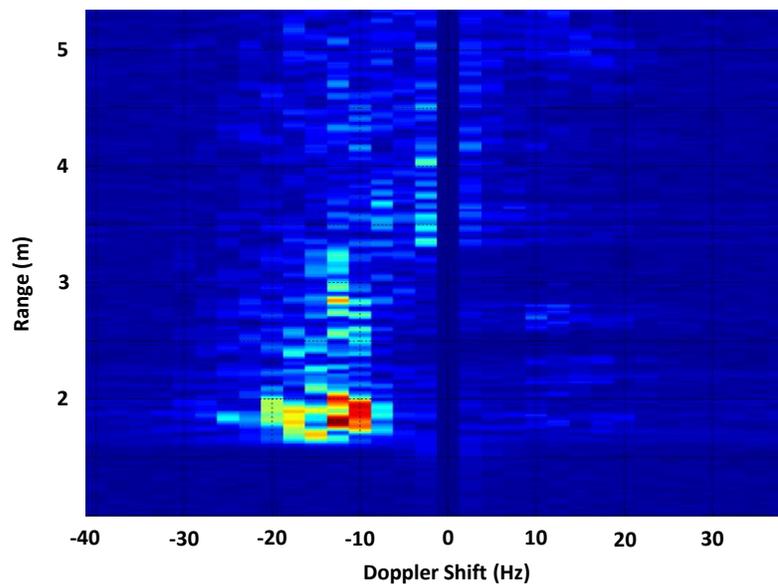
Fig. 2-9: Range vs Doppler shift from an approaching target

Example 2 - SAR imaging: Undergraduates at the University of Alabama in Huntsville (UAH) used the radar and a stepper motor to create a synthetic aperture radar (SAR) image of a collection of aluminum soda cans arranged to form the initials of the university. The results are shown in **Figure 2-10**:
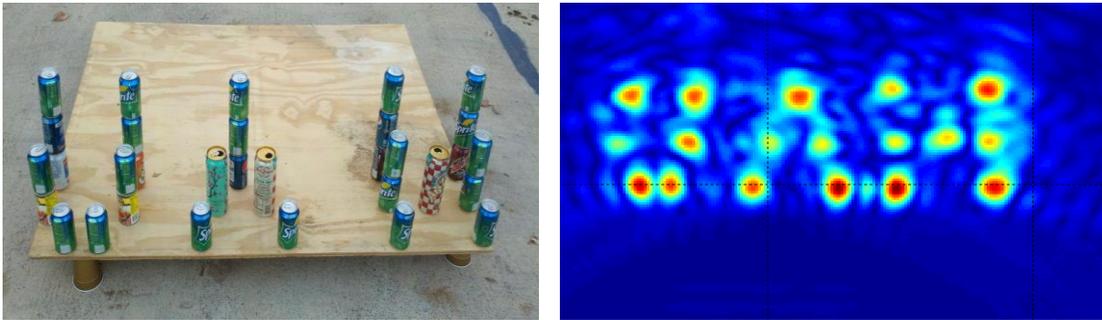
Fig. 2-10: SAR image of soda cans arranged to form the letters UAH

A copy of their project can be found on the Time Domain website at the following link:

http://www.timedomain.com/UAH%20Senior%20Project%20-%20Final%20Presentation%20V4.pdf

Example 3 – ISAR imaging: a team at the University of Texas (Austin) used the radar to build an inverse synthetic aperture radar (ISAR) image of windmill blades. These results are shown in **Figure 2-11**:
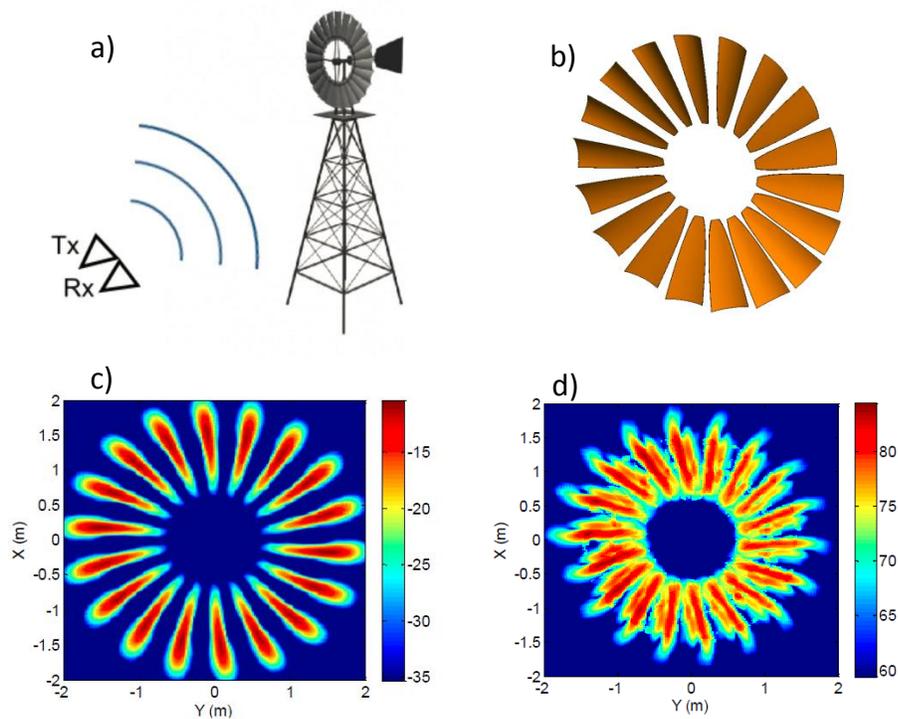
Fig. 2-11: ISAR image of rotating windmill blades – (a) test setup (b) windmill blades (c) blades as modelled (d) blades as imaged by the ISAR

A copy of their paper can be found on the Time Domain website at the following link:

http://www.timedomain.com/white-papers/Univ%20Texas%20Austin%20-%20SAR%20Imaging%20of%20a%20Windmill.pdf

2.4.5 Bistatic Radar and Propagation Tool using CAT (Channel Analysis Tool)

The CAT API and GUI allow the user to operate the P440 either as a bistatic radar or as a communications propagation tool.   This is easy because both applications are simply different ways of viewing the same thing. Consider the waveform shown in **Figure 2-12**. A communications engineer would look at this scan, point out the first arriving energy and comment that the multipath is due to other reflectors in the channel. He might then use this waveform to compute the delay spread of the channel or evaluate the impact of multipath on inter-symbol interference.   A radar engineer would look at this very same scan, point out the first arriving energy and comment that the multipath reflections are due to a mix of fixed clutter and targets operating in the area. He might then use Doppler processing or motion filters to separate the clutter from the targets.
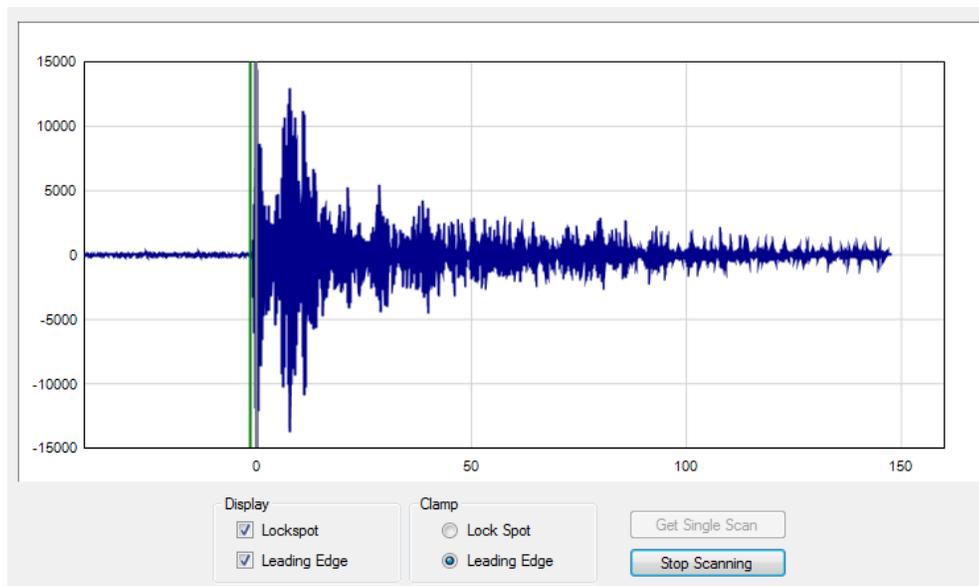
Fig. 2-12: Captured waveforms can be used by either communications or radar engineers

Given this, it is best to ignore the application differences and focus on the functions provided by the CAT API and GUI.

The API allows the user to transmit an arbitrary number of packets at a user-selectable communications channel, over the antenna of choice, at a selected integration rate, at a selected transmit power, and to receive packets from another unit. The receiver would then measure and report the part of the waveform which the user is interested in evaluating. For example, the user could request that the recorded waveform start 50 ns before the beginning of the pulse and end 145 ns after the pulse (as shown in **Figure 2-12**). Note that this waveform was taken with a 61 ps resolution. The CAT API also allows the user to specify other resolutions. For example, it is possible to take waveforms at 4 ps intervals. Shown below in **Figure 2-13** and **Figure 2-14** are two waveforms. The only difference between the two waveforms is that in one case the resolution was at 61 ps while the other was taken at 4 ps.
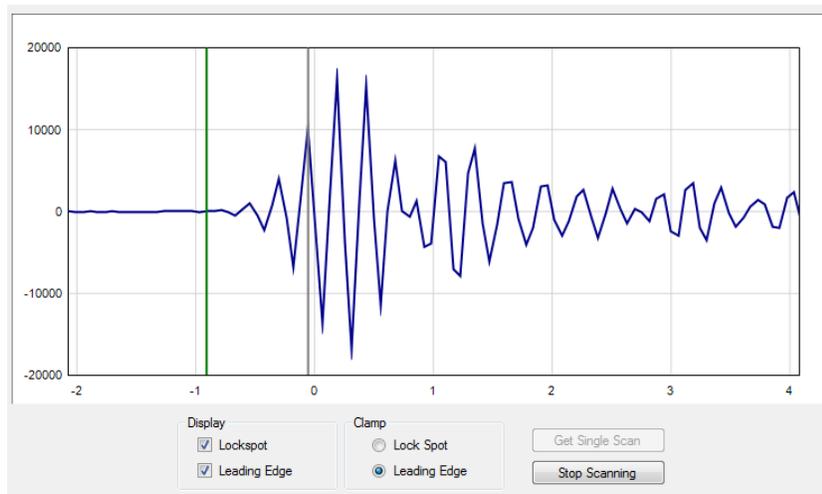
Fig. 2-13: Waveform scan captured at 61 ps resolution
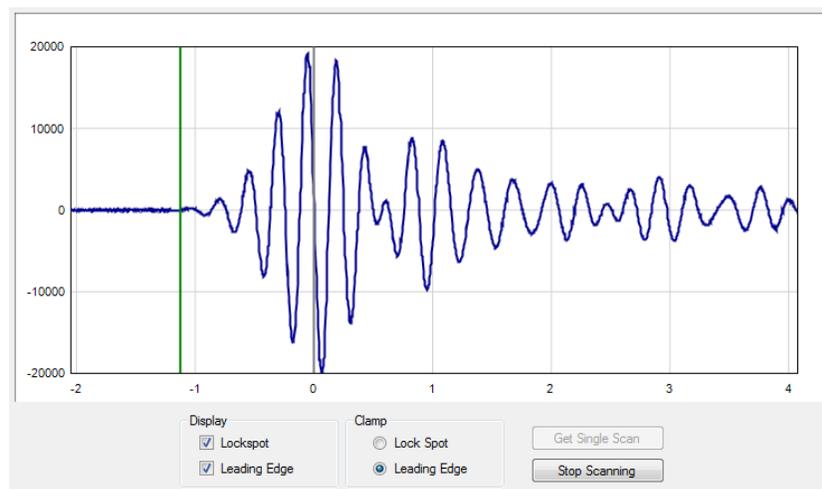
Fig. 2-14: Waveform scan captured at 4 ps resolution

Because transmissions will be received by any radio in the area, the system can have one transmitter and many receivers. Depending on your point of view, this is either a spatially distributed multistatic radar array or an excellent way to quickly collect data for an RF propagation model.

The API also has two final capabilities: (1) the user can send a fixed data pattern with a length of up to 1000 bytes, and (2) the P440 will report the SNR of the signal.

The GUI allows the user to configure the units, initiate transmission, and then collect, display, and log the data. The GUI will also report and log various statistics including packet error rate, bit error rate, packets sent, bits sent, and SNR (Eb/No).

2.5   Networking: RangeNet vs. RangeNet Lite

RangeNet Lite is a node-limited version of RangeNet and is intended to allow users to evaluate and test before considering licensing or purchasing the unrestricted version. RangeNet Lite is provided with all Ranging and Localization Development Kits, as well as the PulsON Lab and MegaLab packages. It is node-locked in that the Lite version will support all of the features of RangeNet as long as the system size is limited to 10 nodes or less.   More specifically, the first 10 nodes that join the system will operate normally.   They can join and leave the network normally, but the 11th unit and all subsequent units will not be recognized by the system.   These units will still operate but will likely interfere with the first 10 units and significantly degrade network performance for the first 10 units.

For information on upgrading from RangeNet Lite, please contact Time Domain directly at sales@timedomain.com.

2.6   Software Support

Time Domain is committed to maintaining full-featured software support for the hardware platforms. We believe that the success of UWB will be largely determined not by the capability of the hardware but by the richness of the software which drives the hardware. This includes improvements to both the embedded software (where the basic functionality of the UWB technology can be changed) and the API interface (where upper layers can be added).

For example, consider recent releases:

> 2010 – Ranging capability demonstrated with P400
>
> 2011 – Monostatic radar functionality added
>
> 2012 – Ranging performance enhanced
>
> 2013 – Channel analysis and bistatic / multistatic radar functionality added
>
> 2014 – RangeNet provides networking capability based on the ALOHA and
>
> TDMA protocol support added
>
> 2015 – RangeNet Lite added
>
> 2016 – ALOHA-based Location Engine added to RangeNet
>
> 2017 - Location Engine expanded to support both ALOHA and TDMA networking as well as localization using either a Kalman or a Geometric solver. Ranging accuracy improved.

It is Time Domain's intention to continue increasing the capability of UWB by adding new and significant software functionality.

3 Hardware Block Diagram

This section provides and discusses at a high level the P440 functional hardware block diagram shown in **Figure 3-1**. Additional detail on the various interfaces is provided in **Section 4**.
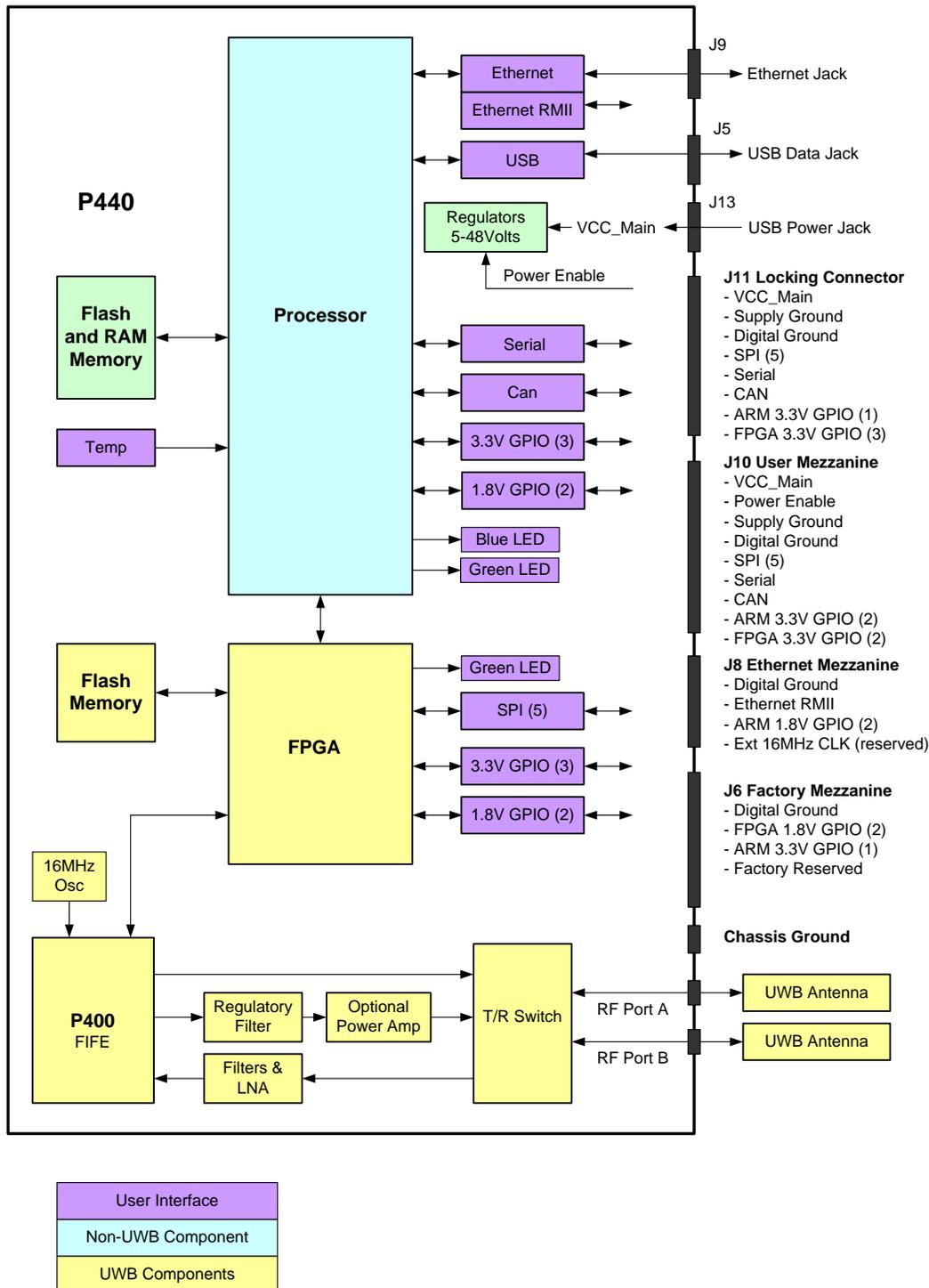
Fig. 3-1: P440 hardware functional block diagram

The P440 requires less than 2.5 Watts from a DC supply that provides any voltage between 5 and 48 volts. This power can be provided through Time Domain's standard external power supply, a battery, or a user-supplied power source. Indicator lights provide operating status information.

The user can interface to the P440 through Ethernet, USB, SPI, Serial, or CAN. Ten GPIO pins are available. If the SPI interface is not used, then these pins can be reassigned yielding an additional five GPIOs for a total of 15.

In addition, the user can request that the P440 report the board temperature.

