

Data Sheet / User Manual

PulsON[®] 440

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Regulatory Approvals

The P440, as supplied by Time Domain, has not yet been certified for use in any particular geographic region by the appropriate regulatory body governing radio emissions in that region. However, other members of the P400 series of devices have received such certification for use in the United States and the P440 is currently in the process of being tested for certification in the US. This certification is expected to be received later in 2015. This will be followed by a similar effort in Europe in 2016.

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).

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1 Summary

The PulsON 440 (P440) module is an Ultra Wideband (UWB) radio transceiver operating between 3.1 and 4.8 GHz and provides the following functions:

- 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.
- 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.
- 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 RF emissions are compliant with both the United States Federal Communications Commission (FCC) Part 15 regulations and 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 Vista 32/64, 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 programmers with a visual example of a host application which interfaces to the P440 through the API.
- They allow users to evaluate ranging and communications performance.

- They allow users 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 system analysts 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 users to operate multiple P440s to form a network of 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 five 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

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 transmitting and receiving UWB pulses.
- 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:
 - Assumes all responsibilities for scheduling communications and range requests
 - Provides the Host with status update information
 - Handles supervisory commands sent by the Host

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

For details on interfaces, refer to:

- *320-087 Using the USB and Serial Interfaces*

2.2 Application Programming Interfaces (APIs)

There are three different APIs:

- Range measurement and network commands are defined in the document *320-0313 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 will be 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 RET** is used to demonstrate simple point-to-point ranging and communications under the control of a host processor as well as operation as a full ranging network under control of the P440.
- **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 – RangeNet Sample C Applications*
- *150-0123 – RangeNet Localization Demo (MATLAB-based executable)*
- *150-0124 – Localization Demo (command line based executable)*
- *150-0118 – RangeNet Sample MATLAB Applications*
- *150-0103 – Ranging Sample C Applications*
- *150-0104 – 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 User Guide and a Quick Start 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 User Guide and Quick Start Guide documentation is provided below:

- **Ranging and Network (RangeNet):**
 - *320-0314 RangeNet Quick Start Guide*
 - *320-0320 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, 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 1**.)

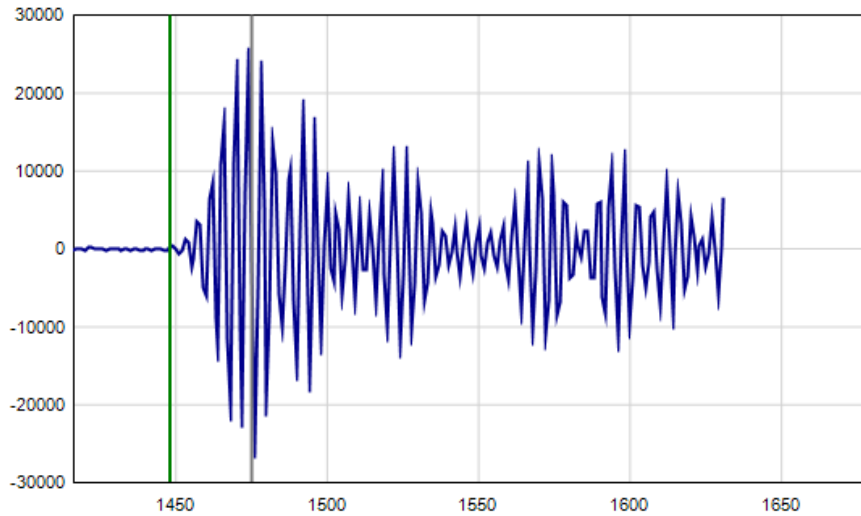


Fig.1: A typical received waveform: signal magnitude (relative strength) vs time (increments of 61ps)

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**.
- 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.

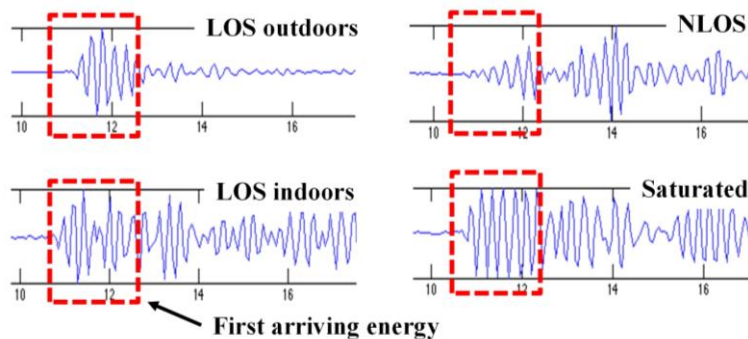


Fig.2: Received waveforms captured at 61ps intervals (2x Nyquist) in a variety of environments

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 takes a PRM it will broadcast the last range measurement to any other radios in the area. 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 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.

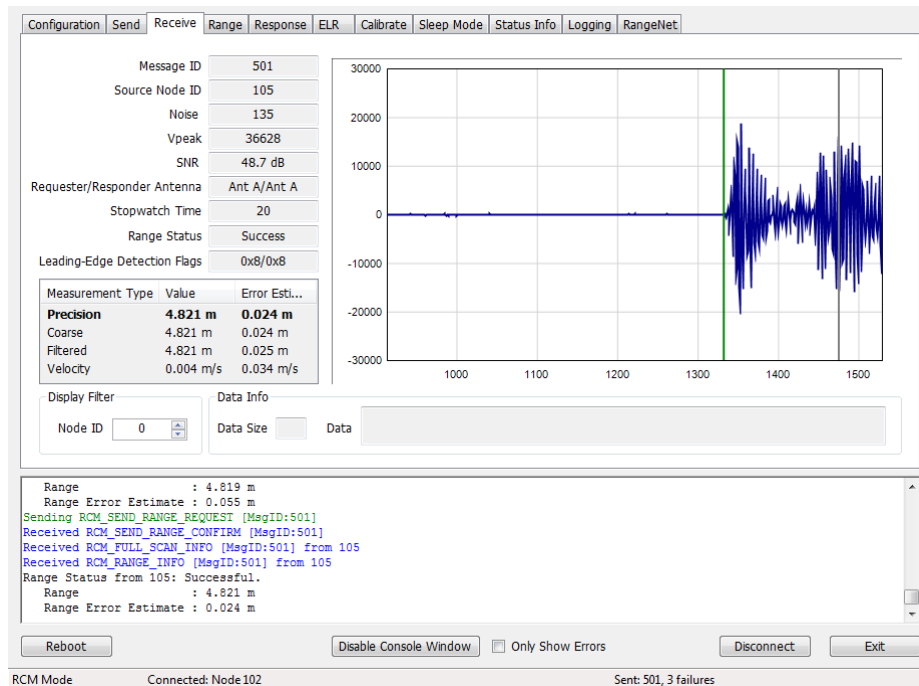


Fig. 3: Typical waveform as displayed by the GUI

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 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 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.

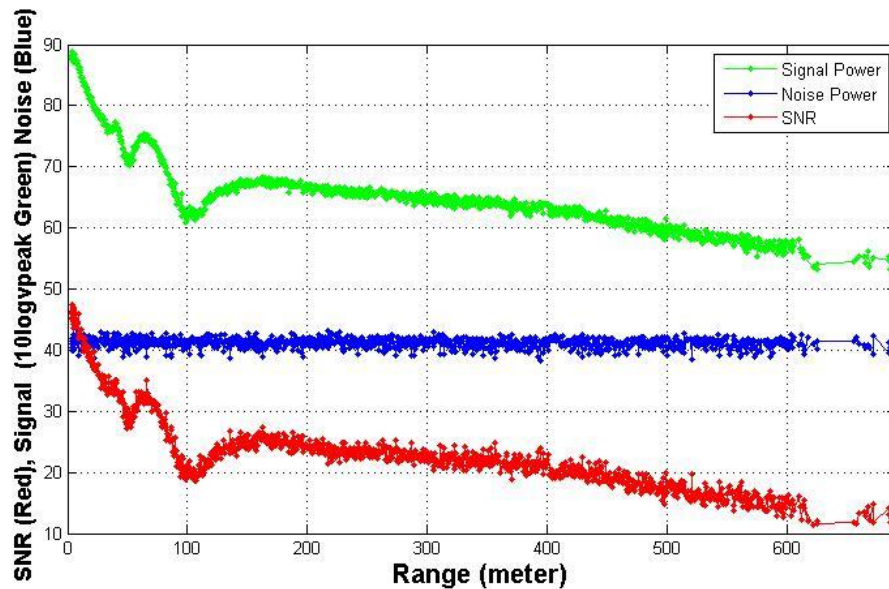


Fig. 4: Signal (green), Noise (blue), and SNR (red) of a link as function of separation distance. (Note the Fresnel cancellation and enhancement.)

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 19%, the

efficiency of this ALOHA network is approximately 38%, 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 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.

Slot #	Requester ID	Responder ID	Pii	Chan.	Antenna Mode	Req. Data	Rsp. Data	Type	Sleep	Manual Time (ms)	Minimum Time (ms)	Get	Set
0	100	101	7	2	Antenna A	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Range	<input type="checkbox"/>	0.000	25.899	Get	Set
1	100	102	7	2	Antenna A	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Range	<input type="checkbox"/>	0.000	25.899	Get	Set
2	100	103	7	2	Antenna A	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Range	<input type="checkbox"/>	0.000	25.899	Get	Set
3	101	100	7	2	Antenna A	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Range	<input type="checkbox"/>	0.000	25.899	Get	Set
4	101	102	7	2	Antenna A	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Range	<input type="checkbox"/>	0.000	25.899	Get	Set
5	101	103	7	2	Antenna A	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Range	<input type="checkbox"/>	0.000	25.899	Get	Set
6	102	100	7	2	Antenna A	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Range	<input type="checkbox"/>	0.000	25.899	Get	Set
7	102	101	7	2	Antenna A	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Range	<input type="checkbox"/>	0.000	25.899	Get	Set

```

Received RCM_SET_OPMODE_CONFIRM [MsgID:1]
Sending RN_SET_CONFIG_REQUEST [MsgID:2]
Received RN_SET_CONFIG_CONFIRM [MsgID:2]
Set RangeNet Configuration: Successful.
Sending RN_SET_TDAMA_SLOTMAP_REQUEST [MsgID:3]
Received RN_SET_TDAMA_SLOTMAP_CONFIRM [MsgID:3]
Set TDMA Slotmap: Successful.
Sending RN_GET_TDAMA_SLOTMAP_REQUEST [MsgID:4]
Received RN_GET_TDAMA_SLOTMAP_CONFIRM [MsgID:4]

```

Fig. 5: Representative RangeNet slot map

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

- 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, RangeNet 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 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.

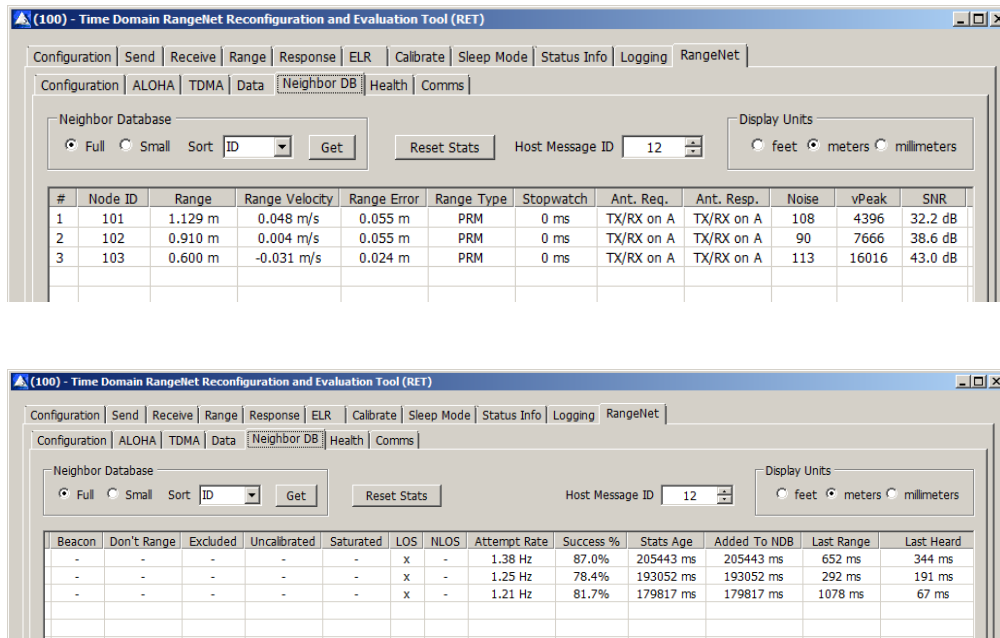


Fig. 6: Representative neighbor database of a 4-node system

2.4.3 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 task which will also:

- 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 7**.

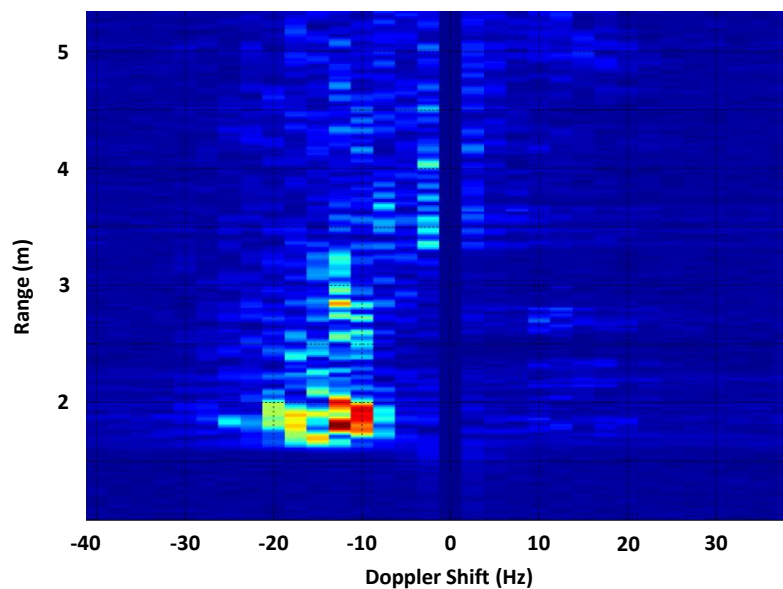


Fig. 7: Range vs Doppler shift from an approaching target

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 8**:

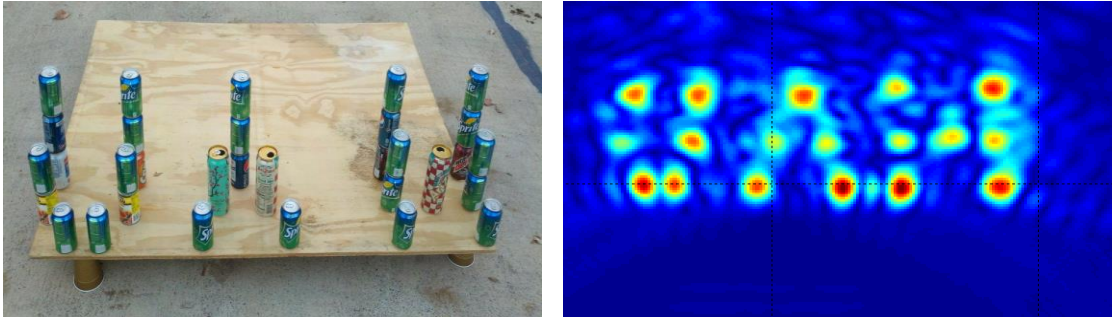


Fig. 8: SAR image of soda cans arranged to form the letters UAH

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 9**:

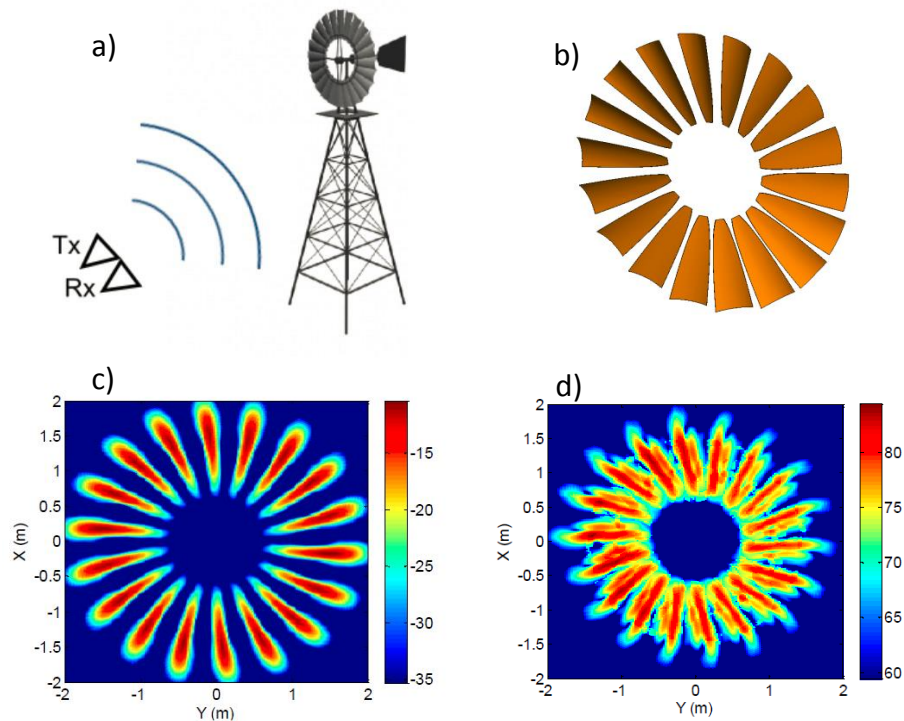


Fig. 9: ISAR image of rotating windmill blades – (a) test setup (b) windmill blades (c) blades as modelled (d) blades as imaged by the ISAR

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>

2.4.4 Bistatic Radar and Propagation with CAT (Channel Analysis Tool)

The CAT API and GUI allow the user to operate the P440 as either 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 10**. 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 and 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.