A variety of means have been provided to physically interface to the P440. These means include USB connectors, an Ethernet RJ45 connector, a locking connector, and three mezzanine connectors. See **Section 4** for details. The mezzanine connectors are suitable for mating directly with a customer-provided board. Mating mezzanine connectors can be ordered with a variety of mated heights, thereby allowing the user to mount low profile devices on their carrier board underneath the P440. See **Section 5** for details.

Two SMA connectors are provided for antennas. Most ranging applications require only one antenna but there are cases where two can provide additional functionality. Most radar applications require two antennas.

The processor controls the UWB front end through a Digital Baseband FPGA interface. More specifically, the FPGA acts as a digital baseband to configure and control Time Domain's Fully Integrated Front End (FIFE) UWB ASIC such that it is possible to transmit and receive packets to measure range and to send/receive data.

There are four other items of note concerning the RF section:

- The FIFE Pulser is provided with a variable attenuator that allows the user to reduce the transmit power by approximately 30 dB below the regulatory limit. The exact amount will vary a bit from unit to unit.
- The T/R switch supports several configurations: Transmit/Receive on Port A, Transmit/Receive on Port B, Transmit on A and Receive on B, and Transmit on B and Receive on A.
- The Receive chain has a series of gain stages and band pass filters.
- An optional power amplifier can be provided to boost the transmitted signal power by up to 20 dB. Additional details are provided in **Section 4 – Electrical Interfaces**. This option is intended for experimentation and evaluation *only*. Using it for any other purpose will exceed regulatory limits in the US. Using the power amplifier in other countries, even for experimentation, may require special permission.

<u>Important:</u> The P400 FIFE ASIC uses flip chip construction and does not have a molded plastic cover. In this assembly technique the circuit side is attached to the substrate and the back of the silicon is visible to the user. It is also visible to bright lights. In some cases, some chips will photo-electrically convert light into electrons which then modify operation of the chip in random and unpleasant ways, making the P440 behave extremely erratically. The solution is simple, the P440 needs to be protected from bright sunlight with an opaque enclosure or, failing that, by covering the unit in electrician's tape or aluminum foil.

4 Electrical Interfaces

This section provides a detailed description of the various P440 electrical interfaces. A standard P440 has the following connections:

- Two antenna ports

- Communications connections via Low Speed Serial, USB 2.0, Ethernet, CAN, SPI

- Connections for up to 15 GPIO pins

- Connections for power (5 to 48V), Supply Ground, Digital Ground, and Chassis Ground

There are also five indicator LEDs, three on the board and two on the RJ45 jack.

The physical interface to Communications, GPIO, and Power are through a mix of connectors (see **Figure 4-1**) including the following:

- Three mezzanine connectors

- One locking connector

- One Ethernet RJ45 connector

- Two USB connectors (one power-only, one for data-only)

- One 0.1" DIP header

This arrangement provides the user with a great deal of flexibility.   However, some users may prefer a reduced set of interfaces. In this case, it is possible to no-load undesired components. Doing so saves a bit of cost and minimizes the board footprint. (Such configurations are possible but not standard and should only be considered for large volume applications of >1000 units. For further details, contact Time Domain directly at sales@timedomain.com.) For standard optional configurations see **Section 10 – Configuration and Ordering Information**.
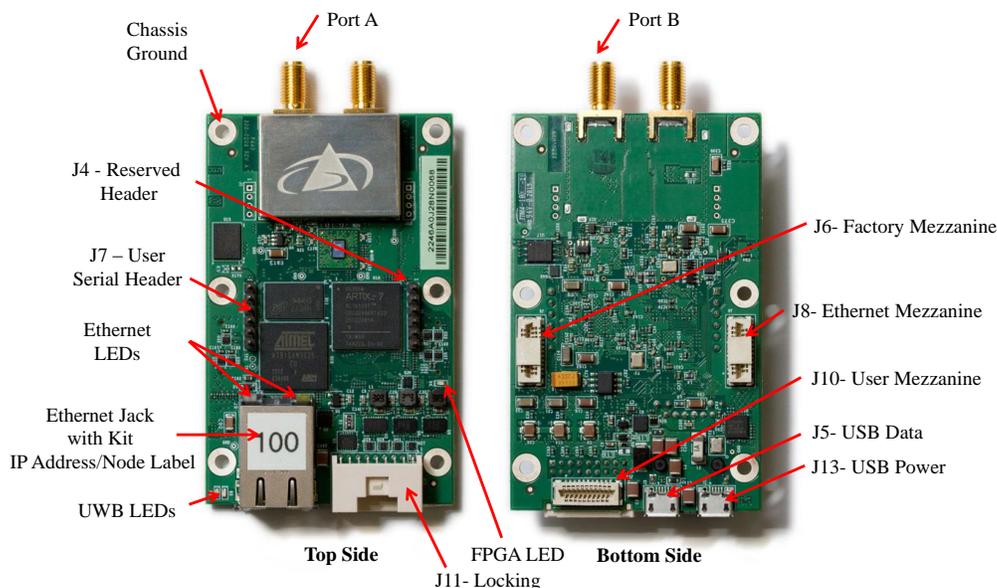
Fig. 4-1: Top and Bottom assembly drawing of the P440 highlighting key interfaces

Finally, the physical interface for the Chassis Ground is through the designated mounting screw hole shown in **Figure 4-1**. (For additional details, see **Section 4.3 – Powering and Grounding the Unit**).

4.1   Connecting to the P440

The user can connect to the P440 in a number of different ways. For example, it is possible to:

- Connect directly to the USB, Ethernet, or Serial connectors

- Build a special purpose cable and connect through the locking connector

- Mount the P440 on a carrier board and communicate through one or more mezzanine connectors

The following are examples of the electrical connections:

Option 1: USB.   The user can connect to the board via the USB Data jack (J5) and power the unit through the USB Power jack (J13).

Option 2: Ethernet.   The user can connect to the P440 via the Ethernet RJ45 jack and then power the unit through the USB Power jack (J13). Details on how the Ethernet IP address is assigned can be found in **Section 4.4.5 – Ethernet and IP Addressing**.

Option 3: Locking Connector. The user can use the locking connector to connect via SPI, User Serial, or CAN.   This connector also provides power and ground. Details on the pinouts for the locking connector and the part number for mating connector are provided in the following section.

Option 4: User Mezzanine Connector. The User Mezzanine connector supports SPI, User Serial, and CAN. It also provides power and ground. See the following section for details.

Option 5: Ethernet Mezzanine Connector. This connector provides power, ground, and all of the Ethernet MAC signal lines necessary to communicate with the unit. However this requires that the user provide an Ethernet PHY chip on a carrier board.

Several of these connection approaches offer access to the GPIO pins. See the following section for details.

4.2   Connector Pinouts

The pinouts of the various connectors are shown in **Figures 4-2, 4-3, 4-4, 4-5,** and **4-6.** The numbering convention that defines pin numbers with connector pins is shown on **Figures 4-7** and **4-8.**

All signal lines are provided with Electrostatic Discharge (ESD) protection (+/- 8 kV contact discharge and +/-15 kV air-gap discharge). The signal line voltage levels are 3.3 Vdc, 1.8 Vdc, or (in the case of CAN) are differential. These inputs are not tolerant to other voltages. Overdriving these lines with too large a voltage or requiring them to source too much current will cause damage to the P440. Please take care to avoid damage. Not only will this compromise or damage the performance of the system but this class of damage is not covered by warranty.

Some of the mezzanine connector pins are marked as "Reserved." The function of these pins may change with time. If the user intends to mount the P440 on a carrier board, then it is advisable to connect any pin marked "Reserved" to a landing point but to NOT connect the landing point to any other trace on the carrier board.

The part numbers of all of the connectors and their mates can be found in **Section 5 – Mechanicals.**

Finally, it may be useful to clarify the directions associated with the Serial transmit (TX) and receive (RX) lines. "User Serial TX" means transmitted by the P440 to the Host. "User Serial RX" means received by the P440 from the Host. All user serial lines operate at 3.3 V.

Pin	Name	Function
1	SPI_MOSI	SPI Master Out Slave In
2	SPI_INT	SPI interrupt
3	SPI_MISO	SPI Master In Slave Out
4	FPGA_GPIO_1_3.3V	FPGA General Purpose IO #1, 3.3VDC
5	Digital_Ground	Digital Ground
6	FPGA_GPIO_2_3.3V	FPGA General Purpose IO #2, 3.3VDC
7	SPI_CLK	SPI Clock
8	Digital_Ground	Digital Ground
9	SPI_CS	SPI Chip Select
10	User_Serial_TX	User serial transmit
11	ARM_GPIO_0_3.3V	ARM General Purpose IO #0, 3.3VDC
12	User_Serial_RX	User serial receive
13	Supply_Ground	Ground
14	Digital_Ground	Digital Ground
15	FPGA_GPIO_3_3.3V	FPGA General Purpose IO #3, 3.3VDC
16	CAN_HIGH	CAN differential high
17	VCC_Main	Input power
18	CAN_LOW	CAN differential low

Fig. 4-2: J11 - Locking connector

Pin	Name	Function
1	SPI_MOSI	SPI Master Out, Slave In
2	Digital_Ground	Digital Ground
3	SPI_MISO	SPI Master In, Slave Out
4	SPI_INT	SPI interrupt
5	Digital_Ground	Digital Ground
6	FPGA_GPIO_1_3.3V	FPGA General Purpose IO #1, 3.3VDC
7	SPI_CLK	SPI clock
8	FPGA_GPIO_2_3.3V	FPGA General Purpose IO #2, 3.3VDC
9	SPI_CS	SPI Chip Select
10	Digital_Ground	Digital Ground
11	ARM_GPIO_0_3.3V	ARM General Purpose IO #0, 3.3VDC
12	User_Serial_TX	User serial transmit
13	Digital_Ground	Digital Ground
14	User_Serial_Rx	User serial receive
15	ARM_GPIO_1_3.3V	ARM General Purpose IO #1, 3.3VDC
16	Digital_Ground	Digital Ground
17	Power_Enable_H	Signal line to enable/disable on-board regulators. This allows the user to turn power to the board on and off with a single digital control line. 0-2.1Vdc = off, 2.1Vdc to VCC_Main = on
18	CAN_HIGH	CAN differential high
19	Supply_Ground	Ground
20	CAN_LOW	CAN differential low
21	VCC_MAIN	Input power

Fig. 4-3: J10 – User Mezzanine connector

SPI users should take note that the SPI interrupt line is pin 4 on the User Mezzanine and pin 2 on the locking connector.

Pin	Name	Function
1	Digital_Ground	Digital Ground
2	E_Rx1	Ethernet Rx1
3	E_Rxer	Ethernet Rxer
4	E_TxEn	Ethernet TxEn
5	E_Tx0	Ethernet Tx0
6	Digital_Ground	Digital Ground
7	E_Tx1	Ethernet Tx1
8	E_CrsDv	Ethernet CrsDv
9	Digital_Ground	Digital Ground
10	E_TxCk	Ethernet TxCk
11	E_Rx0	Ethernet Rx0
12	Digital_Ground	Digital Ground
13	E_MDIO	Ethernet MDIO
14	E_MDC	Ethernet MDC
15	Digital_Ground	Digital Ground
16	Digital_Ground	Digital Ground
17	ARM_GPIO_0_1.8V	ARM General Purpose IO #0, 1.8VDC
18	ARM_GPIO_1_1.8V	ARM General Purpose IO #1, 1.8VDC
19	Digital_Ground	Digital Ground
20	Digital_Ground	Digital Ground
21	Ext_16MHz_In	Reserved

Fig. 4-4: J8 – Ethernet Mezzanine connector

Pin	Name	Function
1		Reserved
2		Reserved
3		Reserved
4		Reserved
5	Digital_Ground	Digital Ground
6	Digital_Ground	Digital Ground
7		Reserved
8		Reserved
9		Reserved
10		Reserved
11	Digital_Ground	Digital Ground
12	FPGA_GPIO_1_1.8V	FPGA General Purpose IO # 1, 1.8VDC
13		Reserved
14		Reserved
15		Reserved
16		Reserved
17		Reserved
18	FPGA_GPIO_0_1.8V	FPGA General Purpose IO #0, 1.8VDC
19		Reserved
20	ARM_GPIO_2_3.3V	ARM General Purpose IO #2, 3.3VDC
21	Digital_Ground	Digital Ground

Fig. 4-5: J6 – Factory Mezzanine connector

The Factory Mezzanine connector has a number of GPIO pins and grounds which the user is free to use. However the remaining lines are NOT available for use. All of these lines are active and are used by the factory to test the unit as it moves through production. This connector can be used by the customer but it is critical that the reserved pins should never be connected to any signal, ground, or power lines. This can result in extreme damage to the unit.

Pin	Name	Function
1	Digital_GND	Digital ground
2	No Connection	Reserved
3	No Connection	Reserved
4	User_Serial_RX	User serial receive
5	User_Serial_TX	User serial transmit
6	No Connection	Reserved

Fig. 4-6: J7 – User Serial 0.1" Header
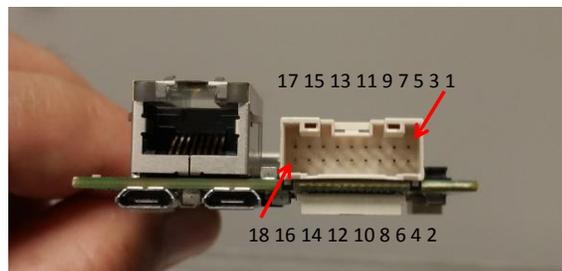
Fig. 4-7: J11 Locking connector pinouts
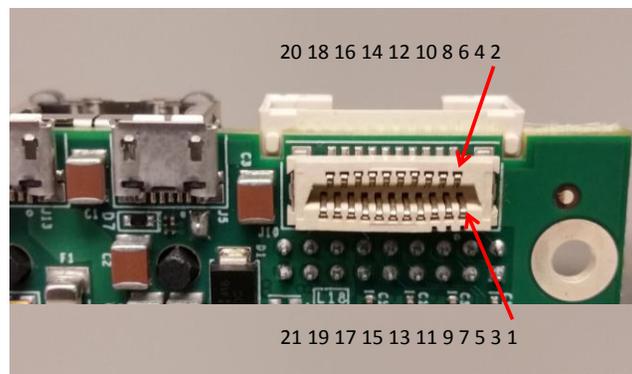
Fig. 4-8: J10 Mezzanine connector pinouts
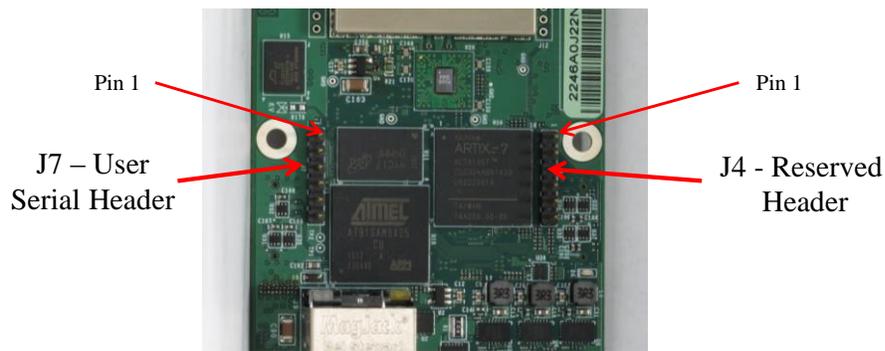
Fig. 4-9: User Serial pinouts

4.3   Powering and Grounding the Unit

When discussing power and ground, one normally thinks in terms of supply voltages and that is the objective of this section.

However, it is also important to note the RF shield and RF SMA connectors are both tied to the ground plane of the electronics. Consequently, if the P440 is installed in a metal housing then it is possible, if not likely, that the SMA connectors or RF shields will be in electrical contact with the enclosure. Depending on the application, this may or may not be an issue.

4.3.1 Powering the P440 through the USB Power Jack vs Locking & Mezzanine Connectors

The means by which the P440 is powered has evolved and improved as new versions of the P440 were built. As of this date four versions of the P440 exist: Rev A, Rev B, Rev C, and Rev D.   The Rev D boards are the current standard.   **Section 6.8 - P440 Version Differences** illustrates how the various versions can be identified.

4.3.1.1   Powering P440 Rev C and D units

The power input circuitry for P440 Rev C and D units, provided as either Kit Radios or Industrial Modules, has been modified such that they can be powered either through the USB Power jack (J13), the Locking connector (J11) or the User Mezzanine connector (J10) without fear of damage.

The P440 has an internal regulator which insures that the power it delivers is exceptionally clean. This regulator has a dropout point of 4.75 V. In theory, one could drive the unit from a 4.75 V supply. However, this 4.75 V must include any ripple or noise that may be present.   To be safe, the minimum specification for operation is specified as 5.0 V. However, margin is always preferred, and the prudent/paranoid designer should provide as much additional margin as is practical.

4.3.1.2   Powering P440 Rev A and Rev B units

P440 Rev A and Rev B units provided as Kit Radios are powered through the USB Power jack (J13). P440 Rev A and Rev B units provided as Industrial Modules can be powered either through the Locking connector (J11) or the User Mezzanine connector (J10).   Kit Radios cannot be powered through the Locking or User Mezzanine connectors and Industrial Modules cannot be powered though the USB Power jack.

This is a safety feature intended to insure that the user cannot accidentally connect power through the Locking connector at voltages as high as 48 V while simultaneously connecting power through the USB Power jack at 5 V. Allowing this to happen would put both the P440 and any computer connected to the USB Data jack at risk of severe damage.

4.3.2 Reverse Polarity Protection

The power input (VCC_Main) is reverse polarity-protected for all versions of the P440.

4.3.3 Two Means of Powering the P440

There are two techniques for supplying power to any P440.   One can connect and disconnect the power connectors or one can power the board continuously and use the Power_Enable_H pin on the J10 User Mezzanine connector to turn on and off the P440 main power regulators. This capability gives the user the opportunity to do a hard reboot of the board without needing to physically break a connection.

4.3.4 Supply_Ground, Fused_Ground and Digital_Ground

The grounding arrangement for the various versions of the P440 has changed as improvements were made to the reverse polarity protection. Grounding for the P440 Rev C and D (current version of the P440) units is different from the Rev A and B units. Rev C and D units use Supply_Ground and Digital_Ground, while Rev A and Rev B units use Fused_Ground and Digital_Ground. The differences are described in the following subsections.