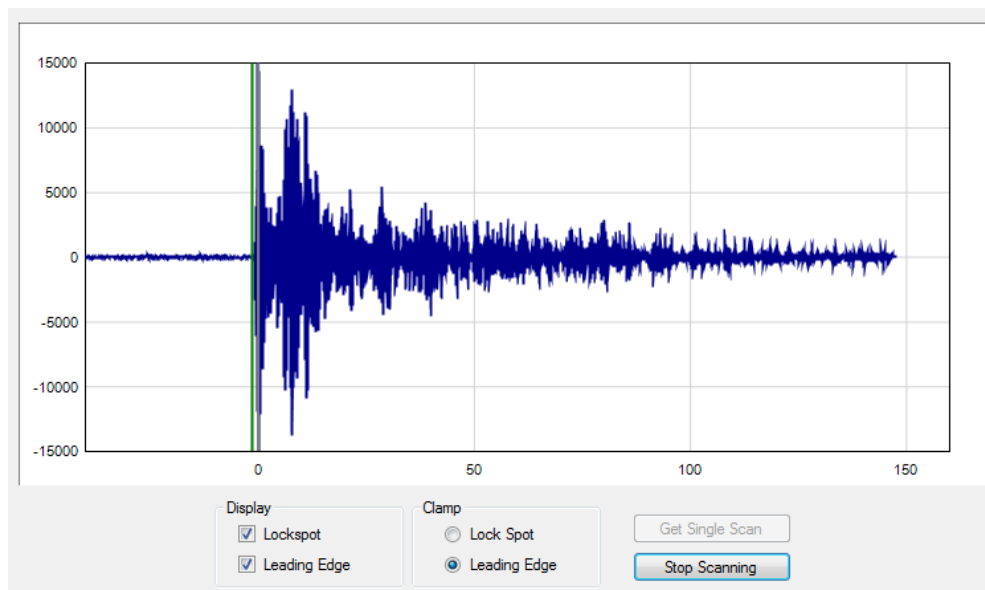


Fig. 10: Captured waveforms can be used by either communications or radar engineers

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 10**). 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 11** and **Figure 12** 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.

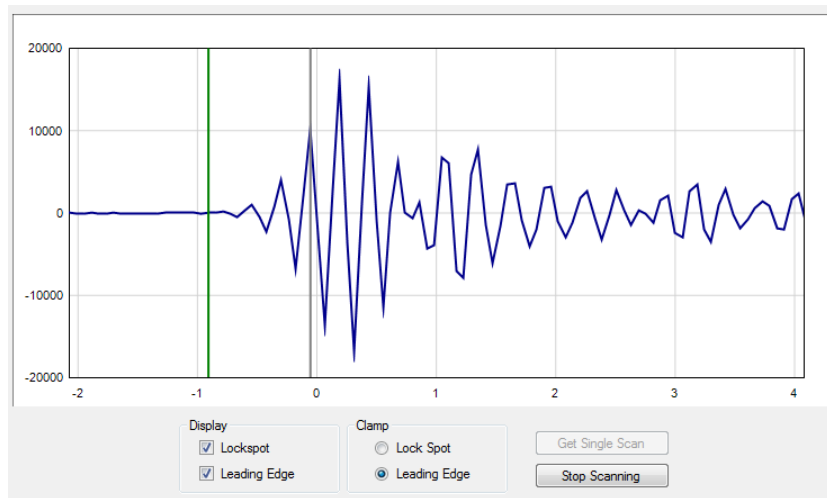


Fig. 11: Waveform scan captured at 61 ps resolution

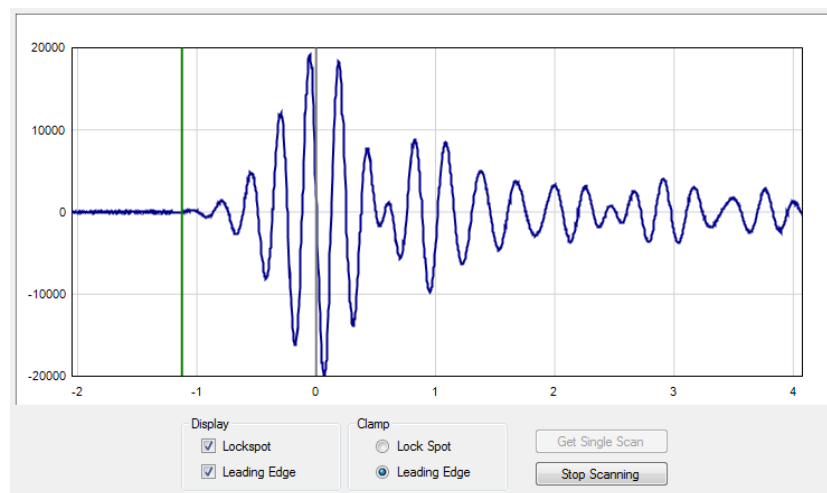


Fig. 12: Waveform scan captured at 4 ps resolution

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

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 13**. Additional detail on the various interfaces is provided in **Section 4**.

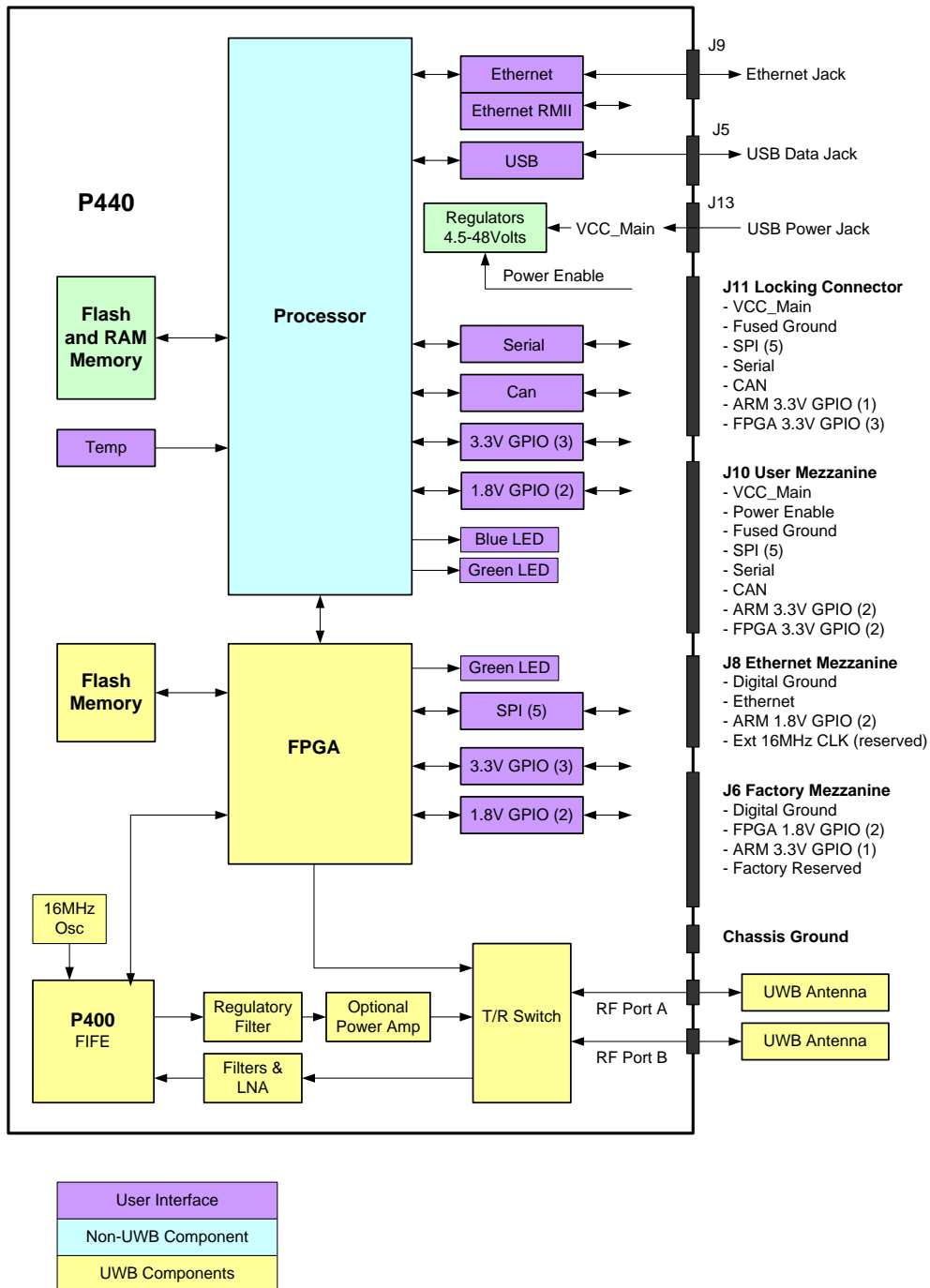


Fig. 13: P440 hardware functional block diagram

The P440 requires less than 2.5 Watts from a DC supply that provides any voltage between 4.5 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 20 dB below the regulatory limit. The exact amount of reduction 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 10 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.

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 via Low Speed Serial, USB 2.0, Ethernet, CAN, SPI
- Connections for up to 15 GPIO pins
- Connections for power (4.5 to 48V), 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 14**) 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**.

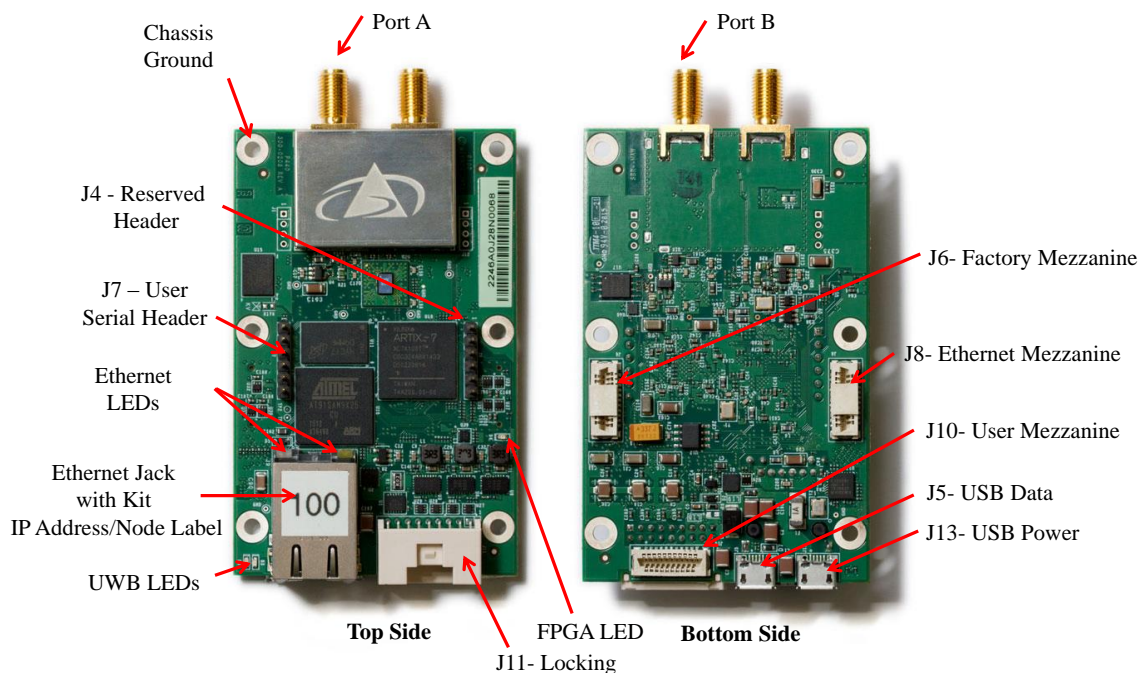


Fig. 14: Top and Bottom assembly drawing of the P440 highlighting key interfaces

Finally, the physical interface for the Chassis Ground is through the designated mounting screw hole shown in **Figure 14**. (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 or Ethernet 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 15a, 15b, 15c, 15d, and 15e**. The numbering convention that defines pin numbers with connector pins is shown on **Figures 15f and 15g**.

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 3.3v.

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	Fused_GND	Ground
6	FPGA_GPIO_2_3.3V	FPGA General Purpose IO #2, 3.3VDC
7	SPI_CLK	SPI Clock
8	Fused_GND	Ground
9	SPI_CS	SPI Chip Select
10	User_Serial_TX	User serial transmit
11	ARM_GPIO_0_3.3V	ARM General Purpose IO #3, 3.3VDC
12	User_Serial_RX	User serial receive
13	Fused_GND	Ground
14	Fused_GND	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 (4.5 to 48v)
18	CAN_LOW	CAN differential low

Fig. 15a: J11 - Locking connector

Pin	Name	Function
1	SPI_MOSI	SPI Master Out, Slave In
2	Fused_GND	Ground
3	SPI_MISO	SPI Master In, Slave Out
4	SPI_INT	SPI interrupt
5	Fused_GND	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	Fused_GND	Ground
11	ARM_GPIO_0_3.3V	ARM General Purpose IO #0, 3.3VDC
12	User_Serial_TX	User serial transmit
13	Fused_GND	Ground
14	User_Serial_Rx	User serial receive
15	ARM_GPIO_1_3.3V	ARM General Purpose IO #1, 3.3VDC
16	Fused_GND	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	Fused_GND	Ground
20	CAN_LOW	CAN differential low
21	VCC_MAIN	Input power (4.5 to 48v)

Fig. 15b: 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_GND	Digital Ground
2	E_Rx1	Ethernet Rx1
3	E_Rxer	Ethernet Rxer
4	E_TxEn	Ethernet TxEn
5	E_Tx0	Ethernet Tx0
6	Digital_GND	Digital Ground
7	E_Tx1	Ethernet Tx1
8	E_CrsDv	Ethernet CrsDv
9	Digital_GND	Digital Ground
10	E_TxCk	Ethernet TxCk
11	E_Rx0	Ethernet Rx0
12	Digital_GND	Digital Ground
13	E_MDIO	Ethernet MDIO
14	E_MDC	Ethernet MDC
15	Digital_GND	Digital Ground
16	Digital_GND	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_GND	Digital Ground
20	Digital_GND	Digital Ground
21	Ext_16MHz_In	Reserved

Fig. 15c: J8 – Ethernet Mezzanine connector

Pin	Name	Function
1		Reserved
2		Reserved
3		Reserved
4		Reserved
5	Digital_GND	Digital Ground
6	Digital_GND	Digital Ground
7		Reserved
8		Reserved
9		Reserved
10		Reserved
11	Digital_GND	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_GND	Digital Ground

Fig. 15d: 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. 15e: J7 – User Serial 0.1” Header