4.3.4.1 Powering P440 Rev C and Rev D Modules

The reverse polarity protection has been greatly improved such that it is now much more difficult to destroy the board and any connected electronics by accidentally reversing the power connection. However, this improvement comes with one very important limitation in that the user *should not* connect Supply_Ground to Digital Ground. Doing so will bypass the protection. This is illustrated in **Figure 4-10.** In this figure Supply_Ground is shown in black, Digital_Ground is green, and +48 V is red.
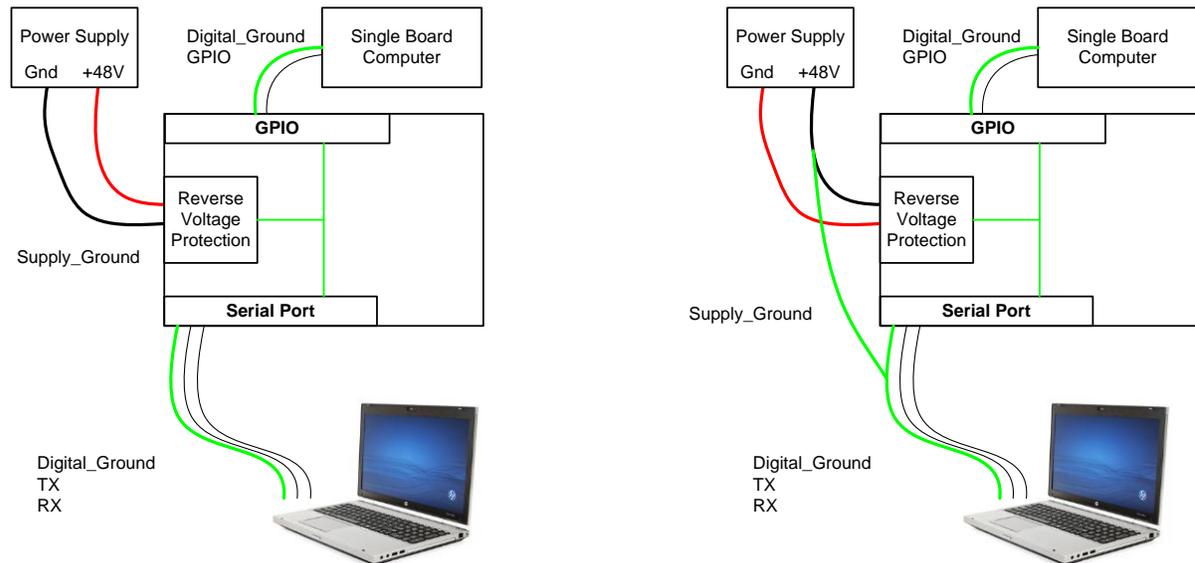
Fig. 4-10: Properly connected configuration (left), dangerous configuration (right)

The configuration shown on the left side of the **Figure 4-10** is safe. Even if the power supply is accidentally reversed, the Reverse Protection Block will protect the P440 as well as the connected laptop and single board computer.

The configuration shown on the right is not safe. Once Digital_Ground is connected to Supply_Ground, the Reverse Voltage Protection circuit is bypassed. If power is connected backwards at the supply, then the P440, laptop, and single board computer will be subjected to a large reverse voltage and all three will likely be destroyed.

There is one exception to the rule for not connecting Supply_Ground and Digital_Ground. If the P440 is powered through a mezzanine connector, then this restriction can be loosened. While it is still generally wise to refrain from connecting the two grounds, the board supplying the power may have been designed such that a reverse voltage situation cannot occur. If that is the case, then the designer may wish to connect the Supply_Ground to some, or perhaps all, of the Digital_Grounds. This would certainly improve grounding to the P440. But the designer should also balance this benefit against the risk of introducing ground loops.

4.3.4.2   Powering P440 Rev A and Rev B Modules

Connecting power to the board is relatively straightforward, but there is subtlety associated with the ground. The subtlety is associated with the difference between Fused_Ground and Digital_ Ground. As a general rule, it is best to connect to the Fused_Ground and avoid the Digital_Ground. This is not a concern for developers who will typically interface to the P440 using either the Ethernet or the USB connectors and power the unit through the USB Power jack.   It is also not a concern when the P440 is integrated into a final product through either the Locking Connector or the User Mezzanine connector.

It might be an issue if the user intends to connect to either the Ethernet Mezzanine connector or GPIO pins on the Factory Mezzanine connector. Normally the Fused_Ground is the preferred connection, but there are some cases in which it might be better to connect to the Digital_Ground. Customers intending to make use of these connections should contact the factory and discuss the issue in more detail.

4.3.5 Chassis Ground

The P440 is provided with a chassis ground. Each of the six mounting holes is copper plated on the top, bottom, and inside of the hole.   The mounting holes are not covered with silk screen. These holes are not connected to any ground planes or signals of any sort. The one exception to this rule is connected to Digital_Ground through the parallel combination of a 0.01uF capacitor and 1.0 MOhm resistor. This hole is Chassis Ground and the location of this hole is shown in **Figure 4-1.**

4.3.6 P440 Power Requirements

When operating continuously, a standard P440 requires approximately 2 watts. However, two other factors need to be considered. First the power consumption of electronics will vary with temperature. Second, the efficiency of the regulators declines with increasing input voltage. Basically, the regulators have been designed for optimum efficiency when operated at 5 volts.

Figure 4-11 indicates how the power consumed from a 5 volt supply changes with temperature for two different P440s. The temperatures shown were measured by the onboard temperature sensor. Note that the units require a bit more power when operated as a receiver than as a transmitter.   These results are typical.
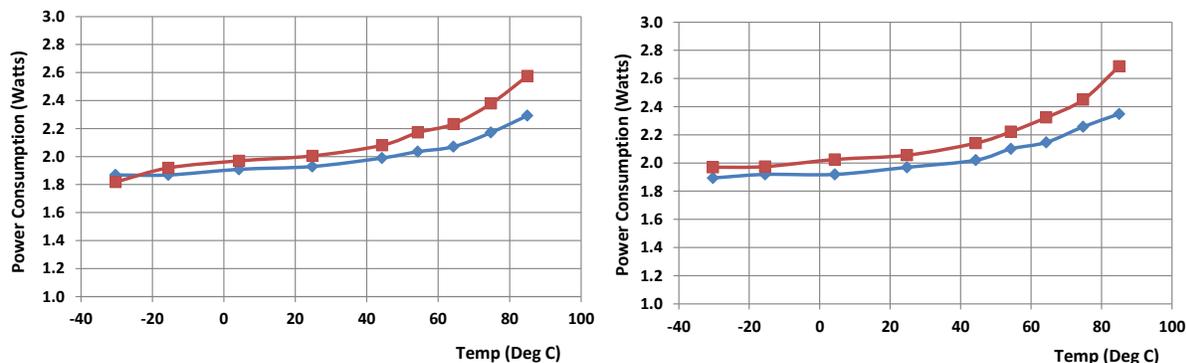
Fig. 4-11: Power Consumption as a function of board temperature for two representative P440s (red and blue) when operated as a transmitter (left) and as a receiver (right)

Figure 4-12 indicates how the efficiency of the onboard regulators changes with input voltage.   This data was measured while the P440 was transmitting and the onboard temperature sensor indicated a temperature of 37°C.

Supply (Volts)	Current (ma)	Power Consumption (Watts)	Power increase due to loss in efficiency
5.06	395	1.999	100%
5.95	337	2.005	100%
7.02	287	2.015	101%
8.04	253	2.034	102%
9.07	225	2.041	102%
10.04	205	2.058	103%
12.16	171	2.079	104%
14.07	150	2.111	106%
16.04	134	2.149	108%
18.03	121	2.182	109%
20.07	111	2.228	111%
22.09	102	2.253	113%
24.01	95	2.281	114%
26.05	89	2.318	116%
28.07	84	2.358	118%
30.06	80	2.405	120%
32.15	76	2.443	122%
34.12	73	2.491	125%
36.05	70	2.524	126%
38.07	68	2.589	130%
40.08	66	2.645	132%
42.03	64	2.690	135%
44.07	62	2.732	137%
46.08	61	2.811	141%
48.03	60	2.882	144%

Fig. 4-12: Increase in P440 power consumption with increased supply voltage

When selecting a power supply to drive the P440, the system designer should take both of these factors into consideration and apply a safety margin. For example, a P440 which is intended to operate at 5 volts and at a maximum board temperature of 85°C should be provided with at least 2.8 watts. If the same system was operated at 48 volts and 85°C, then the P440 should be provided with at least 144% more power or 4.032 watts. These values do not include any additional safety margin which the application might require.

The P440 also has an idle state during which it is neither transmitting nor receiving. In this idle state the power consumption is reduced by approximately 30%.

4.4 Host to P440 Interface Options

The P440 supports five different Host interfaces: USB, Serial, SPI, Ethernet, and CAN. This wide choice of interfaces provides the user with the freedom to experiment with and to optimize the means by which the overall system (P440 plus the user Host) communicates for their specific application. The characteristics of these interfaces are summarized below. For information on pin assignments see **Section 4.2 – Connector Pinouts.**

The protocol used to communicate with the P440 is fully defined in the various Time Domain API Specifications, various C and MATLAB examples, and in the document *320-0287 Using the USB and Serial Interfaces*. All of these resources are provided on the delivery disks and are also available on the Time Domain website, www.timedomain.com.

4.4.1 USB 2.0 High Speed Device

The P440 supports USB 2.0 High Speed Device connection through the USB Data microUSB jack (J5). When connecting through J5 it is important to remember that this jack only provides the data communications lines to the P440. To power the board, the user should apply power to the board either through the USB Power microUSB jack (J13), through the locking connector (J11) or through pin 21 on the User Mezzanine connector.

The maximum data rate for the USB is 480 Mbps. However, the maximum effective throughput will be greatly limited by many factors, including the speed of the Host computer, the specific implementation of the USB driver, processing overhead at the P440, and processor overhead at the Host computer.

While USB is very convenient to use in a laboratory or testing environment, we do not recommend it for use in deployed final products that require 100% availability. Instead we recommend Ethernet, Serial, SPI, or CAN because these protocols have been designed for high availability.   The USB protocol is excellent for occasional connection, but we have found it to be inconsistent if used continuously.   For example, there are times when the USB may drop off or fail to be recognized. When this happens, the unit and/or Host need to be rebooted and/or powered off and on.

4.4.2 User Serial

The User Serial interface is RS-232 Universal Asynchronous Receiver/Transmitter (UART) Serial operating at 3.3V TTL logic levels. The maximum speed of the interface is 115.2 kbps. Lower rates of 9.6, 19.2, 38.4, and 57.6 kbps are also supported. The default rate is 115.2 kbps.

However, the maximum rate is largely a function of the ability of the system to drive the cable capacitance. If a shorter cable is used or if the user provides an external line driver, then the communications rate can be increased by factors of 2 up to 921.6 kbps. Operation at these higher ranges is also limited by the serial interface circuit on the user-provided Host computer. The maximum length of cable must be determined empirically.   Time Domain has found that a cable length of 1 foot (30 cm) will support the 460.8 kbps rate quite reliably.

User Serial is provided on the Locking connector (J11), the User Mezzanine connector (J10), and the User Header (J7).

The Serial interface uses 3.3 volt logic. Do not connect 5 volt serial cables to the P440. In fact, do not connect any serial cables that operate at greater than 3.3 volts.   The increased voltage will physically damage the P440.

While most users will connect to the serial port through either J11 or J10, doing so requires the construction of a dedicated cable or interface. To use the serial interface, the user can connect directly to J7 using a standard cable available from a number of sources including the following:

- FTDI (part number TTL-232R-3v3) or
- Digikey (part number 768-1015-ND www.digikey.com).

4.4.3   SPI

The SPI interface is designed to operate at a maximum clock rate of 16.0 MHz with signals operating at 3.3V TTL levels. The actual throughput of the link is limited by the various communications overheads. However, transfer rates of 6-7 Mbps have been achieved using an un-optimized system.

The SPI interface allows the user to control the P440 with a co-located single board computer. Since the operating speed of the link is subject to noise and line capacitance, the length of the SPI wiring should be kept as short as possible. When operating the SPI interface at a maximum rate of 16 MHz, the cable length should be no longer than a few inches (10-15 cm).   The exact length needs to be confirmed empirically. If, for a given length of cable, the link experiences communications problems, then the user should reduce the SPI clock rate.

The SPI port consists of five signals. Four of these are the typical SPI signals: CLK, CSn, MOSI, and MISO, each with a 100k pull-up resistor to 3.3 V. The fifth signal (INT) is active-high and is used to indicate that data exists in the slave output FIFO. The INT signal does not have a pull-up resistor and is not driven during initial power-up. The signals are illustrated in **Figure 4-13**. The SPI slave RX and TX FIFOs are 4k x 8.
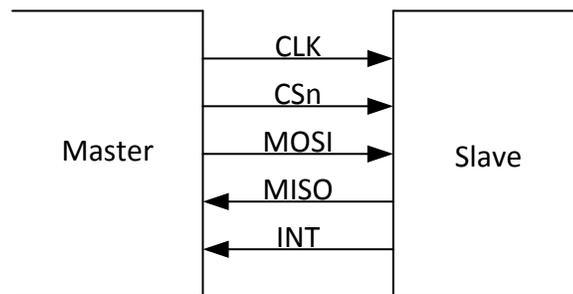
Fig. 4-13: SPI interconnect signals

The SPI port uses 8-bit bytes sent MSb first. The CLK idle state is high. The data is propagated on the falling-edge (leading-edge) of clock and sampled on the rising-edge (trailing-edge) of clock as shown below in **Figure 4-14**:

P440 Data Sheet / User Guide
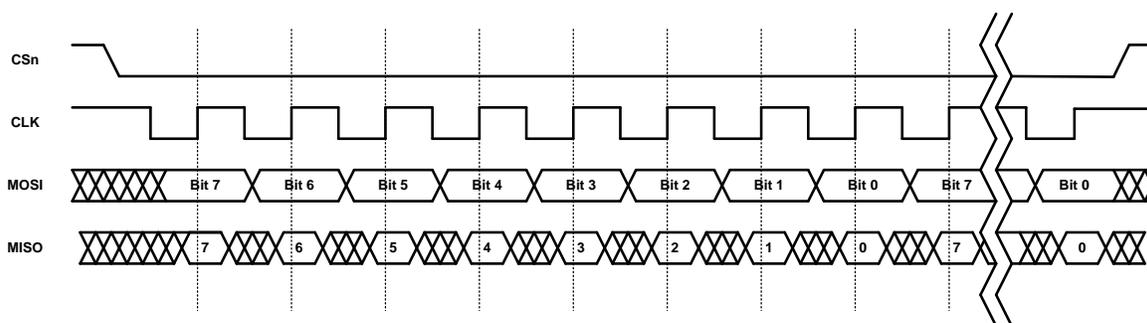
Fig. 4-14: Signaling timing diagram

The master drives the SPI chip-select low (CSn in above figure) and shifts an 8-bit command, possibly followed by data. The first bit (MSb) of a command is always set. If the second bit is set, then it is a read command, otherwise it is a write command. The commands are listed below in **Figure 4-15**. The chip-select must stay active-low for the entire transaction, which is required to be on 8-bit boundaries. This and other timing diagrams are shown in **Figure 4-16.** Timing constraints are shown in **Figure 4-17.**

Command	Function	Command Format	Response Format
0x80	Write to slave input FIFO	Command followed by data	N/A
0xC0	Read from slave output FIFO	Command	Slave output FIFO data
0xC2	Read slave output FIFO byte count	Command	Two bytes: MSB followed by LSB

Fig. 4-15: SPI command structure
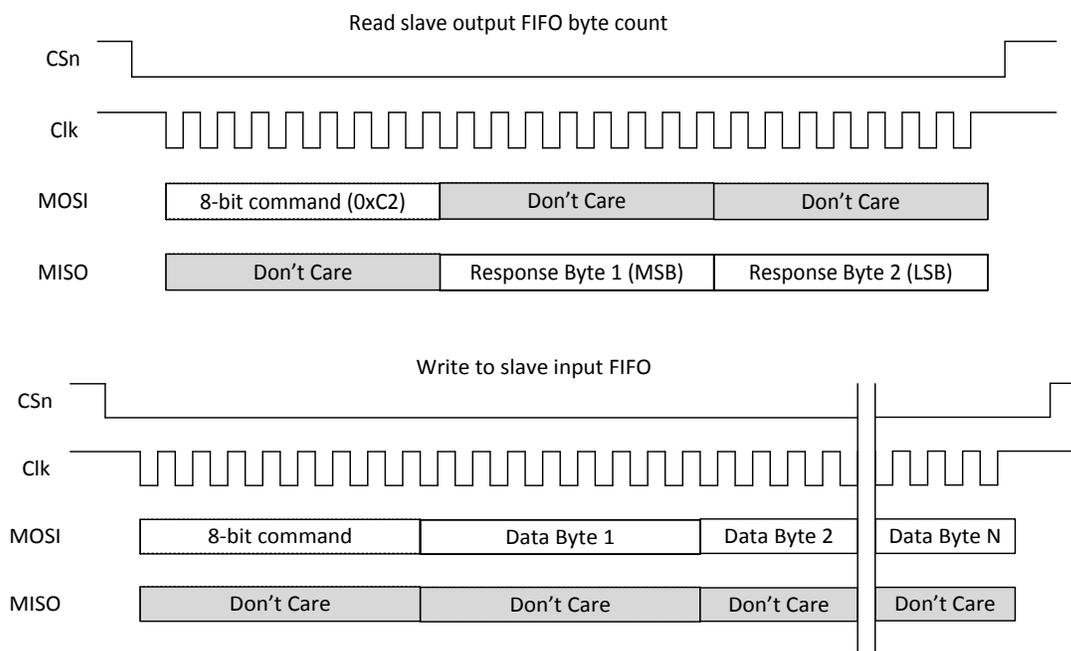
Fig. 4-16: Timing diagrams
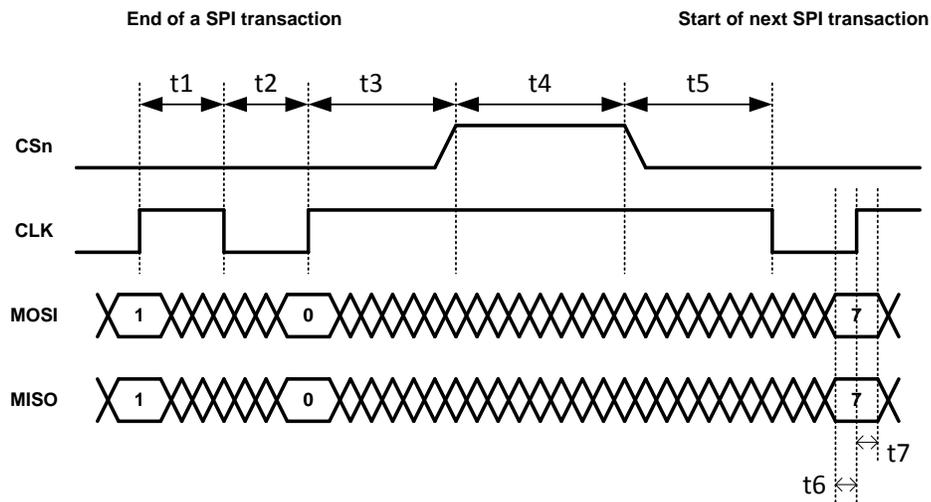
Timing	Function	Minimum
t1	CLK high to CLK low (high pulse)	30 ns
t2	CLK low to CLK high (low pulse)	30 ns
t3	CLK rising-edge to CSn rising-edge (inactive)	50 ns
t4	CSn rising-edge (inactive) to CSn falling-edge (active) or time between transactions	60 ns
t5	CSn falling-edge (active) to CLK falling-edge	50 ns
t6	Data setup to CLK rising-edge	12 ns
t7	Data hold from CLK rising-edge	12 ns

Fig. 4-17: Timing constraints

4.4.4   Ethernet and IP Addressing

Ethernet 10/100 is provided either through the standard Ethernet RJ45 Jack or as Ethernet RMII signal lines through the Ethernet Mezzanine Connector (J8). As such, the RMII signals cannot be interfaced to directly. The user must provide a carrier board and an Ethernet PHY chip. The PHY chip should be configured for Address 1.