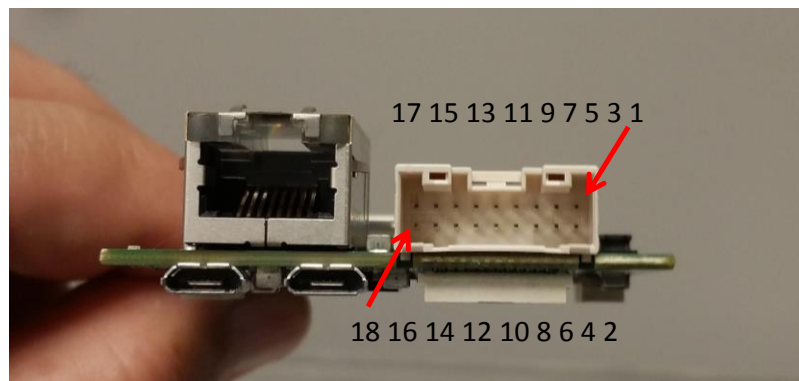


Fig. 15f: Locking connector pinouts

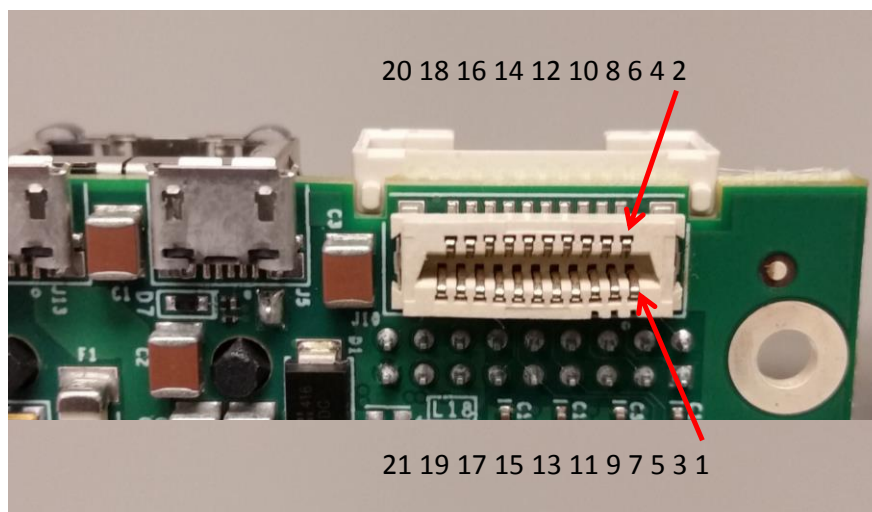


Fig. 15g: J10 Mezzanine connector pinouts

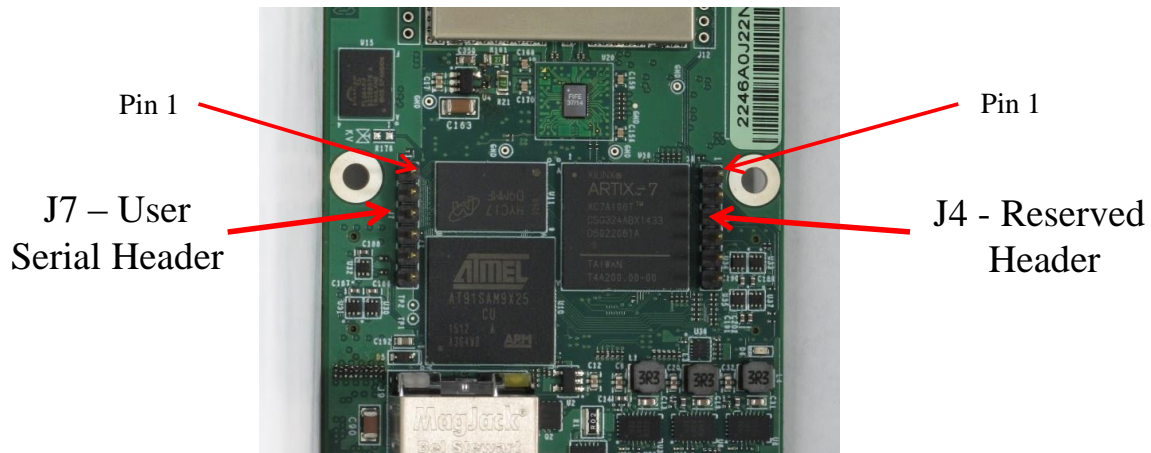


Fig. 15h: User Serial pinouts

4.3 Powering and Grounding the Unit

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

The P440 is provided in Development Kits or Labs as a “Kit Radio” and individually as an “Industrial Module.” The difference between the two is a configuration option. P440s provided as Kit Radios are powered through the USB Power jack (J13). P440s 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 through 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 volts while simultaneously connecting power through the USB Power jack at 5 volts. 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 and can be driven by any voltage between 4.5 and 48 volts.

4.3.3 Two means of Powering the P440

There are two techniques for supplying power to the 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 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. The position of this hole is shown in **Figure 14**.

4.3.5 Fused_Ground and Digital_Ground

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.

4.3.6 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 16 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.

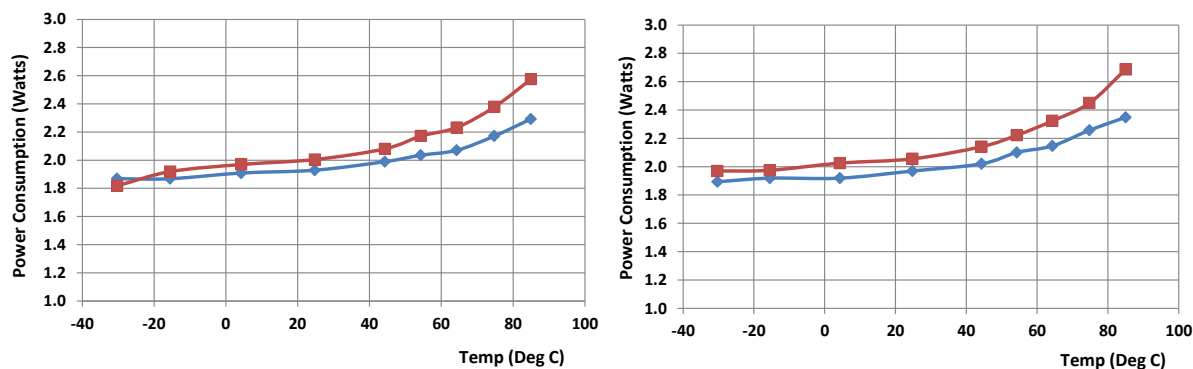


Fig. 16: Power Consumption as a function of board temperature for two representative P440s (red and blue) when operated as a transmitter (left) and as a receiver (right)

Figure 17 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. 17: 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 “*Using the USB and Serial specifications*. 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 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.

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.

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 port consists of five signals. Four of these are the typical SPI signals: CLK, CS_n, 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 18**. The SPI slave RX and TX FIFOs are 4k x 8.

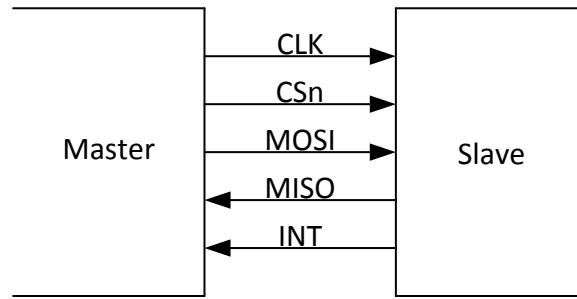


Fig. 18: SPI interconnect signals

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 19**:

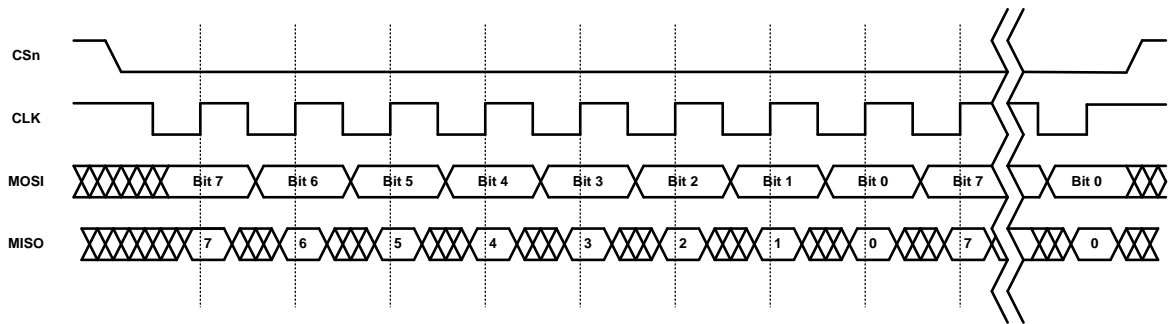


Fig. 19: Signaling timing diagram

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 20**. 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 21**. Timing constraints are shown in **Figure 22**.