The communications rate through this interface is limited not only by the Ethernet 10/100 protocol but also by the processing capability of the connected computer and various system overheads. For example, when transferring radar scans, the typical maximum transfer rate using a low grade laptop PC is approximately 2 Mbps. This transfer rate can be increased by a factor of four by using a faster computer and by running C code unencumbered with displays and other user interface features. For details, see the UWB radar sample C application, *150-0107 MRM Sample C Application*. This document can be found on the Time Domain website or on your release disk.

The IP address of a unit is assigned in one of two ways. If the P440 came as part of a Development Kit or a PulsON Lab then the IP addresses will be set at the factory to 192.168.1.x, where "x" is indicated on a label mounted on the P440's RJ45 jack. If the P440 was ordered as an "Industrial Module" then the IP address is normally set to 192.168.1.100. The RangeNet GUI gives the user the ability to change the IP address or to select the Dynamic Host Configuration Protocol (DHCP). Upon special request and in conjunction with volume orders, Industrial Modules can alternatively be shipped using DHCP.

As a side note, the Node ID of the P440 is set in a similar fashion. If the P440 came as part of a Kit then the Node ID will likewise be set to "x." If the P440 came as an Industrial Module, then the Node ID is set at the factory and can be determined through the API or any of the GUIs provided with the system. When using a GUI, the Serial Number shown on the Status Info Tab will be identical in value to the Node ID. However, the Status Info Tab shows the value in hexadecimal while the Node ID is shown in decimal.

Instructions on how to connect to the P440 via Ethernet or change the IP address and Node ID are provided in the following documents: *320-0328 Connecting to P440 with Ethernet* and *320-0320 P4xx RangeNet User Guide* (Appendix A).

4.4.5   CAN

The CAN interface is provided with a TI SN65HVD231 CAN line driver. That driver provides a 5 volt differential signal. For additional details on the driver, a link is provided to the TI part. The maximum data rate is 1 Mbps. http://www.ti.com/lit/ds/symlink/sn65hvd231.pdf

Time Domain's application note *320-0326 CAN Interface Application Note* provides additional information on the software interface. This document is available on the Time Domain website.

4.4.6   Detection of Failures

When the P440 is powered, it will boot and execute a series of self-diagnostic checks (Built-In Test or BIT). This process takes approximately 10 seconds. At the end of this process the unit will respond to commands issued by the Host. If the unit has failed to boot, then there will be no communications. If the unit has failed self-diagnostics, it will set the "BIT Results" parameter to a non-zero number and attempt to function normally. "Attempting" to function normally does not guarantee that the unit will actually function properly. Therefore, it is a good practice for the Host computer to initiate communications with the P440 by first checking the BIT Results. (This is accomplished with the Status Info Message. See the API for details.) If the returned parameter is not zero, the unit should be power-cycled.

For users operating the equipment for long periods of time, it is worth considering periodically checking BIT results. There are two ways to run BIT. First, the user can reboot the radio either by dropping power or by executing the reboot command through the API. A full reboot will take the unit out of commission for about 10 seconds. Second, the user can issue a BIT request command through the API. This will take the unit off line for less than 1 second after which the unit will continue operation as before. In other words, if the unit was in Network Mode and actively computing the location of a Mobile when the BIT request command was executed, then on completion of the BIT it would continue to operate as before.

4.5 GPIO

The P440 has fifteen user-definable general purpose input/output (GPIO) pins. Most of these pins operate on 3.3 Vdc but there are several that operate at 1.8 Vdc. Approximately half come from the ARM processor and the remaining ones are connected to the FPGA. These pins can be defined as inputs, outputs, or as having a special function. The SPI pins are special function pins. If the user chooses not to use the SPI interface, then the SPI pins can be reallocated for general use. The state and direction of these pins are controlled through the software API.

GPIO output pins can be used to source 1mA of current per pin. Do not exceed this limit. Exceeding this limit will damage the P440.

The GPIO pins are not associated with a specific connector but are instead distributed through the various connectors. Some GPIO pins are available from multiple connectors. **Figure 4-18** lists the various GPIO pins and their associated connector and pin number.

For information on how the GPIOs operate, please see *320-0320 P400 Series RangeNet User Guide* or *320-0313 P400 Series RangeNet API Specification*. Pins can (a) be used as inputs and outputs, (b) operate as SPI pins, and (c) support special functions, such as indicating when Slot Zero in a TDMA signal has occurred or driving counters.

J11 - Locking

1	SPI_MOSI
2	SPI_INT
3	SPI_MISO
7	SPI_CLK
9	SPI_CS
4	FPGA_GPIO_1_3.3V
6	FPGA_GPIO_2_3.3V
11	ARM_GPIO_0_3.3V
15	FPGA_GPIO_3_3.3V

J10 - User Mezzanine

1	SPI_MOSI
3	SPI_MISO
4	SPI_INT
6	FPGA_GPIO_1_3.3V
7	SPI_CLK
8	FPGA_GPIO_2_3.3V
9	SPI_CS
11	ARM_GPIO_0_3.3V
15	ARM_GPIO_1_3.3V

J8 - Ethernet Mezzanine

17	ARM_GPIO_0_1.8V
18	ARM_GPIO_1_1.8V

J6 - Factory Mezzanine

12	FPGA_GPIO_1_1.8V
18	FPGA_GPIO_0_1.8V
20	ARM_GPIO_2_3.3V

Fig. 4-18: GPIO and associated connector and pin locations

4.6 Antenna Ports

The P440 has two antenna ports, designated Port A and Port B. The connector used on each port is a standard polarity female SMA connector (Digi-Key part number J801-ND). The two ports enable single and dual antenna modes of operation.

An RF transfer switch on the P440 controls how the RF electronics are connected to the SMA connector. Normal operation can be defined as:

1) Transmit/Receive on Port A

2) Transmit on A, Receive on B

3) Transmit/Receive on Port B

4) Transmit on B, Receive on A

RF energy generated by the UWB FIFE chip for radiation from the antenna will travel through the RF transfer switch on its way to the antenna. In doing so, some of the energy will leak through the transfer switch directly into the receiver. In fact, energy received on the transmit antenna will also leak through the transfer switch directly into the receiver. Normally this is not an issue, but the user is advised that the isolation of the transfer switch is approximately 20 dB.

When connecting the port to an SMA cable or antenna, be careful not to overtighten the connection. This can cause damage to the board. Beware of loose connections as these can degrade performance. As long as the connectors are "finger-tight," the system will work well. To insure an optimal connection, the user should use a calibrated SMA torque wrench. These are generally available and cost about $100.

The P440 is intended to be used with Time Domain's Broadspec antenna. Using any other antenna will require recertification to confirm compliance with the relevant emissions regulations.   However, it is possible to add passive extension cables between the antenna port and the antenna. Be aware that using alternate UWB antennas, additional fixed attenuators, additional cabling and/or connectors will change the RF time-of-flight electrical distance between the antenna port and the phase center of the antenna. Failure to account for such changes will result in an offset or bias error in range measurements.

4.7 RF Transmit and Receive Characteristics

Two versions of the P440 are available, one which is compliant with the U.S. FCC transmission mask as described in FCC Part 15.519 and one which is compliant with the EU ETSI EN 302 065 mask.

The major difference between these two versions is in the nature of the transmitted pulse. The band edges on the EU mask are much more severe than for the FCC mask and as a result they require more severe filtering. The EU waveform is therefore more narrow in frequency and longer in time (contains more lobes) than the FCC version.   The transmit spectra for the EU and FCC masks are shown in **Figures 4-21** and **4-22**. Note that since the EU mask is effectively a subset of the FCC mask, units designed for compliance with the EU mask are also compliant with the FCC mask.

The P440 transmitter is provided with a software adjustable, variable gain attenuator. This allows the user to reduce the transmit power of the unit (by as much as 30dB) by setting the value of a register to number between 0 and 63. (See any of the API or User Manuals for details).   It is important to note that units are calibrated such that the value of 63 allows the unit to radiate at the maximum legal value. Reducing the value from 63 will reduce the magnitude of the transmitted signal, but the amount of reduction will vary from unit to unit. For example, the relationship between Tx gain setting (variable gain attenuator setting) and the radiated power for two representative units is shown in **Figure 4-19.**
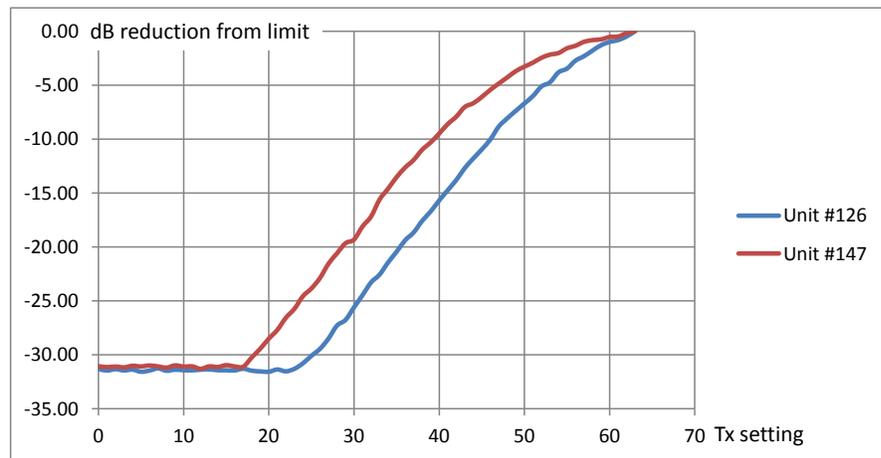
Fig. 4-19: Radiated power (relative to regulatory limit) vs. Tx gain setting for two representative units

The receive characteristics of the EU and FCC devices are identical. Both devices use the same bandpass filter arranged as a dual bandpass/LNA architecture. The characteristics of a single bandpass filter are shown below in **Figure 4-20.**
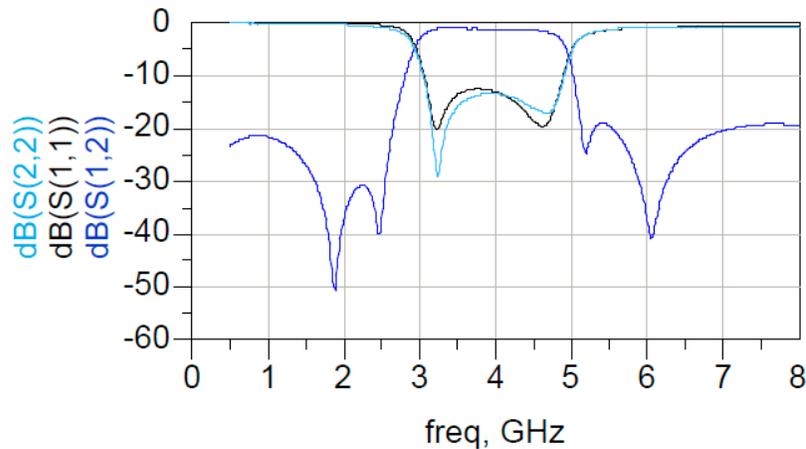
Fig. 4-20: Characteristics of a single bandpass filter

4.8 Optional Power Amplifier

The P440 can be provided with an optional power amplifier which boosts the transit power by approximately 17 dB. The exact amount varies from unit to unit with a range from about 15 to 20 dB. Also, below 10 degrees Celsius, the efficiency of the power amplifiers increases such that they provide an additional 3-6 dB. In some cases, this can be valuable for evaluation or research activities.

However, this option is provided with two very important caveats. First, operation with the power amp will exceed the transmit power of most (but not all) regulations in most (but not all) countries.

For example, in the US and Europe it will be very difficult to certify a commercial product that makes use of this power amp. Units which are provided with an optional power amplifier will *not* carry any emissions certification mark. While this option is available for experimentation and research, the user is responsible for ensuring that its use is permitted by their country's regulatory authorities.

Second, not only does the power amp increase the in-band transmit power, but it also increases the out-of-band transmit power. The increase in out-of-band power does not necessarily increase in a linear fashion relative to the increase in-band power.

The following two figures illustrate the performance of the high power amplifier in comparison with both the EU/ETSI and FCC emission regulations. Note that the regulatory limits shown are for radiated emissions, while the P440 spectra shown are conducted measurements (i.e., without benefit of antennas). If one were to take radiated measurements using a standard P440 with a Time Domain Broadspec antenna, then the radiated energy between 3.1 and 4.8 GHz would increase, thereby reaching the regulatory limit and the out of band energy would decrease by a few dB. In the case of P440 Region 2 (EU/ETSI) compliant devices, the out of band energy radiated at 2.5 GHz will decrease below the regulatory limit.

Addition of the high power amplifier increases the radiated energy by about 15-20 dB. The antenna also adds a bit more gain between 3.1 and 4 GHz and broadens the signal.
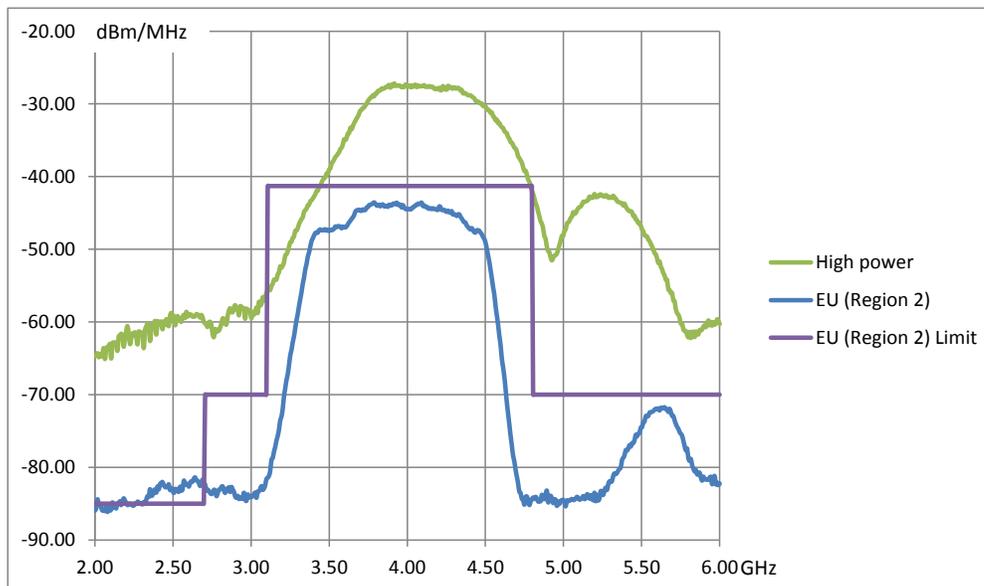
Fig. 4-21: EU/ETSI regulatory emissions limit compared with conducted spectra of P440 Region 2 unit and P440 high power unit
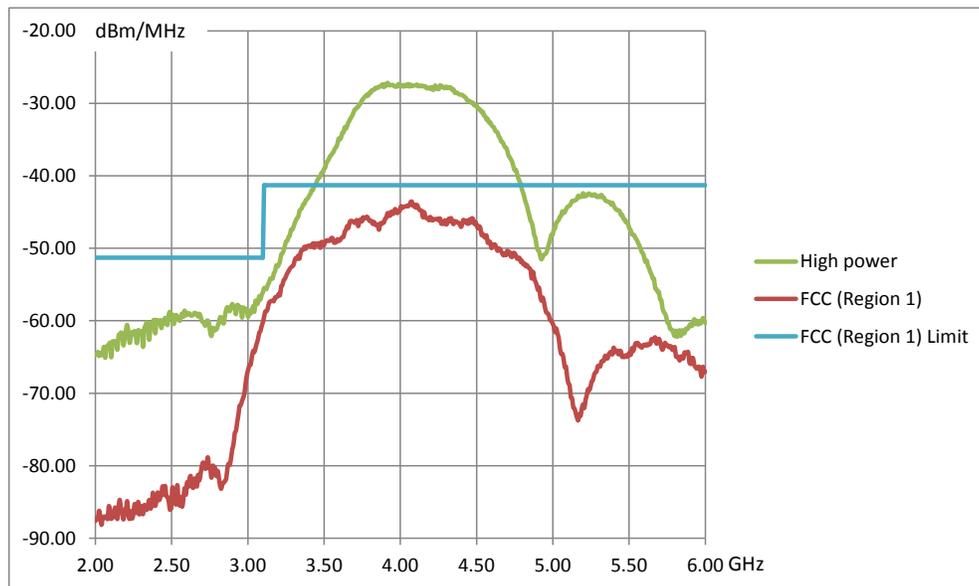
Fig. 4-22: FCC (Region 1) regulatory emissions limit compared with conducted spectra of P440 Region 1 unit and P440 high power unit

Finally, the benefit achieved by using the power amp varies by application. Bistatic radar, ranging, and communications users will see the expected 15-20 dB of improved performance. Users of monostatic radars will see a 15-20 dB improvement in transmitted power, but they will also see an increase of 6 dB in received noise. Therefore, the net improvement for monostatic radars will be 9-14 dB.

4.9 Indicator Lights

The P440 is provided with five indicator LEDs. See **Figure 4-1** for exact locations. The following is an explanation of the LED functions.

Ethernet LEDs (located on the back of the RJ45 connector)

- Green: Lit indicates operation at 100 Mbps, off means the link is operating at 10 Mbps.

- Yellow: Lit indicates the link is available, flashing indicates activity, and off means no link.

UWB LEDs (located adjacent to the RJ45 connector)

- Blue (Built in Test – BIT): flashing slowly (approximately 0.5 Hz) indicates that the unit is operating normally. Flashing quickly (approximately 10 Hz) or solidly on or solidly off also indicates a failure.

- Green (UWB activity): Toggles (if off, turns on – if on, turns off) as follows:
    - On initiation of a Range or Network Request packet transmission
    - On initiation of a Range or Network Response packet transmission

o   On initiation of a Range or Network Data packet transmission

o   On initiation of a Network Beacon transmission

o   On initiation of a CAT packet transmission

o   On initiation of a CAT packet reception

o   On completion of an MRM monostatic radar scan

FPGA LED (located on the same side but opposite edge from the UWB LEDs)

- Green: Blinking indicates that the FPGA is loaded, acting as baseband, and is ready to transmit or receive. Off indicates an FPGA fault or that the FPGA is in a low power sleep mode.

The following is a description of the LED activity when the unit powers up. When power is applied to the P440, the FPGA LED will begin blinking at approximately a 2 Hz rate.   At the same time, the Green UWB LED will turn off and the Blue LED will turn on. The Blue LED will stay on for approximately 8 seconds. During this time, the unit will boot and execute a Built in Test (BIT) of the system.   Once the unit has successfully booted, and has passed BIT, then the Blue LED will blink approximately every 2 seconds.

If the unit fails BIT, then the Blue LED will blink at approximately 2Hz.   Such a failure generally will not result in the processor failing.   It normally means that the RF section did not initialize properly. As a consequence the radio will work but at a substantially lower level of performance. Since the LEDs status may not always be visible, it is a good practice to check the status of the unit and confirm that the BIT flag is 0. Anything else indicates an error.   If BIT is set, then the user should reboot the P440.

The Green UWB LED will blink every time a packet is transmitted.

Any behavior other than what is described above should be considered to be a fault.

4.10 Heat Management

The P440 consumes approximately 2 watts. By way of reference this is approximately the same power consumption as a typical cell phone.   While this isn't very much power, this energy is sufficient to warm the board. In some extreme cases, this can cause issues. For example, if the board is operated in a sealed enclosure, in a high ambient temperature, with solar heating then the resulting thermal rise can raise the board temperature above its rated limit.

The P440 is equipped with a built in temperature sensor which will report the board temperature. The user should monitor this temperature sensor and insure that the unit is not operated in excess of the maximum rated temperature.

The following examples are provided to illustrate the effect of self-heating on temperature rise.

Case 1: Ambient 23°C, bare board sitting on a table with light air circulation.   Board Temp: 32°C

Case 2: Ambient 23°C, bare board sitting on a table in still air.   Board Temp: 41°C

Case 3: Ambient 23°C, board mounted in Time Domain enclosure accessory.   Board Temp: 47°C

Most of the heat generated is produced in the large ASICs. **Figure 4-23** is a thermal image of a board mounted in an enclosure but before it had reached equilibrium. The light colors indicate the points

that are at the highest temperature and correspond to the locations of the large ASICs. (The + sign indicates the point at which the unit measured 44.7**°C**).
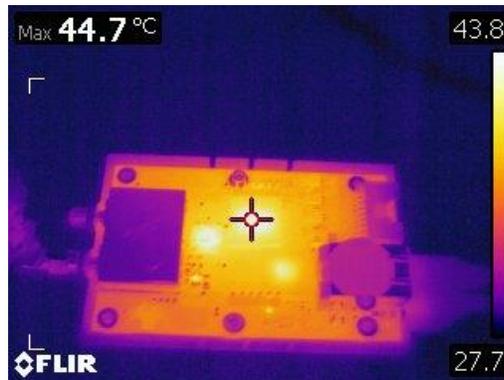
Fig. 4-23: Temperature map of the P440 taken with a FLIR thermal imager

What is not apparent from this photo is that the heat flows through the ASIC BGA pins into the ground plane and then raises the temperature of the RF shield. Putting the RF shield in contact with a heat sink will reduce the board temperature. Connecting a heat sink to the three ASICs will also reduce the board temperature. Doing both will keep the temperature rise to about 9**°C** over ambient. It is also possible to reduce the board temperature by placing the back (circuit) side of the board in contact with a heat sink. Care should always be taken to insure that the board is in thermal contact but not electrical contact. While this method works, it is not as effective as connecting to the RF shield and the three ASICs.

It is tempting to consider using the board mounting holes to extract heat from the P440. However, the mounting holes are not connected to the ground plane and are effectively thermally insulated from the board. Relying on the thermal conductivity of the mounting screws is therefore ineffective.

4.11 Accessories

When the P440 is ordered as part of a Development Kit or Lab, it is provided with a number of accessories. These accessories include: a custom plastic enclosure, a power supply, USB battery and cabling and antennas. Ranging Kits are supplied with 1 antenna per P440 while Radar Kits and Labs are provided with 2 antennas per P440. Units shipped outside the US are typically provided with a power plug adapter to ensure compatibility with the user's AC power plugs. This is illustrated in **Figure 4-24**.

Fig. 4-24: P440 with full set of accessories

4.11.1 Enclosure

The enclosure is intended to provide a modest level of protection for the boards.   The primary goal is to avoid damage from light handling, accidental drops on the floor, coffee spills, and the like. The enclosures also make it easy to safely and conveniently take measurements in buildings and outdoors. The enclosures are NOT waterproof or rain proof.   A photo of the enclosure is shown in **Figure 4-25**. Note that underneath the enclosure are 4 rubber feet which conceal four 4-40 (not metric) mounting holes. Those holes are suitable for attaching the unit to a fixed object.

Fig. 4-25: P440 in standard enclosure (left) and view of enclosure bottom showing feet and mounting holes for 4-40 screw

4.11.2 Power Supply/Charger with Battery and Cables

P440s provided with Kits and Labs are powered through the USB Power jack. Time Domain also provides each P440 with a USB Power Supply/battery charger, two USB cables (1.8 m and 15 cm) and a 4000 mAh USB battery.

Power supply: The power supply is intended for use with the standard North American wall plugs. For units shipped outside North America, the power supply is also provided with an interface plug (see **Figure 4-25**).   Every attempt is made to provide an adapter compatible with the end user's power system, but this cannot be guaranteed. Please indicate your preference when ordering your equipment.

Fig. 4-25: USB Power Supply and interface plug

Cables: The 1.8 m (6 ft) cable is a standard USB cable and can be used to power the unit or communicate through the USB data port.   The 15 cm (6 in) cable is intended to connect the unit to the USB battery but it can also support USB data communications.

In principle, there is nothing special about these components and they are almost universally available. The user is free to provide substitutes and replacements for units that are lost or damaged. While Time Domain does stock the USB battery, all of these components are available on the web from a variety of sources. It should also be noted that specific USB battery versions have short product life times.   They are typically available for 6 months to a year, then become obsolete and are no longer available. The replacement battery is typically provided by a different supplier. **Table 4-1** shown below provides source information for these components.   Where possible it includes specific suppliers and part numbers.   Entering the product description into your favorite internet search engine will lead you to any number of suppliers.

Description	Searchable description	Source and part number
USB battery	AFENDO 4000mah External Portable Rechargeable Battery	
6 ft/ 1.7 m USB cable	6ft USB 2.0 A Male to Micro 5pin Male 28/24AWG Cable	Monoprice product number: 5458
6 in /15 cm USB cable	Premium USB to Micro USB Charge & Sync Cable 0.5 ft –Black	Monoprice Product Number: 4868
Charger/supply	Anker 10W (2A) Home and Travel USB Wall Charger Adapter	

Table 4-1: Accessory source information

WARNING: In practice, USB devices are not provided with a uniform level of quality. The devices listed above work well and are recommended.   The same cannot be said about other USB devices. Some suppliers of cables use undersized wiring that is so small that it is not capable of providing sufficient power to the P440s. (Use nothing smaller than 28/24AWG where 28 is the size of the signal lines and 24 is the size of the power lines.) Some produce power with a great deal of ripple. We have seen outputs with 1 V spikes on a 5 V signal! This is not acceptable for driving the P440s.

Some batteries and power supplies have very poor connectors. These connections are so flimsy that they provide power only intermittently. Some cables use remarkably inferior connectors that provide intermittent connection after only a few dozen connections.

Consider the devices shown in **Figure 4-26**. The connector on the left provides a high quality connection. The one on the right will cause endless problems. Speaking from experience, nothing will ruin a multiday measurement campaign more completely than a few cheap and worthless USB cables and connections.

Two sets of pins guarantee a good connection   Nothing to insure a proper connection
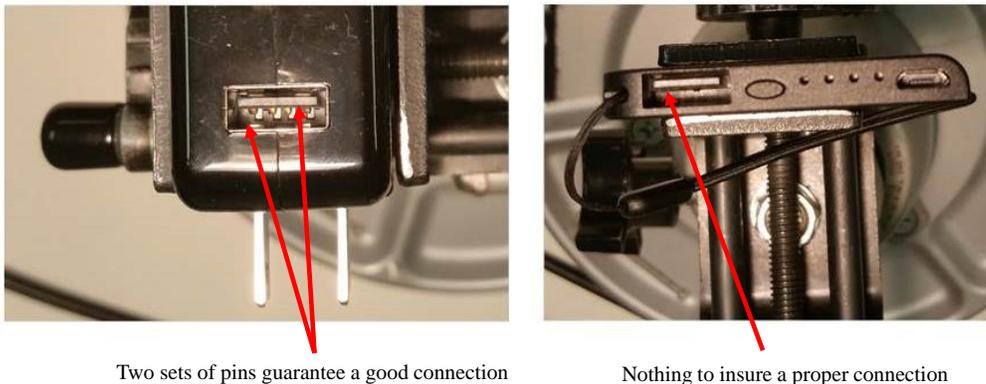
Fig. 4-26: Superior connections (left) and inadequate product (right)

When providing power from USB devices do <u>NOT</u> use USB extension cables. There is sufficient voltage drop across these cables that they will not provide sufficient power to drive a P440.

5   Mechanical Interface

Figures 5-1, 5-2, 5-3, 5-4, and **5.5** provide the information which defines the board size, the height of key components, as well as the location and dimensions of all connectors. Dimensions are shown in British Imperial units (inches). Dimensions shown in [brackets] are in metric (millimeters). **Table 5-1** lists the part numbers of all connectors and their respective mating pair. STP files for the P440 are available on request. Contact sales@timedomain.com for assistance.
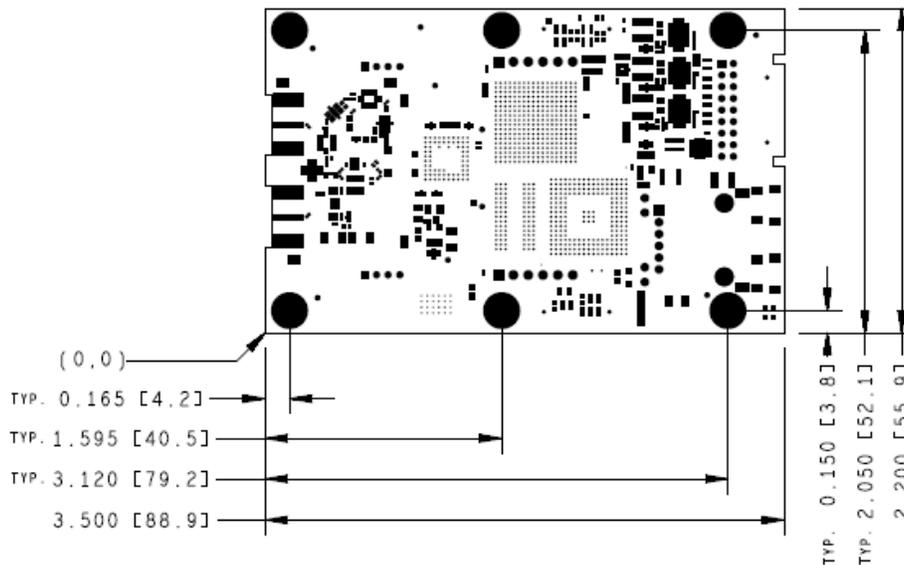
Fig. 5-1: P440 board dimensions

The six mounting holes have an inside diameter of 0.125 inches (3.175 mm) and are sized for a #4 screw. The pads have an outside diameter of 0.250 inches (6.35 mm). The minimum distance between the center of the hole and the closest component or circuit trace is 0.140" (3.556 mm).

It is anticipated that the number of mounting holes, size of the holes and placement separations are sufficient to satisfy most vibration requirements. Several customers have already satisfactorily tested the vibration performance of the P440 in extremely challenging end applications.

The P440 board is built to IPC Class 2 standards. The tolerances associated with hole size and centering are consistent with this standard.
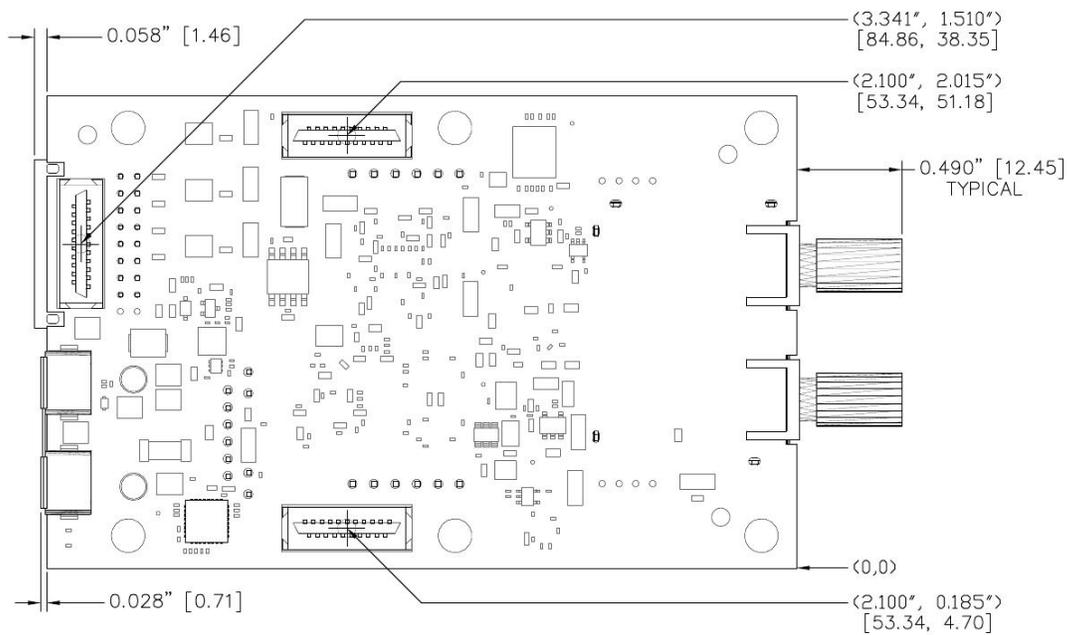
Fig. 5-2: Locations of Mezzanine connectors

Also shown in **Figures 5-2** and **5-3** are all of the parts which extend out beyond the board dimensions. This includes the RF SMA connectors, the Locking connector, the USB micro connectors, and the RJ45 jack.
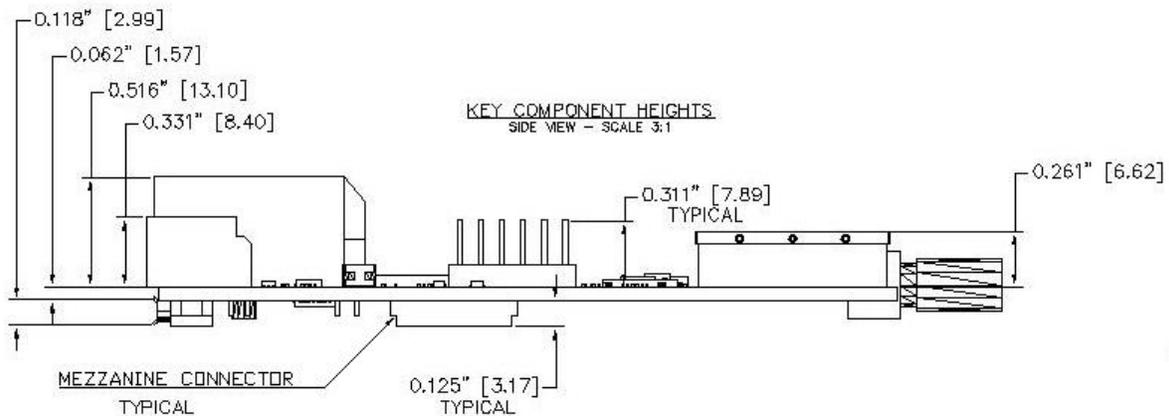
Fig. 5-3: Components which limit vertical height

When the P440 is mounted on a carrier board, the designer should be careful not to place any components within 0.125" (3.17 mm) of the bottom of the board. This is a keep-out area and it is reserved for components on the bottom side of the P440 board. Note that mating parts for the mezzanine connectors are available with different lengths. By selecting a suitably tall mating connector, the user can accommodate a wide variety of parts under the P440 without compromising the keep-out area.

POWER — I/O CONNECTORS
"FRONT" VIEW — SCALE 3:1

1.896" [48.16]
1.246" [31.66]
1.082" [27.49]
0.297" [7.55]

0.516" [13.10]
0.331" [8.40]
0.062" [1.57]
0.118" [2.99]

1.189" [30.20]
1.337" [33.95]
1.484" [37.70]
1.802" [45.76]
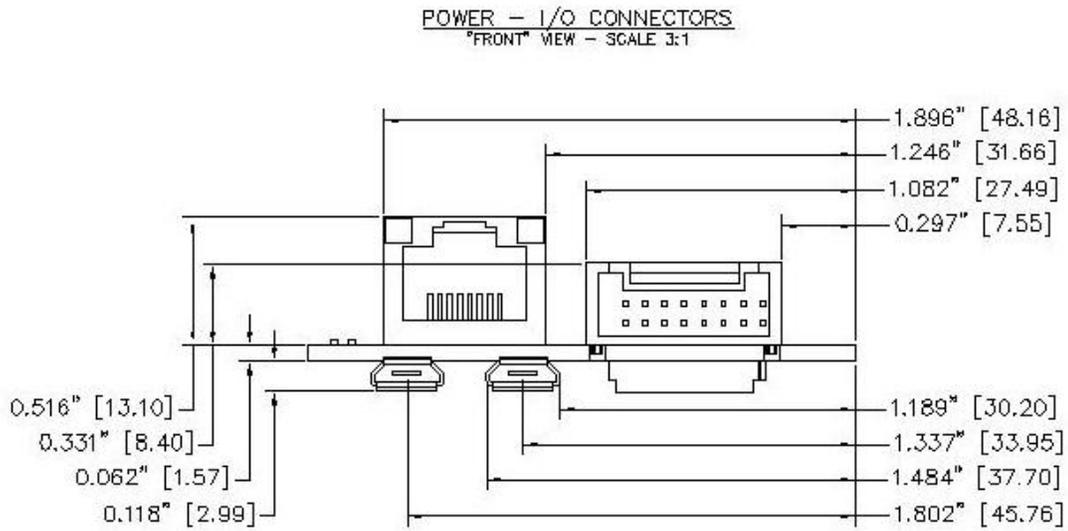
Fig. 5-4: Locations and dimensions of Power and I/O connectors at the rear of the P440

RX—TX CONNECTORS
"FRONT" VIEW — SCALE 3:1

0.133" [3.38]
0.163" [4.14]

1.410" [35.81]
0.972" [24.70]
0.785" [19.94]
0.597" [15.17]

0.062" [1.57]
0.055" [1.40]
0.085" [2.16]
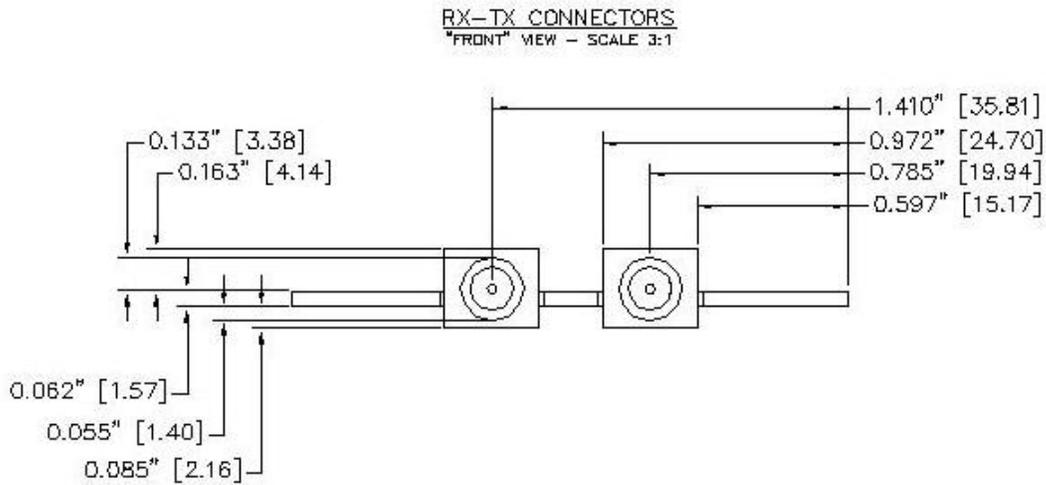
Fig. 5-5: Locations and dimensions of RF SMA connectors

The part numbers for the P440 connectors and their mating pair are shown in **Table 5-1**.