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. 20: SPI command structure

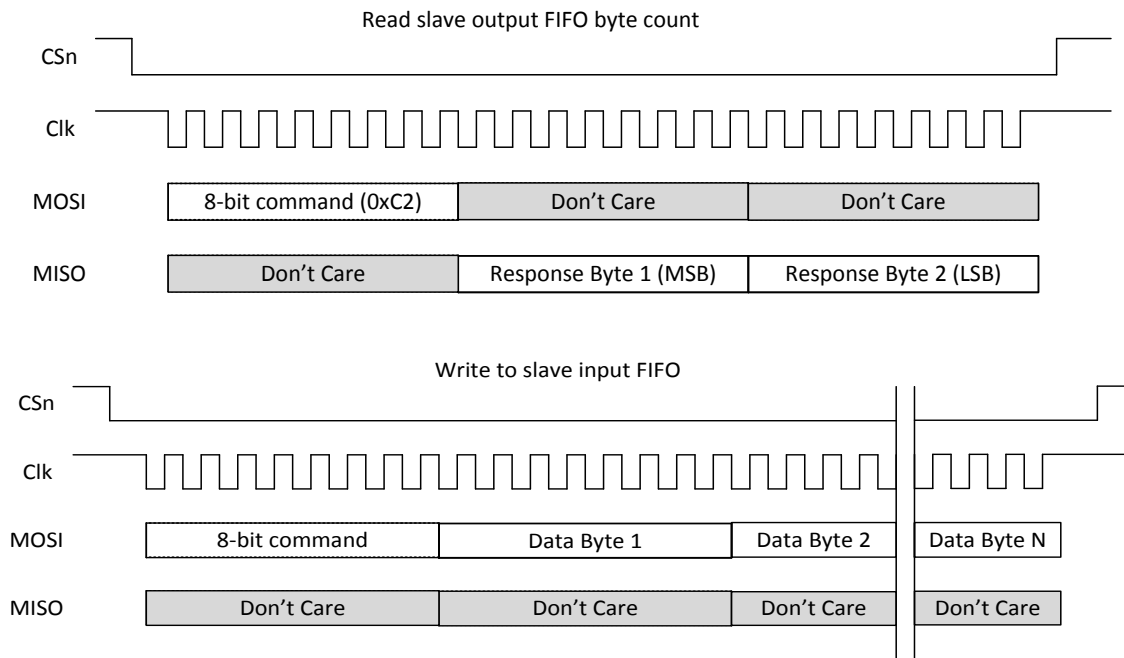
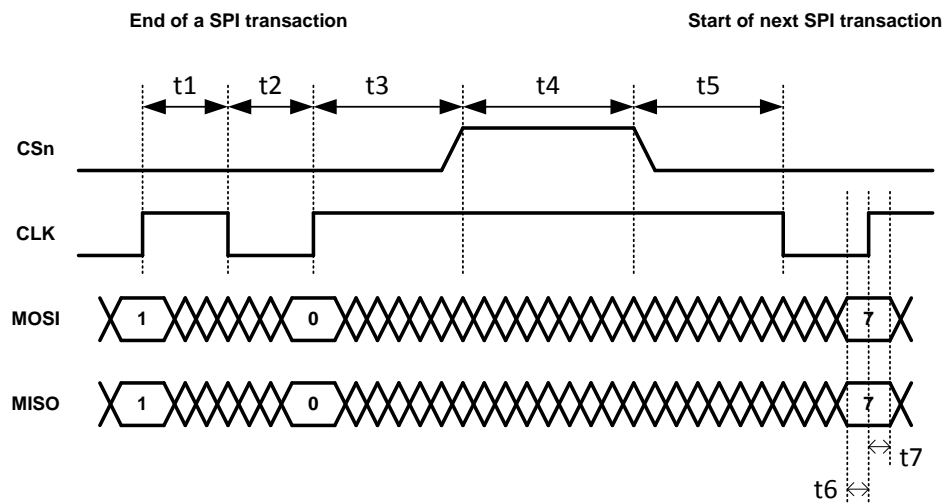


Fig. 21: Timing diagrams



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. 22: 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 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, *150-0107D 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 set by the Dynamic Host Configuration Protocol (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 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.

Instructions on how to connect to the P440 via Ethernet or change the IP address and Node ID are provided in the following document: *320-0328 Connecting to P440 with Ethernet*.

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.

4.5 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.

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 23** lists the various GPIO pins and their associated connector and pin number:

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. 23: GPIO and associated connector and pin locations

As of this date, there is currently no software support (i.e. API commands) for controlling the state of the GPIOs. Similarly, the function of the SPI lines is currently fixed such that these lines can only be used for SPI. Time Domain expects to provide expanded support for GPIOs in an upcoming software release.

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 US 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 receive characteristics of the EU and FCC devices are identical. Both devices use a pair of identical bandpass filters arranged in a bandpass/LNA architecture. The characteristics of a single bandpass filter are shown below in **Figure 24**.

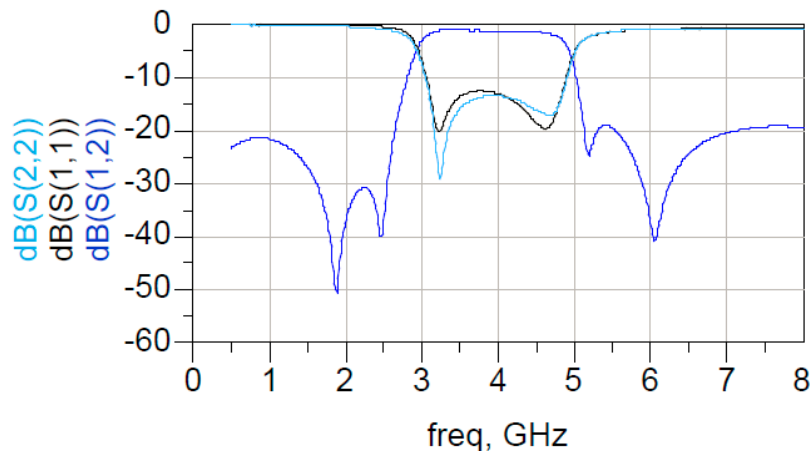


Fig. 24: Characteristics of a single bandpass filter

4.8 Optional Power Amplifier

The P440 can be provided with an optional power amplifier which boosts the transmit power by approximately 16 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.

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.

Units which are provided with an optional power amplifier will *not* carry an FCC 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.

4.9 Indicator Lights

The P440 is provided with five indicator LEDs. See **Figure 14** 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
 - On initiation of a Range or Network Data packet transmission
 - On initiation of a Network Beacon transmission
 - On initiation of a CAT packet transmission
 - On initiation of a CAT packet reception
 - 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 be on. The Blue LED will stay on for approximately 5 seconds. This period is the boot time of the radio. Once the unit has successfully booted, the Blue LED will blink approximately every 2 seconds. 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

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 25**.



Fig. 25: 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 26**. 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. 26: 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 3000mAh 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 27**). 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. 27: 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.

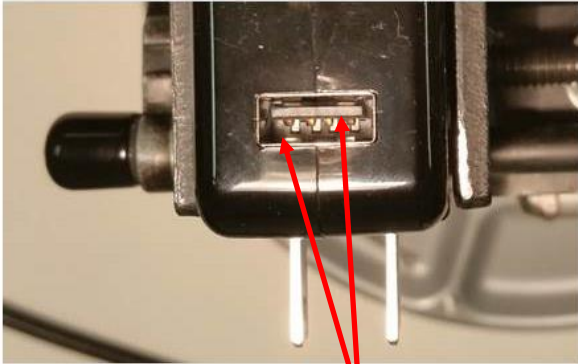
In principle, there is nothing special about these components and they are almost universally available. The user is free to provide substitutes and replacements for units that are lost or damaged. While Time Domain does stock the USB battery all of these components are available on the web from a variety of sources. **Table 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 3000mah External Portable Rechargeable Battery	
6 ft/ 1.7 m USB cable	6ft USB 2.0 A Male to Micro 5pin Male 28/28AWG Cable	Monoprice product number 12002
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 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. Some batteries and power supplies have very poor connectors. These connections are so flimsy that they provide power only intermittently. Consider the devices shown in **Figure 28**. The connector on the left provides a high quality connection. The one on the right will cause endless problems. 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. 28: Superior connections (left) and inadequate product (right)

When providing power from USB devices do NOT 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 29, 30, 31, 32, and 33 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 2 lists the part numbers of all connectors and their respective mating pair.

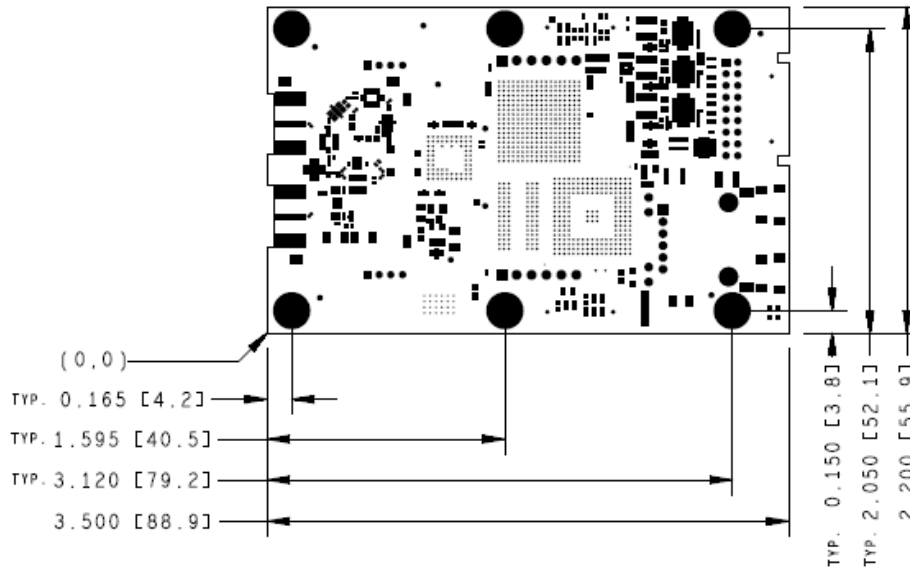


Fig. 29: P440 board dimensions

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.