Name and Number	P440 Connector Part Number	Mating Connector Part Number
J2 - SMA Port A	Cinch Connectivity# 142-0701-871, Digikey# J610-ND	Many different choices. *
J3 - SMA Port B	Cinch Connectivity# 142-0701-871, Digikey# J610-ND	Many different choices. *
J5 - USB Data	FCI# 10103594-0001LF, Digikey# 609-4050-1-ND	Many different choices. *
J6 - Factory Mezzanine	FCI# 91931-31121LF, Digikey# 609-3520-2-ND	FCI# 91911-31321LF, Digikey# 609-3424-2-ND
J7 - User Header	3M# 961106-6404-AR, Digikey# 3M9451-ND	Many different choices. *
J8 - Ethernet Mezzanine	FCI# 91931-31121LF, Digikey# 609-3520-2-ND	FCI# 91911-31321LF, Digikey# 609-3424-2-ND
J10 - User Mezzanine	FCI# 91931-31121LF, Digikey# 609-3520-2-ND	FCI# 91911-31321LF, Digikey# 609-3424-2-ND
J11 - Locking	JST Sales America: S18B-PUDSS-1(LF)(SN), Digikey# 455-2490-ND	JST Sales America: Connector = PUDP-(18)V-S, Digikey# 455-2473-ND, Pins = SPUD-001T-P0.5, Digikey# 455-2518-1-ND
J13 - USB Power	FCI# 10103594-0001LF, Digikey# 609-4050-1-ND	Many different choices. *

Table 5-1: Connector part numbers

* These are standard SMA, USB, or 0.1" headers, for which the user has a very large number of choices. The right choice is application-specific. Fortunately, there is an option for almost every conceivable application.

6 Technical Specifications

6.1 Summary of Key Performance Parameters

Table 6-1 summarizes the P440 specifications and key performance parameters.

P440 Specs	Value
Physical Parameters	
Board Dimensions (without SMAs):	3.5 x 2.2 inches (89 x 56 mm)
Assembly height (bottom to top connectors):	0.703 inches (17.9 mm)
Weight:	1.6 ounces (45 grams)
Storage Temperature:	-40°C to 85°C

Operating Temperature range:
    Industrial units:
    Kit radios:
	
	-40°C to 85°C
	-40°C to 70°C

Max allowable board temperature:	As reported by on board temp sensor: 85$°$C for Industrial, 70$°$C for Kit radios
Humidity:	Up to 95%, non-condensing
Vibration:	Designed to meet most vibration specs. Existing customers have already tested the P440 for operation in extreme vibration environments.
Reliability:	FIT value = 380, MTTF = 300 years. Supporting report is available.
RoHS compliant	Yes
Power	
Power Input (User Mezzanine and Locking)	
Absolute Minimum Input Voltage:	4.8V with 0 ripple
Recommended Min Input Voltage:	5.0V with <100 mV ripple
USB Power Input	Compatible with USB supplies
Protection and Boot Times	
Power Protection:	Reverse voltage. See Section 4.3.2 and 4.3.4.
Electrostatic Discharge Protection:	+/-8 kV contact discharge and +/-15 kV air-gap discharge
Chassis Ground:	Available. See Section 4.3.5 for details
Time from power on to completion of boot:	11 seconds (no cables connected, with Serial connected or USB connected, or no cables connected) 7 seconds (Ethernet connected)
Minimum time the power must be turned off to force the processor to reboot:	1 second
Power & Temperature when Operating as a Ranging Radio	
Typical Power Consumption (board	See Section 4.3.6 for details

temp 40°C, Vin= 5.0 V with state transition times shown)	
- Active (transmitting) - Active (receiving) - IDLE, Standby_E, Standby_S	2.0 Watts 2.1 Watts 1.4 Watts (Enter: 1.2 ms, Exit: 1.2 ms)
Typical Power Consumption (board temp 40°C, Vin= 48.0 V with state transition time shown)	See Section 4.3.6 for details
- Active (transmitting) - Active (receiving) - IDLE, Standby_E, Standby_S	2.9 Watts 3.0 Watts 2.0 Watts (Enter: 1.2 ms, Exit: 1.2 ms)
Operating Temperature 23°C: - On flat surface, receiving, light air circulation - On flat surface, receiving, no air circulation - In Time Domain standard enclosure, receiving	32°C (9° over ambient) 41°C (18° over ambient) 47°C (24° over ambient)
Power &Temperature when Operating as a Radar	
Typical Power Consumption (board temp 45°C, Vin= 5.0 V with state transition times shown)	See Section 4.3.6 for details
- Active and scanning - Active but not scanning - IDLE, Standby_E, Standby_S	2.2 Watts 1.5 Watts 1.5 Watts (Enter: 1.2 ms, Exit: 1.2 ms)
Typical Power Consumption (board temp 40°C, Vin= 48.0V with state transition time shown)	See Section 4.3.6 for details
- Active and scanning - Active but not scanning - IDLE, Standby_E, Standby_S	3.2 Watts 2.2 Watts 2.2 Watts (Enter: 1.2 ms, Exit: 1.2 ms)
Operating Temperature 21°C: - On flat surface, scanning, light air circulation - On flat surface, scanning, no air circulation - In Time Domain standard enclosure, receiving	27°C (6° over ambient) 43°C (21° over ambient) 46°C (25° over ambient)
User Interfaces/Devices	
USB:	USB 2.0 Client – Micro-B connector Maximum Rate: 480Mbps See Section 4.4.2 for more details
Serial:	3.3 V TTL Serial UART (8, n, 1) 115.2 kbps (typical) 921.6 kbps (over short, ~15cm cable) See Section 4.4.3 for more details
Ethernet:	10/100 See Section 4.4.5 for more details

SPI:	3.3 V TTL levels 16Mbps maximum clock rate See Section 4.4.4 for more details
CAN:	See Section 4.4.6 for details
GPIO available:	• 3 Processor GPIO pin (3.3 V) • 2 Processor GPIO pin (1.8 V) • 8 FPGA GPIO pins (3.3 V), 5 of which can be used for SPI • 2 FPGA GPIO pins (1.8V) See Section 4.5 and the RangeNet User Guide for more details
GPIO TDMA Slot Zero Timing Jitter	+/- 11 μsec. See the RangeNet User Guide for additional information
On Board Temperature Sensor:	-40°C to 125°C, +/- 2.0^{o}C
RF Characteristics	
Transmit Operating Band:	Generally 3.1 to 4.8 GHz Region 1: Compliant with U.S. FCC mask. Certification has been received. Region 2: Designed for compliance to ETSI 302 065 mask. See Sections 4.7 and 8.0 for more details
Receiver Operating Band:	3.1 to 4.8 GHz Performance set by a pair of band pass filters See Section 4.7 for more details
Center Frequency:	4.3 GHz
Average Transmit Power:	Max power spectral density: -41 dBm/MHz (This spectral density equates to approximately ~50 uW or -13 dBm with an adjustability range: ~ -33 to -13 dBm)
Antenna Ports A&B:	Standard 50 Ohm SMA coaxial connector
Antennas Supported:	Compatible with Time Domain Broadspec^{TM} Toroidal Dipole Antenna as well as a wide variety of 3rd party antennas
Antenna Control:	Transfer switch allows user to configure antennas as either a) Tx/Rx on either, or b) Transmit on one, Receive on the other
Transfer Switch Tx to Rx Isolation:	~20 dB
Dynamic Range:	
Integration: 1 (instantaneous)	30 dB
Integration: 16:1 (PII=4)	42 dB (Min Ranging Integration)
Integration: 64:1 (PII=6)	48 dB (Min Radar Integration)
Integration: 1024:1 (PII=10)	60 dB (Max Ranging Integration)
Integration: 32768:1 (PII=15)	75 dB (Max Radar Integration)

Nominal Pulse Repetition Rate	10.0 MHz (others available)
Receive Noise Figure	~4.8 dB
Receive Sensitivity	- 98 dB @ PII 4, -101 dB @ PII 5, -104 dB @ PII 6, -107 dB @ PII 7, -110 dB @ PII 8, -113 dB @ PII 9
RF Communications	
Channelization:	11 user selectable pseudo-random pulse interval channels. Others available for special applications.
Communications Type:	Packet transmission
Max Data Throughput:	19.2 kbps to 612 kbps. See Section 6.6 for details
Max User Bytes/packet:	1000
Pulse Integration Rates (PII):	4 (16:1), 5 (32:1), 6 (64:1), 7 (128:1) 8 (256:1), 9 (512:1)
Ranging Performance	
Ranging Techniques:	Pulsed Two-Way Time-of-Flight (TW-TOF) and Coarse Range Estimation (CRE)
Two-Way Time-of-Flight	
Max Range (with Broadspec Antennas)	Free Space: 240 m Level ground: 1000 m (3200 ft.) See Section 6.2 for details
Precision	Outdoors: 1 cm (typical) Indoors: 2 cm (typical) See Section 6.4 for details
Bias error:	1 cm (typical) See Section 6.4
Unit to Unit Bias variation	0.6 cm (typical) See Section 6.4
Range Measurement Rate	14 – 125 Hz See Section 6.3
Non-Line of Sight Performance	See Section 6.4
Coarse Range Estimation (LOS only)	See Section 6.5
Localization Performance	
Localization Technique:	Non-Linear Least Squares Fit during a short initialization period. Afterwards user option of either (a) a Kalman Filter-based localizer incorporating a motion model and GDOP calculations or (b) Geometric Non-Linear Least Squares Fit.
Localization Accuracy (Bias & Precision):	Accuracy achieved is a function of the user's ability to calibrate out system bias errors (exact location of Anchors, P440 to P440 bias). Accuracies of +/-1 mm have been achieved.
Radar Performance	
Approximate Detection Range (high power transmission)	Person Walking: 80 m Person Crawling: 40 m Vehicle: 100 m (See Section 6.7)

Table 6-1: P440 performance characteristics

From time to time changes will be made to the P440 design. **Section 6.8** describes how the version number of any given board can be determined and describes the version to version differences.

6.2   Maximum Operating Range of a P440 Radio

Operating range in any given application will be a function of various obstructions, the height of the antennas above the ground, various interference and Fresnel constructive and destructive cancellation. For example, when operating over open fields the Fresnel ground bounce provides signal enhancement which increases overall range. The Fresnel effects can change with soil wetness, by season, from point to point, and over time as vegetation grows. When operating at PII=8 with antennas 2.5 meters above the ground one can expect to operate out to 600 meters. An example is shown in **Figure 6-1.** There are also exceptional cases. For example, where the antennas are ideally placed or the ground topology is providing significant antenna gain, it is possible to operate out to 1000 meters. One customer has reported operating in a tunnel (without clear line of sight) to a range of 3000 meters.

There are also cases where Fresnel destructive interference (cancellation) can be the dominating factor. Consider the deep null at 100m in **Figure 6-1**. At this point, the Fresnel cancellation is at a maximum. If the system were operating at a much lower PII, then the received SNR would drop. At some point, the SNR would be too low for the radio to operate. Note that in **Figure 6-1** the radio works well until the SNR drops below about 15 dB. For the sake of argument let us assume that the radio does not operate when the SNR drops below 24 dB. (In practice this reduction could be accomplished by reducing the PII by 3 steps from PII=8 to PII=5). This 24 dB limit is represented by the dashed black line. In this case, the radio would range successfully between 0 and 90 meters and from 120 to 210 meters. But between 90 and 120 meters it would not operate because the SNR is below the 22 dB needed for the receiver to operate.
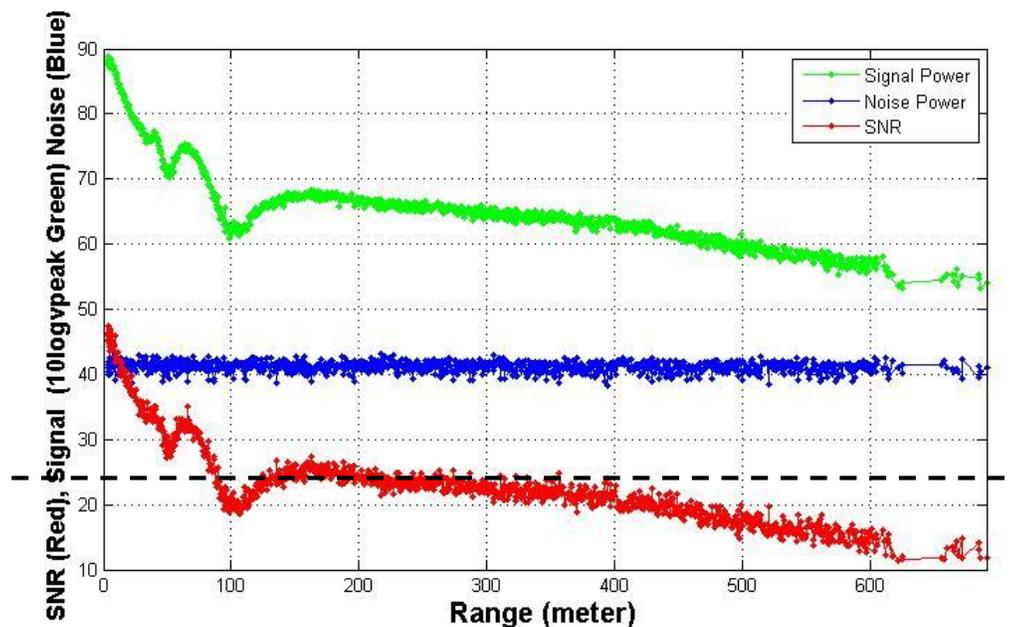

Fig. 6-1: Fresnel cancellation at 100 m can limit performance. If the SNR required to operate was 23 dB as shown by the black line, then the radio will work out to 210 m but not between 90 and 120 m.

When operating over long distances one must take Fresnel into consideration.   If the operating environment is such that Fresnel is neither a help nor a hindrance, then the operating range will be set using free space propagation. If Fresnel is both a help and a hindrance, then the maximum operating distance should be determined by the Fresnel enhancement, assuming that the Fresnel cancellation is not so deep as to cause a problem.

The magnitude of the ambient RF noise can also be a limiting factor.   In **Figure 6-1**, the blue line is a measurement of the magnitude of the noise as a function of receiver location. If the ambient RF noise were 9 dB higher than shown, then the received SNR would be 9 dB lower. In this case, the maximum range of the link operated in **Figure 6-1** would be 200 meters and there would be a coverage gap between 90 and 120 meters. Ambient noise can be increased by an exceptionally strong out-of-band transmitter or other transmitters operating in the P440's operating band.

Assuming that ambient noise is not a factor, and there are no other factors in play, then a standard P440 with a standard Broadspec antenna should operate as shown in **Table 6-2.** Two performance columns are shown, one for Free Space and the second for Open Field. The difference between the two reflects that fact that the Open Field performance benefits from Fresnel constructive interference caused by the ground reflection. The Free Space performance would be expected if the ground reflection were not a factor. Examples include operation between two drones well above the ground and operation at short range (<70 m) where the Fresnel benefit is not significant.

This data for the Free Space calculation was taken with the units placed at 1 meter separation, in a low noise environment, with fixed attenuators inserted to provide loss associated with distance. Max Range in this case means the maximum range at which >98% of the range requests completed successfully. At longer ranges, the range request success rate will drop. If a 50% success rate can be tolerated, then the maximum ranges can be extended by about 20%. The Open Field data was taken experimentally with actual P440s operating in an actual open field.

PII	Max Range (m) (Free Space)	Typical Max Range (m) (Open Field)
4	66	
5	101	
6	145	
7	207	500
8	260	600
9	410	800

Table 6-2: Maximum operating range of a P440 range measurement system in Free Space and over an Open Field for various Pulse Integration Index (PII) settings

6.3   Range Measurement Rate

Ranging Conversation Time is the amount of time required to take a single TW-TOF range measurement. The maximum measurement rate is limited by the Host to P440 overhead required to initiate a range request. This overhead will limit the measurement by approximately 30% of the values shown in the table below. This overhead is eliminated when the range requests are handled through RangeNet.

The **Maximum Range Measurement Rate** is shown in **Table 6-3** and is achieved when two radios are operated as a network consisting of a single requester unit and a single responder unit. The Maximum Rate varies by a few percent depending on which communication code is selected. The values shown in Table 5 were generated in Network Mode, with no appended data, using code channel #5.

Pii	Range Conversation Time (milliseconds)	Maximum Range Measurement Rate (Hz)
4	8.1	123.5
5	9.8	102.0
6	13.8	72.5
7	21.2	47.2
8	36.4	27.5
9	67.3	14.9

Table 6-3: Data and ranging performance characteristics at maximum legal transmit power

6.4 Range Measurement: Precision, Bias, and Accuracy

The precision, bias, and accuracy of the range measurements is a function of P440 electronics and signal processing. The P440 electronics have proved to be stable over time, from unit to unit and from board type to board type. However, the signal processing has improved with time. The more recent the software release, the more robust and accurate the range measurements will be. For example, RangeNet 2.1 (release 170330-final) included the use of an FFT which improved the SNR of the received waveform scan by 6 dB with the result that the range readings have a better standard deviation and are less likely to produce outliers. Therefore, the user is encouraged to update both the Host and P440 embedded software whenever a new software release is made available.

In addition, users are advised that:

- The typical precision of the Region 2 units (EU compliant) is not quite as good as that of a Region 1 unit (FCC compliant). For example, where an EU device experiences a 3 mm standard deviation, the FCC version will see 2 mm.

- The units have not been calibrated for accurate inter-type ranging. In other words, while an FCC compliant unit will range successfully to an EU compliant unit, the ranging performance will not be as robust or accurate as FCC-to-FCC or EU-to-EU ranging.

6.4.1 Precision and Accuracy in LOS Conditions

Most measurement devices produce readings which have both a random error component (precision) and a systematic error component (bias). Precision is a measure of the repeatability of measurement. Measurements with a high precision will have a low standard deviation. The difference between the mean of the standard deviation and the actual value is called the bias. If the bias is zero, then the system accuracy will be equal to the precision. If the bias is non-zero, then the accuracy of the

measurement is closer to the square root of the sum of the squares of the precision and bias.

The RangeNet 2.1 software (release 170330-final) has resulted in further improvements. In open clear line-of-sight situations one typically measures precisions (standard deviations) of 0.2 to 0.4 cm.

The precision of measurements can be improved with averaging. Measuring 6 readings will normally improve the accuracy by a factor of 2. Averaging more than 6 readings will have only marginal improvements.

By constraining operation to a narrower field of application, users have achieved higher performance. One user has reported precisions of 0.5 cm while a second reports 0.2 cm.

Bias is discussed in the next section.

6.4.2   Bias and Calibration

The bias of the P440 is set by the electronics. Characterization experiments were conducted using a standard P440, a Broadspec antenna, and a right-angle SMA connector. The results have been incorporated into the P440 software such that all range readings will be reported with zero bias.

The unit to unit variation has proven to be quite good. The bias of 10 P440 Region 1 (FCC compliant) and 10 P440 Region 2 (EU/ETSI compliant) radios has been tested. The Region 1 units were all within 1.2 cm of each other and the Region 2 units were within 0.7 cm. While these tests were limited to a relatively small number of units, we believe that these are typical results.

If a different antenna or cable configuration is used, then the bias will need to be adjusted. Such adjustments can be done through the API or by using the RangeNet GUI. (See **Section 5.2 - Antenna Delay A & B** of the *320-0320 P400 Series RangeNet User Guide*) For example, if the Broadspec antenna is connected directly to the P440 board (without a right-angle SMA connector) then the ranges reported will be shortened by about 2.5 cm. In this case, the proper value to enter for Antenna Delay A & B is -91.

There are three reasons why a user may find it necessary to manually adjust the bias.

First, the users may be interested in maximizing the accuracy of range measurements. In this case, recalibrating the unit such that the bias is zero will improve the accuracy of the range measurement.

Second, the user may decide to want to use the P440 with a different cable, connector, or antenna. Using anything but a standard Broadspec antenna with a 90-degree SMA connector will change the bias.

Third, the user may decide to protect the antenna from weather by adding a radome. While prudent, the radome will change the bias by up to a few cm.

In any of these cases it will be necessary to characterize and adjust the bias for this new configuration. Application note *320-0327 Distributed Calibration of Time Domain UWB Radios* describes such a process. Calibration is necessary because the speed of light in the cabling, connectors, or radome is not known. For example, while an RF cable might be 1 meter in length, the time required for a pulse to traverse the cable could easily be equivalent to a 2 meter bias.

6.4.3   Range Accuracy

Accuracy can be estimated as the value equal to the square root of the sum of the square of Precision

error and the square of the Bias error.

Many, perhaps most, users will find such a result acceptable. Some users may require range measurements with even higher accuracy.

Both sets of users should be aware of factors that affect accuracy.   With such an understanding most users will see satisfactory results and demanding users will be able to optimize their systems such that they can achieve superior results.

First, it should be noted that in general the precision of the range measurement is very reliable. Having said that, the user should be aware of the situations in which precision can degrade.

- Operation at the edge. Measurement precision will degrade when the link is operating at the edge of its range or when the direct path is occluded or is non-existent.

- Leading edge ambiguity. Sometimes the leading edge detection algorithm will be unable to decide which of the lobes in the received waveform represents the first arriving energy. In this case, the algorithm will generate a bi-modal distribution separated by 3.8 cm. This can also appear to be a change in bias. This can be mitigated by using the BSDC feature in RangeNet. See the *320-0320 P400 Series RangeNet User Guide* for more information.

- Leading edge errors. Sometimes the range computation algorithm will very occasionally generate a range measurement which is quite wrong.   In all cases, reported range measurements are also accompanied with an estimate of the range accuracy as well as various warning flags. By monitoring the reported range error estimate and the various flags, the user should be able to eliminate most errors.

- Compression and Fresnel Cancellations. Precision will degrade (standard deviation will increase by a few cm) when the signal is in compression or when the link is operated in a deep Fresnel cancellation.

In general, the maximum value for precision (highest standard deviation) will be largely determined by outliers generated either when the SNR is very low (at very large ranges outdoors) or when operating indoors at the edge of performance or in locations where the direct path is occluded or non-existent.

Second, while the precision of the range measurements is very reliable, the bias can change in some situations. The following is a list of factors which affect the bias, with insights on how these effects can be minimized. All of these effects are on the order of a few centimeters.

- Variations due to antenna pattern. While the gain of the Broadspec Antenna is reasonably uniform, it is not perfect. The bias has been zeroed assuming that the antennas are in each other's boresight. If one antenna is rotated 90-degrees then the bias will change by 1-2 cm. This can be addressed either by fixing the orientation of the antennas or by using a more omni-directional antenna.

- Variations due to antenna orientation. Inverting the antenna will actually invert the transmitted pulse. If both antennas in a ranging conversation are oriented in the same direction then range measurements will show a bias of zero. If one of the antennas is inverted, then there will be a change in the range bias of approximately 4 cm. Intermediate mismatches will produce intermediate changes in range bias. RangeNet 2.1 (embedded version 170330-final) provides the user with the ability to define whether the antenna is pointing up or down. This ability eliminates the change in bias for 180-degree mismatches. Intermediate mismatches will still produce intermediate changes in bias.

- Variations due to increasing range.   At maximum range, the range readings will tend to understate the actual range. This variation appears as a linear change in bias and is on the

order of 1 cm/100 meters.

- Variations due to temperature.   The bias of a P440 does vary slightly over temperature. From 0°C to -40°C, the bias will increase by about 2 cm.   This is repeatable from unit to unit and Time Domain has an extensive database that characterizes this behavior. Using the temperature sensor resident on the P440, this variation can be calibrated out. In a coming release, this compensation will be made automatically. Users interested in learning more can contact that factory.

- Variations due to operation in buildings.   When signals pass through walls the bias can increase (sometimes significantly) due to the RF characteristics of the material in the walls. Signals may also diffract around objects or people, thereby increasing the RF path and thereby effectively increasing the bias.

- Variations due to compression. When units are operating "too" closely to each other, the strength of the transmitting unit will be so great that receivers of other units will compress. When a receiver compresses, the bias of the reported range measurements will change by as much as a few centimeters. Region 1 (FCC) units are affected when they are within 2 meters of each other, Region 2 (EU) units are affected at ranges up to 5 meters, and High Power units will be affected out to 25 meters. In these cases, the ranges reported will tend to overstate the distance by a few millimeters and increase to several centimeters as the separation distance decreases. This can be dealt with in two ways. First, a P440 will measure the signal strength of the received signal and will report when it is close to operating in compression and thereby warn the user. Second, the changes due to compression are repeatable and can be characterized. Time Domain is in the middle of a characterization process and expects to include an automatic compensation in a future release.

- Variations due to Fresnel cancellation effects. Fresnel cancellation occurs when the direct path signal is partially cancelled by a reflection from the ground. **Figure 6-2** illustrates this issue.
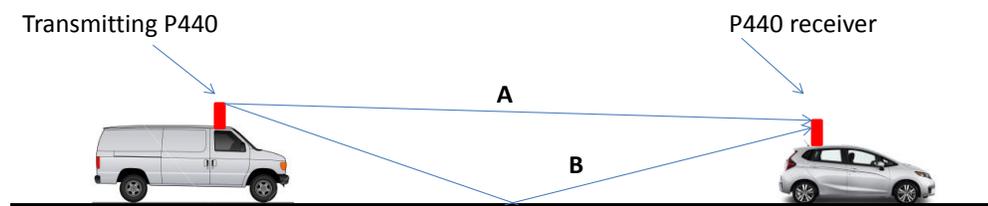

Fig. 6-2: Transmitted signal A arrives at the P440 receiver and is destructively interfered by signal B

In this example, the transmitted signal B arrives at the P440 receiver ½ wavelength after signal A arrives. As a result, signal A will experience destructive interference by signal B. The received signal will not only have a lower SNR but it will also change the characteristic shape of the received signal. This unexpected change will increase the standard deviation and change the bias. These changes have been quantified. The data shown in **Figure 2-4** was collected using the configuration shown in **Figure 6-2**. (For convenience, **Figure 2-4** is repeated below as **Figure 6-3**.) You will notice that there are two points in **Figure 6-3** at which the Fresnel cancellation is apparent, 60 and 100 meters. At these locations, the standard deviation (precision) increased to 1.5 and 3.0 cm and the bias decreased by 1.5 and 3.5 cm, respectively.
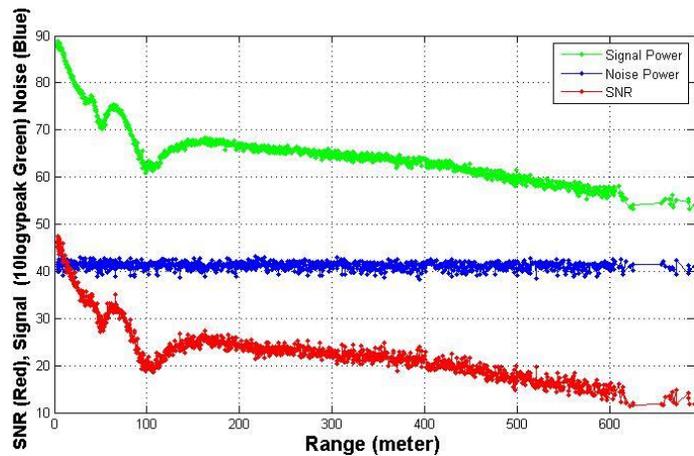
Fig. 6-3: Data collected from configuration shown in Figure 6-2

Since the degradation in performance is due to a change in the characteristic shape of the waveform, it is possible to detect this situation and either correct for it or warn the user. Time Domain is characterizing this effect and plan to include this in a future release.

With these factors in mind (all of which will affect the maximum values of precision) **Table 6-4** summarizes the performance one should expect.

	Min	Typical	Max
Bias	-	1cm	-
Bias: unit to unit	-	+/- 0.6 cm	-
Precision (outside)	0.3cm	1cm	-
Precision (inside)	0.3cm	2cm	-

Table 6-4: Bias and Precision for a P440 operating with RangeNet 2.1 (embedded 170330)

6.4.4   Precision in NLOS Conditions

Time Domain does not have a specification for accuracy in Non-Line of Sight (NLOS) environments. This is because of the wide variety of conditions that can be encountered.   For example, if one is measuring range inside a building that is constructed of wood frame and drywall (also known as sheetrock or gypsum board), then one will experience a level of performance that is less than but close to LOS conditions.   This is because wood and drywall do not significantly attenuate or disperse RF signals at the P440's operating frequency. Such errors generally appear as changes in bias that vary from a few to several cm.

On the other hand, RF can be totally or partially blocked by metal objects or thick concrete. In these cases, it is more likely that any ranges reported would be based on fortuitous and erratic multiple reflections and not a direct path. Consequently such readings will generally be long and suffer from a high standard deviation (degraded precision). In these situations it is also possible for the signal

processing to report noise as a leading edge, thereby producing a range which is too short. Errors on the order of fractional to multiple meters are possible.

6.5   CRE Range Measurement Precision and Accuracy

There are three key factors that affect the Precision and Accuracy of a CRE measurement: stability of the RF channel, changes in antenna pattern and signal strength.

If RF channel characteristics are stable, then the accuracy of the CRE measurement should be close to that of the reference precision range measurement (PRM). However, if the P440 is physically moving, such that the associated antenna pattern changes, then the RF channel will change with time. Therefore, the recalibrating PRMs should be taken frequently enough such that the rate of change ("drift") of the RF channel will be small.   This rate of change will vary with node speed and change in orientation and must be determined empirically.

Random effects, including sampling variability, can cause a static node's signal strength measurement to vary by as much as 10%. The CRE error is also a function of distance between the transmitter and receiver largely because as a weaker signal contains a higher proportion of noise elements. This translates into a CRE standard deviation error of approximately 10% at short distances, growing up to 30% at very long distances. CRE should not be used at distances greater than 100 meters. At these distances, the change in signal strength with distance is very small and can be less than the average reading-to-reading variation at any given point. In addition, one will normally encounter Fresnel enhancement beyond about 100 meters. In these cases the SNR will actually increase with distance. This is illustrated in **Figure 6-1**.

6.6   Data Communications Rate and Throughput

The P440 has been optimized for operation either as a Radar or as a Ranging Radio.   While the P440 can be used to transmit large quantities of data, this capability will come at the expense of ranging update rate.   It is also important to note that data transmissions are limited to a maximum of 1000 bytes per packet. While fewer bytes can be transmitted, the highest throughput is achieved when the bytes sent per packet are maximized.   **Table 6-5** shows the relationship between PII (Pulse Integration Index) and data throughput.

| | Bytes sent using Code Channel 2 | |
| | 100 | 1000 |
PII	Bit rate (kbps)	Bit rate (kbps)
4	270.46	612.48
5	192.77	308.48
6	138.56	144.64
7	62.14	76.80
8	34.88	39.04
9	17.41	19.20

Table 6-5: Throughput for different Pulse Integrations and buffer sizes

It should also be noted that the bit rate will vary by a few percent depending on which Code Channel is selected.

6.7   Operating Range of P440 Radar

The detection range of a UWB Radar is a strong function of the antennas used, the ambient environment, clutter, target size and movement characteristics, as well as the robustness of the user developed signal processing. The quoted detection ranges have been achieved by others and represent close to the maximum detection range achieved to date without using heroic measures such as power amplifiers and high gain antennas. Users limited to the legal maximum transmit power and with no antenna flexibility should half the numbers shown in **Table 6-1**.

For additional insight into this subject, a validated Radar Range Equation for the P440 is provided on the Time Domain website.

6.8   P440 Version Differences

From time to time slight changes or improvements are made to the P440 design. The version or revision level of any given P440 is indicated in the bar code of that particular P440 (See **Figure 6-4** below).
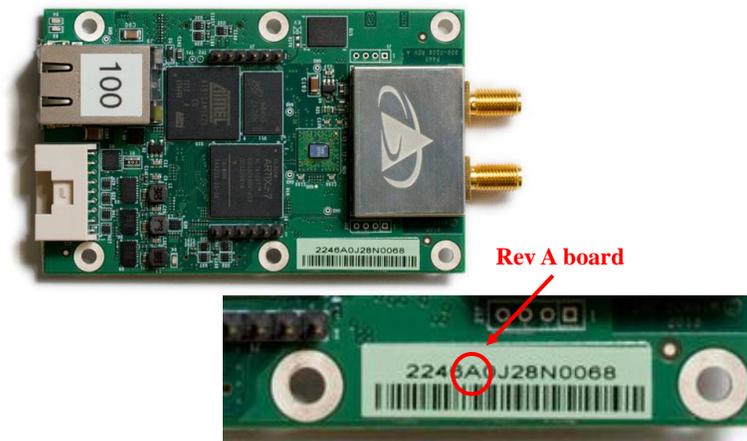

Fig. 6-4: P440 Version indicated in bar code. Unit shown is a Rev A board.

To be more complete, the number 2246A0J28N0068 can be decoded as follows:

> 2246:   board type
> A: board revision
> 0:   board sub version
> J: year of manufacture (in this case year J = 2015, K = 2016)
> 28:   week of the year assembled
> N: contract house
> 0068:   serial number

Note that when the user electronically polls the unit for its serial number, the returned value will be a multi-digit number. These two values are linked in such a way that any board can be referenced by either number.

The following is a list, by revision level, of any deviations or changes/improvements from this data sheet:

P440 Rev A
- Ethernet through the mezzanine connector is not supported.
- Operation of the unit at the temperature limits is not recommended. Failures have been reported. Avoid using the equipment in extreme outdoor temperatures.
- Avoid operating units in high vibration.
- If failures do occur in either high vibration or extreme temperature contact Time Domain customer support.
- P440 Rev A units equipped with a high power amp will increase the transmit power by approximately 10 dB.

P440 Rev B
- Ethernet through the mezzanine connector is not supported.
- P440s delivered in Development Kits or PulsON Labs may not meet the low temperature spec. All Kit/Lab units are guaranteed to operate between 0° to 70°C and about half of them will operate over the full -40° to 85°C temperature range. All P440s delivered as industrial units will operate over the full -40° to +85°C temperature range.
- P440 Rev B units equipped with a high power amp will increase the transmit power by approximately 15-20 dB.

P440 Rev C
- Power interface changed such that the user can use either the USB power or the Locking connector to supply power to the board.
- Power supplied to the board must be at least 5 volts and no higher than 48 volts.
- Three different versions are supplied (Version/sub-version):
  - (CA) = EU Mask
  - (CB) = FCC Mask
  - (CC) = High Power
- Additionally, Kit radios are typically provided to Commercial Temperature range (-40° to 70°C) but will frequently work beyond that range. Industrial radios can be operated over the Industrial Temperature range (-40° to 85°C). Note that these temperatures apply to the temperature reported by the onboard temperature sensor and NOT the AMBIENT temperature.

P440 Rev D

- Ethernet operation is now fully supported through the mezzanine connector. Previous versions either would not work (Rev A or B), or would work a slight modification (Rev C). Rev D boards do not require any modifications.
- Operating temperature of all radio modules (Kit, Lab, and Industrial) are rated from -40° to +85°C.

7 Broadspec Antenna

The P440 is designed to operate with the Broadspec antennas shown in **Figure 7-1**. While this is the antenna provided with the P440, the unit can accommodate a wide variety of standard and custom antennas. The only electrical requirement is that the antenna used has a 50 ohm SMA connection.

Using a different antenna will likely change the beam pattern and gain, either of which will affect certification.   Using a different antenna may change the phase linearity and compromise the pulse shape and integrity. This can affect the performance of the range measurement algorithms.

However, all of the transmit settings have been set assuming that the P440 is connected to the Broadspec. In fact, the pending US certification effort will require use with the Broadspec antenna. Using any other antenna (or even adding cabling between the P440 and the antenna) will require recertification of the equipment.