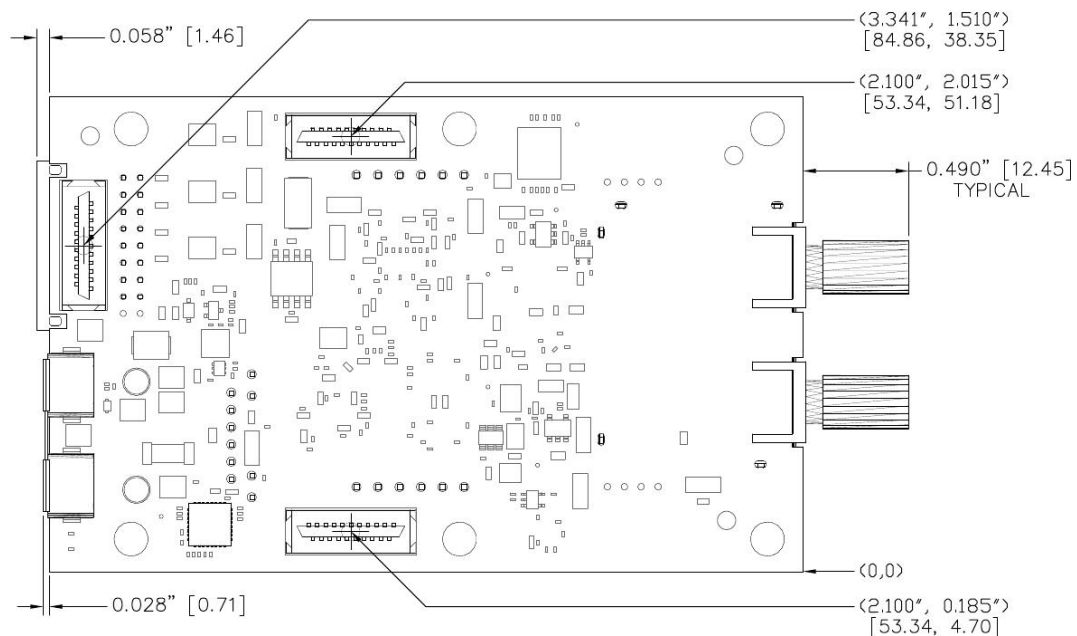


Fig. 30: Locations of Mezzanine connectors

Also shown in **Figures 30** and **31** 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.

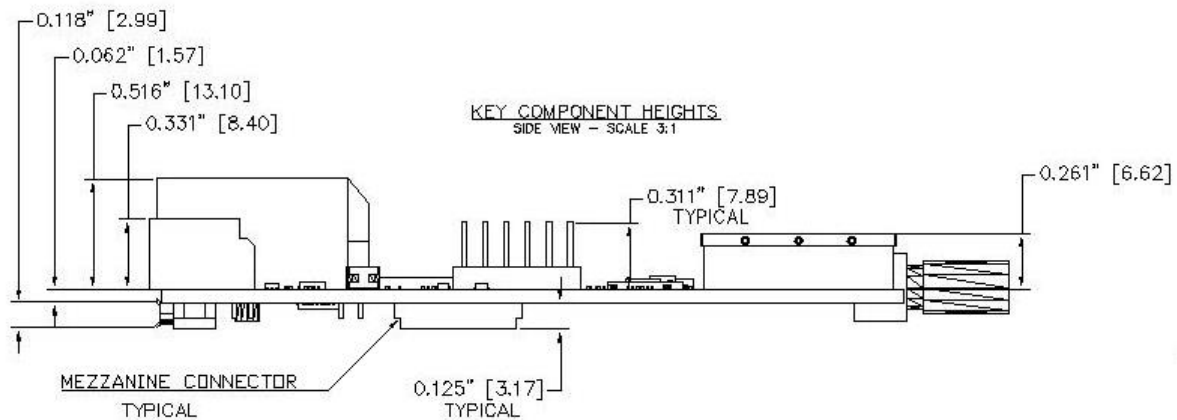


Fig. 31: Components which limit vertical height

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.

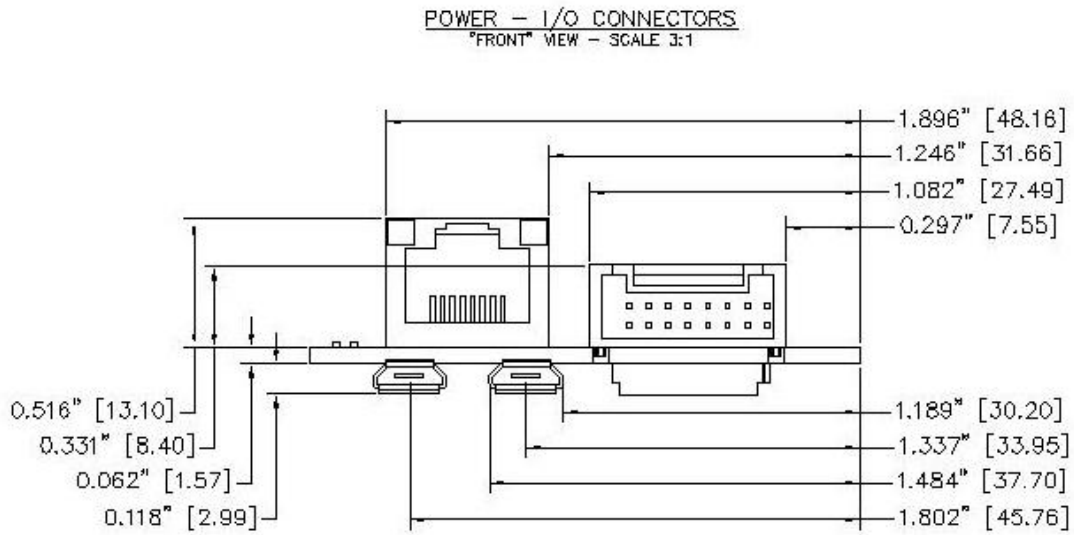


Fig. 32: Locations and dimensions of Power and I/O connectors at the rear of the P440

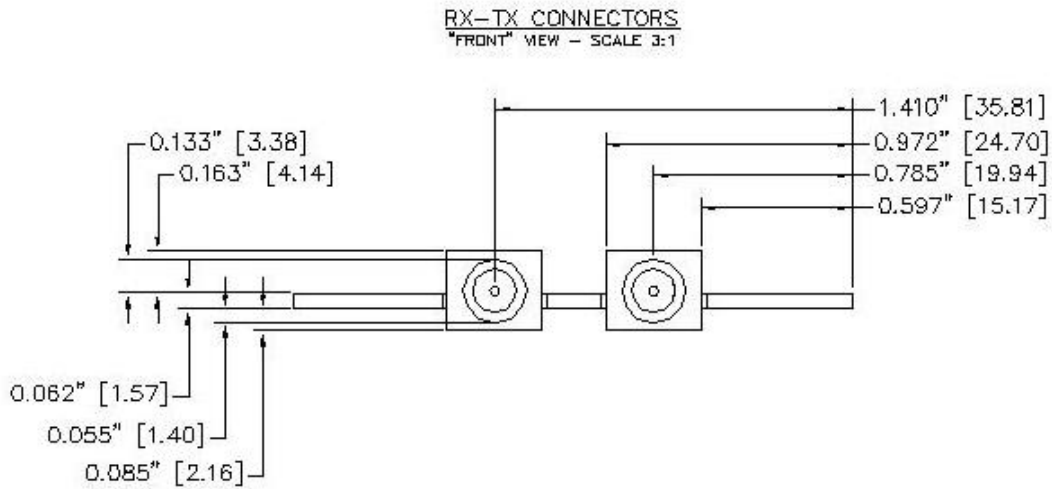


Fig. 33: Locations and dimensions of RF SMA connectors

The part numbers for the P440 connectors and their mating pair are shown in **Table 2**.