For example, as per FCC 15.203, the Broadspec antenna must be professionally installed and the installer has the responsibility to insure that the Broadspec antenna is used. EU regulations have similar restrictions.

The P440 can be operated with a single antenna (used for transmit and receive) or with two antennas (where one is dedicated for transmit and the second for receive).

The Broadspec antenna (~3 dBi) provides an omni-directional transmit/receive pattern supporting a frequency range of 3.1-5.3 GHz. It has a standard SMA male connector and measures 1.2" x 2.5" x 0.063" (30.5 x 63.5 x 1.6 mm). When ordered with a Kit it is also provided with a 90-degree connector as shown in **Figure 7-1**.

The connector can also be ordered with a standard SMA female connector. See **Section 10** for ordering details.

Specifications are available on the web at:

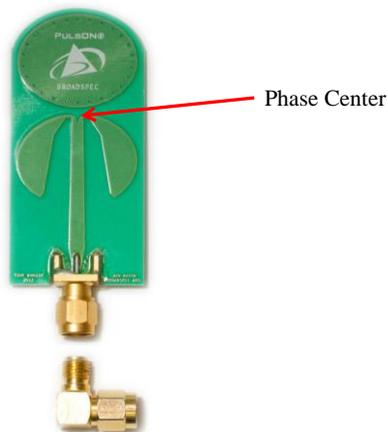 http://www.timedomain.com/datasheets/TD_Broadspec_Antenna.pdf

Fig. 7-1: Broadspec antenna with phase center indicated

8 Regulatory Compliance

The P440 has been designed to be in compliance with both the U.S. FCC Part 15 subpart F regulations, sections 15.519 and 15.521 and with the European Union ETSI EN 302 065 standards. Two different versions of the P440 are available, one version supports the FCC emissions mask (Region 1) and the second supports the ETSI standard mask (Region 2). This is discussed in greater detail in the following subsections and in **Section 10 – Configuration and Ordering Information**.

Any version provided with the optional power amplifier is not certified.

The P440 with Broadspec has been certified in the US for resale or incorporation into other equipment as a standalone device.

Integration of the P440 into other user equipment will require certification of the resultant system. While that certification is the responsibility of the end user, Time Domain will be happy to assist in this process.

The design difference between a Region 1 and Region 2 device is very slight. The key difference is then severity of the filter band edges.   Since the Region 2 device (EU) has the more severe requirement, that design is inherently also in compliance with the Region 1 regulations.

8.1   Compliance with the U.S. FCC Regulations

The standard Region 1 P440 has been designed to be in compliance with the FCC regulations governing UWB hand-held systems (Part 15.519) also known as "battery powered devices" or "mobile devices." This means that the device can be incorporated in a wide variety of products including mobile tracking systems, mobile locators, radar-based locators, guidance and position systems, and communication devices.   Note that there are other applications which are specifically forbidden, such as use of the devices in toys. See FCC Parts 15.519 and 15.521 for more details.

More specifically:

> *This device complies with 47 CFR Part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) This device may not cause harmful interference, and (2) this device must accept any interference received, including interference that may cause undesired operation.*

Furthermore:

> *The user is cautioned that changes or modifications not expressly approved by the party responsible for compliance could void the user's authority to operate the equipment.*

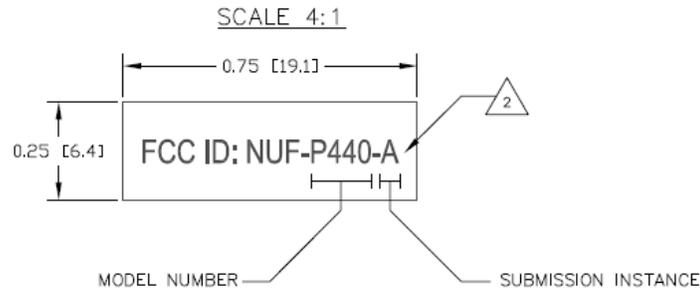The label which provides the certification number is shown below in **Figure 8-1.**

Fig. 8-1: FCC ID number

This label is located on the back or bottom side of the P440. See **Figure 8-2.**
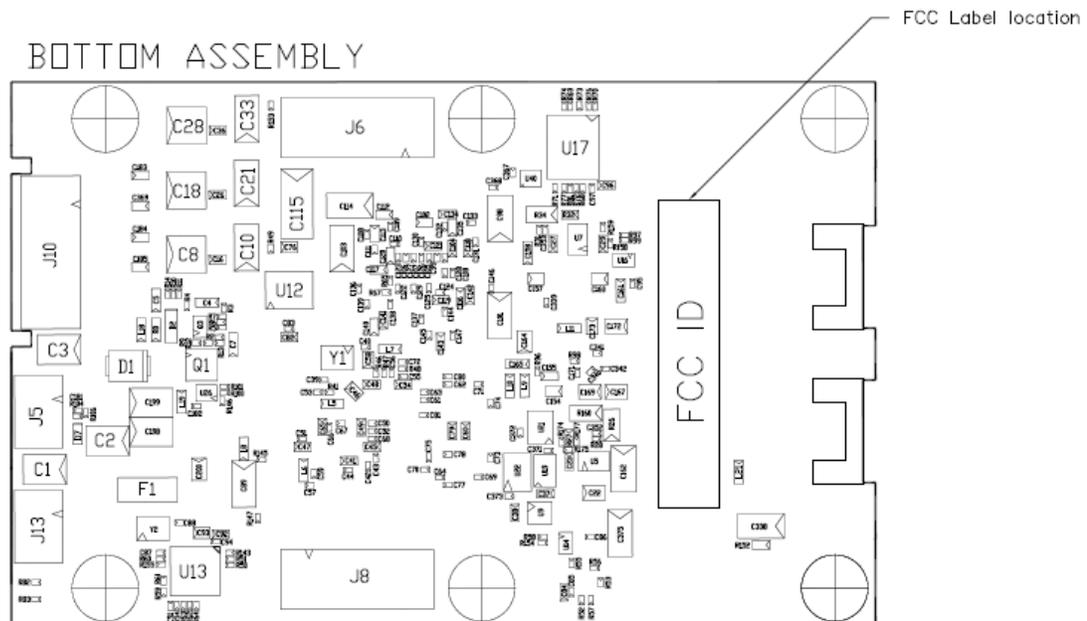

Fig. 8-2: Location of certification number

If the P440 is incorporated into a different enclosure it is possible that the enclosure can alter the unintentional and intentional emissions respectively.

Based on requirements from a number of government and site-license customers, the P440 is capable of transmitting at power levels in excess of the FCC limits for enhanced performance. In order to use these higher powers, please consult and seek authorization from the appropriate regulatory agencies. Time Domain has expertise in working with regulatory agencies and can help as needed. However, the responsibility for obtaining such authorization rests with the end user.

Additionally, the FCC regulations do not apply for US government or military applications. Proper governmental use is described in "Government Regulations for Non-Licensed UWB Systems - Annex

K." Developers interested in building a device for a particular government agency should discuss their application and Annex K with that agency's spectrum manager.

Time Domain is available to assist you with the certification process.

8.2 Compliance with the EU ETSI Standards

The standard Region 2 P440 has been designed to be in compliance with the emissions mask defined in the ETSI EN 302 065 standard.

The user is free to buy the equipment for evaluation and demonstration purposes. But before the device can be generally marketed as an end product, its operation must be tested for compliance with the ETSI standard. The ETSI standard places additional requirements on operation of UWB devices beyond just the emission mask. These requirements are related to the specific end application. For example, depending on the user's intended application, there can be additional limitations (or flexibilities) on the location of fixed and mobile transmitters as well as on the rate at which transmissions can be generated. There are also alternate mitigation strategies which can be used to accomplish the intent of the standard. These strategies need to be considered in the context of the target application.

The ETSI regulations also evolve over time with changes being introduced periodically. Product developers need to keep this in mind as they evaluate applications and target products.

Finally, the P440 by itself cannot be certified. The P440 must be certified by the relevant body in the context of the final product in which it is to be used.

Time Domain is available to assist you with the certification process.

9 Import/Export Considerations

The U.S. Department of Commerce's Bureau of Industry and Security has assigned to the P440 the Export Commodity Control Number (ECCN) of 5A001b.4 with license exceptions GBS and CIV. Products falling under ECCN 5A001b.4 are controlled for export purposes pursuant to the Commerce Control List for National Security and Antiterrorism. Plainly stated, the P440 is eligible for export to 95% of the countries in the world. For the latest information from the Commerce Department on Export, please go to: http://www.bis.doc.gov/licensing/exportingbasics.htm.

While Time Domain has shipped products to more than thirty-five countries (and takes pride in doing so) there are a small number of countries for which export license approval may be required. Furthermore, these rules change with time. Therefore, the company reluctantly reserves the right to refrain from selling P440s if there is a significant export concern.

10 Configuration and Ordering Information

The P440 is available either as a single board (Industrial Module) or as part of a Development Kit or Lab package (Kit module).   When ordered as part of a Kit, the P440 module is provided with a number of hardware and software accessories. The only performance difference between Kit and Industrial modules is their operating temperature range. All radios (Kit, Lab, and Industrial Modules) operate from -40° to +85°C. For details on how the IP address and Node ID are defined for Kit and Industrial Modules see **Section 4.4.5 – Ethernet and IP Addressing**.

The hardware accessories include the following:

*   **Enclosure for P440 module**: Housing made of damage-resistant plastic with clear polycarbonate cover. Provides protection from improper handling during evaluation, testing, and development activities.

*   **Broadspec antenna:** Time Domain's standard UWB antenna as described in **Section 7**.

*   **USB wall charger, battery, and cables**: The USB battery can drive the P440 directly for approximately 7.0 hours. The USB wall charger can drive the P440 directly from an AC power source or can be used to recharge the battery. A short USB cable is provided for connecting the battery to the P440 and a longer cable is provided for driving the P440 from an AC plug or for USB communications. Most (but not all) commercially available USB battery packs will drive the unit, so the user has the freedom to experiment with alternate battery approaches.

The P440 software offerings include the following:

*   **RangeNet / RangeNet Lite:** RangeNet is Time Domain's GUI for demonstrating two different capabilities. First, it allows the user to measure the distance between two P440 units using TW-TOF ranging. Second, it allows the user to define a network of P440s. More importantly, this network has been optimized for use with TW-TOF ranging. RangeNet supports both the ALOHA and TDMA network protocols. It can also be configured to transfer low rate data. Third, RangeNet takes advantage of range data produced by the network to compute the location of units in the system. RangeNet "Lite" is a node-locked version of RangeNet in that it is limited to operation with 10 nodes. RangeNet Lite is provided to allow the user to easily experiment with units both as standalone pairs and as members of a network.   Users interested in unrestricted operation of RangeNet should contact the factory for information on purchase and licensing options.

*   **MRM RET:** This is Time Domain's GUI for demonstrating the operation of the P440 as a monostatic radar. MRM RET can be used as a training tool to familiarize the user with the API commands or as an actual development tool.

*   **CAT:** The Channel Analysis Tool (CAT) allows the user to operate the P440 either as a bistatic or multistatic radar.   It is also well-suited for performing studies to determine the RF channel propagation studies.

All of the software packages come with sample C code and sample MATLAB code to illustrate the API interface from a Host computer to the P440.

Table 10-1 provides the name of the configuration, a part number, and a short description of the part or kit. Two hardware versions are available and are designated as Region 1 or Region 2. Region 1 hardware is intended for those countries that follow the U.S. FCC emissions regulations and Region 2 hardware is intended for those countries that follow the EU ETSI standards.

KIT Series	Part number	Description
P440 Ranging and Localization Development Kit	440RL01 (Region 1) 440RL02 (Region 2)	Contains 5 P440 modules 140RM01 for Region 1 140RM02 for Region 2 5 Broadspec antennas (100ANR4) 5 enclosures 5 rechargeable USB batteries 5 USB wall chargers 5 long USB cables (6 ft./1.8 m) 5 short USB cables (6 in./15cm) - RangeNet Lite (ranging and network software, node-locked to 10 nodes) 5 hours of technical support - MATLAB-based localization demonstration
P440 Radar Development Kit	440MR01 (Region 1) 440MR02 (Region 2)	Contains 2 P440 modules 140RM01 for Region 1 140RM02 for Region 2 4 Broadspec antennas (100ANR4) 2 enclosures 2 rechargeable USB batteries 2 USB wall chargers 2 long USB cables (6 ft./1.8 m) 2 short USB cables (6 in./15cm) - MRM and CAT (monostatic and multistatic radar as well as the Channel Analysis Tool for communication RF channel analysis and modeling) 5 hours of technical support
LAB Series		
P440 PulsON Lab	540PL01 (Region 1) 540PL02 (Region 2)	Contains 10 P440 modules 140RM01 for Region 1 140RM02 for Region 2 20 Broadspec antennas (100ANR4) 10 enclosures 10 rechargeable USB batteries 10 USB wall chargers 10 long USB cables (6 ft./1.8 m)

		• 10 short USB cables (6 in./15cm) • RangeNet Lite (ranging and network software, node-locked to 10 nodes) • MRM and CAT (monostatic and multistatic radar as well as the Channel Analysis Tool for communication RF channel analysis and modeling) • 10 hours of technical support

P440 PulsON MegaLab	540PL04(Region 1)
	540PL05 (Region 2)
		Contains
		• 20 P440 modules
		   ○ 140RM01 for Region 1
		   ○ 140RM02 for Region 2
		• 40 Broadspec antennas (100ANR4)
		• 20 enclosures
		• 20 rechargeable USB batteries
		• 20 USB wall chargers
		• 20 long USB cables (6 ft./1.8 m)
		• 20 short USB cables (6 in./15cm)
		• RangeNet Lite (ranging and network software, node-locked to 10 nodes)
		• MRM and CAT (monostatic and multistatic radar as well as the Channel Analysis Tool for communication RF channel analysis and modeling)
		• 10 hours of technical support

Single P440 boards		
P440 Kit Module	140RM01 (Region 1) 140RM02 (Region 2)	Single P440 Module (board only, no accessories)
P440 Kit Module with high power amp	140RM03	Single P440 Module (board only, no accessories) with onboard power amp
P440 Industrial Module	140RM04 (Region 1) 140RM05 (Region 2)	Single P440 Module (board only, no accessories)
Antenna Series		
Broadspec Antenna	100ANR2	Single Time Domain UWB Antenna (3-6 GHz) male SMA connector
Broadspec Antenna	100ANR4	Single Time Domain UWB Antenna (3-6 GHz) male SMA connector and right angle SMA connector
Accessory Series		
P440 Enclosure	340EN01	Single P440 Enclosure

Table 10-1: P440 Configuration, Part Numbers and Description

High Power Amplifier Option: These boards can also be provided with an optional high power amplifier. This amplifier will boost the transmit power of the P440 by 15-20 dB above the regulatory

limit. This capability is provided as an aid in evaluating the performance or performance potential of UWB. Approval to operate at these higher powers is the responsibility of the end user.

While this capability can be used for evaluation or demonstration, resale of P440s with this option will require recertification of the unit to the relevant RF emissions requirements. Even recertification to overcome extra cable loss will require recertification.   If the goal is to increase radiated power, it should be noted that most (but not all) regulations and regulators are unsympathetic to requests to radiate above the published limits. See **Section 8 – Regulatory Compliance** for additional information.

When ordering, please specify whether or not the high power amplifier option is required.

For pricing and ordering information, please contact sales@timedomain.com.

11 Changes from Previous Versions

Notable differences between this version of the Data Sheet (320-0317E) and the previous version (320-0317D):

- Document reflects additional software functionality introduced in release 170330 (RangeNet 2.1). This includes the following:
    - The Location Engine
        - now supports operation in both ALOHA and TDMA networks
        - provides either 2D or 3D localization
        - support localization with either the Kalman or Geometric solver
    - Accuracy of range readings has been improved and error mechanisms are better described.
    - Software support for GPIOs has been added.
- Additional information has been provided regarding operation of Ethernet through the mezzanine connector.
- FIT (Failure in Time) value added to the specification.
- Proper use of supply and digital (signal) grounds is discussed in greater detail.
- More information supplied on minimum supply voltages.
- Recommend that USB power be connected with 28/24AWG USB cables (not 28/28AWG)
- Accuracy of the range measurements has improved and more information has been provided regarding range bias errors.

Notable differences between this version of the Data Sheet (320-0317D) and the previous version (320-0317C):

- The latest software release (160315) provides support for a Location Engine which operates in any version of P440. (It also operates on any member of the P400 family including P400s, P410s and P412s). The Location Engine is resident on the P440 processor and can be initialized, controlled and monitored through the API and the RangeNet GUI.

Notable differences between this version of the Data Sheet (320-0317C) and the previous data sheet version (320-0317B):

- The previous data sheet indicated that the P440 is available for operation over the Commercial and Industrial temperature ranges (0° to 70°C and -40° to +85°C). Testing of several hundred of the P440 Rev C units has revealed that <u>all</u> units operate down to -40°C. Therefore, the Commercial rating greatly understates performance. Units shipped as Kit radios (in Development Kits or PulsON Labs) will operate over at least -40° to +70°C. Units shipped as Industrial modules will operate from -40° to +85°C.
- The USB protocol is recommended for intermittent operation in testing and laboratory environments. (**Section 4.4.1**)
- **Section 4.4.6** is new. It describes the boot and self-diagnostics operation and recommends best practices for monitoring boot and built-in-test.

Notable differences between Data Sheet version 320-0317B and the previous data sheet version (320-0317A):

- The P440s are now FCC approved. (**Section 8** and other sections)

- Minimum voltage required to power a P440 has been increased from 4.5 to 5.0 volts (various sections)
- The user can power P440 Rev Cs through either the USB or Locking connectors. In previous versions the selection was set at the factory. P440 Rev A and Rev B units were set such that Kit radios were only powered through the USB and Industrial radios were only powered through the Locking connector. (**Section 4.3.1**)
- SPI interface cables need to be short.   (**Section 4.4.3**)
- Unit is calibrated such that a setting of 63 will produce the full transmissions at the full regulatory limit. Operation at lower settings will reduce transmit power, but those levels are *not calibrated* and change from unit to unit. (**Section 4.7**)
- Additional information provided on the performance of the optional power amp. (**Section 4.8**)
- Additional information provided on the meaning of the indicator lights. (**Section 4.9**)
- Rev C units of all types are available as Kit radios (and operate over at least the commercial temperature range of 0° to 70°C) or as Industrial units (and operate over the Industrial temp range -40° to 85°C). (**Section 6.1**)
- Receive sensitivity spec added (**Section 6.1**)
- Description of the meaning of the bar code has been provided (**Section 6.8**)
- Description of the differences between P440 Rev A, B, and C units and how they may deviate from the specification. (**Section 6.8**)
- US Department of Commerce has assigned an Export Commodity Control Number for the P440. This will make it easier to export equipment.
- The capacity of the battery supplied with the Kits has been increased from 3000 mAh to 4000 mAh. (**Section 4.11.2**)