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: PUDP-(18)V-S, Digikey# 455-2473-ND
J13 - USB Power	FCI# 10103594-0001LF, Digikey# 609-4050-1-ND	Many different choices. *

Table 2: 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 3 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:	-40°C to 85°C
Max allowable board temperature:	85°C (as reported by on board temp sensor)
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.
Power & Ground & Boot Times	
Input Power Range:	4.5 V to 48 V DC
Input Power Ripple:	100 mV pk-pk
Power Protection:	Reverse voltage
Electrostatic Discharge Protection:	+/-8kV contact discharge and +/-15kV air-gap discharge
Chassis Ground:	Available. See Section 4.3.4 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 temp 40°C, Vin= 5.0 V with state transition times shown)	See Section 4.3.6 for details
- Active (transmitting)	2.0 Watts
- Active (receiving)	2.1 Watts
- IDLE, Standby_E, Standby_S	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)	2.9 Watts
- Active (receiving)	3.0 Watts
- IDLE, Standby_E, Standby_S	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: 480 Mbps See Section 4.4.2 for more details
Serial:	3.3V TTL Serial UART (8, n, 1) 115.2kbps (typical) 921.6kbps (over short, ~15cm cable) See Section 4.4.3 for more details
Ethernet:	10/100 See Section 4.4.5 for more details
SPI:	3.3V TTL levels 16Mbps maximum clock rate See Section 4.4.4 for more details
CAN:	See Section 4.4.6 for details
GPIO available:	<ul style="list-style-type: none"> • 3 Processor GPIO pin (3.3V) • 2 Processor GPIO pin (1.8V) • 8 FPGA GPIO pins (3.3V), 5 of which can be used for SPI • 2 FPGA GPIO pins (1.8V) See Section 4.5 for more details
On Board Temperature Sensor:	-40°C to 125°C, +/- 2.0°C

RF Characteristics	
Transmit Operating Band:	Generally 3.1 to 4.8 GHz Region 1: Designed for compliance to US FCC mask with certification expected late 2015 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™ Toroidal Dipole Antenna (0 dB) as well as a wide variety of 3 rd 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 Transmit to Receive 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)
RF Communications	
Channelization:	11 user selectable pseudo-random pulse interval channels. Others available for special applications.
Max Range (with standard BroadSpec Antennas):	Free Space: 240m Level ground: 1000m (3200ft) See Section 6.2 for details
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 (standard Broadspec Antennas)	Free Space: 240 m Level ground: 1000 m (3200 ft) See Section 6.2 for details
Precision (3 Standard Deviations)	2.3 cm (See Section 6.4)
Accuracy (Bias error):	2.1 cm (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
Radar Performance	
Approximate Detection Range (high power transmission)	Person Walking: 80 m Person Crawling: 40 m Vehicle: 100 m (See Section 6.7)

Table 3: 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. 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 34**. 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 34**. 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 34** 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.

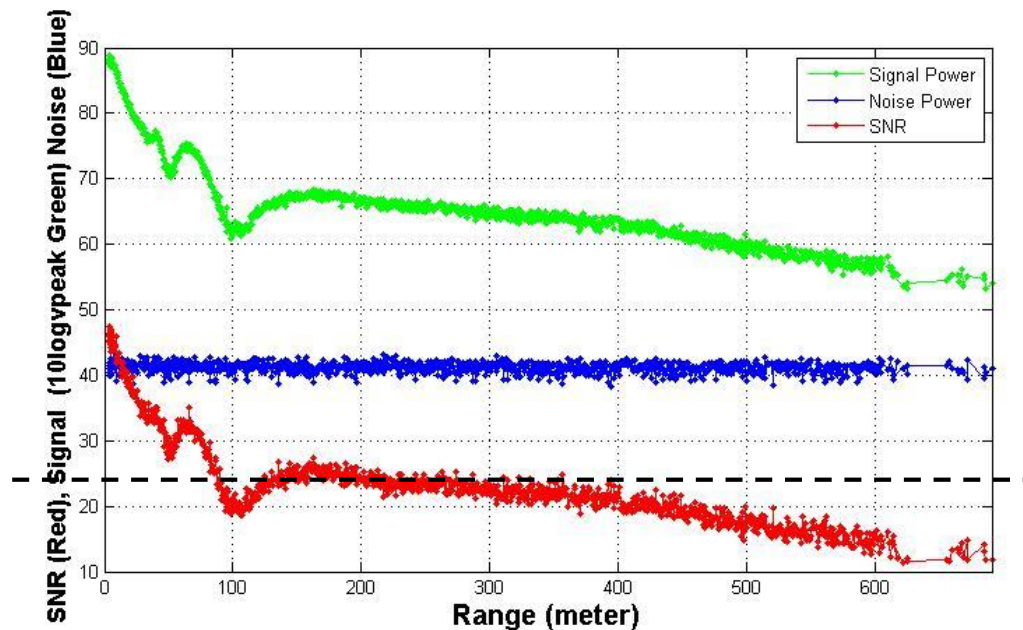


Fig. 34: Fresnel cancellation at 100 m can limit performance. If the SNR required to operate was 23 dB as shown by the black line, then the radio will work out to 210 m but not between 90 and 120 m.

When operating long distance 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 34**, 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 34** 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 4**. 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 4: 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 5** and is achieved when two radios are operated as a network consisting of a single requester unit and a single responder unit.

PII	Range Conversation Time (milliseconds)	Maximum Range Measurement Rate (Hz)
4	8.0	125.0
5	9.7	103.1
6	13.7	73.0
7	21.3	46.9
8	36.7	27.2
9	68.0	14.7

Table 5: Data and ranging performance characteristics at maximum legal transmit power

6.4 Precision Range Measurement Precision, Accuracy, and Bias

6.4.1 Precision and Accuracy in LOS Conditions

The Line of Sight (LOS) Precision and Accuracy specification is based on a measurement campaign that included 20,000 range measurements taken in an open field, over an operating range that varied from 2 ft. to 300 ft., for PII's 4 through 8 inclusive, at minimum and maximum transmit gain, when the received signal was linear and also when it was in compression. The quoted values are the results of the composite of all of the measurements. This includes combinations of settings that may not be

reasonable (e.g., operation at minimum range and maximum transmit power). It is believed to be a conservative estimate of the system's ranging Precision and Accuracy.

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.

The measurement campaign referenced above was conducted in 2011. Since that time several significant improvements have been made to the range measurement algorithm. The overall measurement accuracy (precision and bias) has been field-verified using a survey-grade laser. While the test was limited in scope, the results suggest that the overall measurement accuracy is substantially better than the value quoted in this specification. These tests were conducted in an open field and indicate overall accuracy closer to 1 cm. While the tests' size is too limited to warrant a change in the published specification, the user should expect similar results, especially when operating in a similar environment.

By constraining operation to a narrower field of application, users have achieved higher performance. One user has reported accuracies of 0.5 cm while a second reports 2 mm accuracy.

6.4.2 Precision and Accuracy 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. At the opposite end of the propagation spectrum would be operation inside a metal ship. Because metal blocks radio frequencies, the operating range would be limited to the size of the room. Operation in NLOS conditions must be determined empirically. Having said that, we routinely measure range from one side of our office space to the other (a distance of 30 meters through an environment that is not only NLOS but is also occluded by large amounts of metal) with an accuracy of better than +/- 1 meter.

6.4.3 Bias and Calibration

The Precision (Standard Deviation) and Accuracy (Bias error) of the TW-TOF range measurement are called out in **Section 6.1, Table 3** and discussed in **Section 6.4.1**.

It should be noted that Bias is measured using the standard Broadspec antenna with a 90-degree SMA connector.

When a P440 leaves the factory its bias will be zeroed to within a few centimeters. This ensures that when a user takes a range measurement, the result should compare favorably with a measurement taken with a laser. This assumes that the measurement is clear line of sight, not in compression and not affected by Fresnel cancellation or enhancement. If that is the case, then most users will find the result satisfactory. Furthermore, this result will not change materially over the operating temperature range.

However, sometimes it is necessary to use a different cable, connector or antenna. In this case the Bias will change. Furthermore, some applications may require a more accurate zeroing of the Bias than what is normally provided from the factory. In either of these cases it will be necessary to characterize and adjust individual P440s. Application note *320-0327 Distributed Calibration of Time Domain UWB Radios* describes such a process. Once the user has determined by how many cm the calibration needs to be adjusted, then this number should be converted to picoseconds and entered through the RCM_Set_Config_Request API message or through the Configuration Tab on the

RangeNet RET GUI. To convert from cm to picoseconds, use the following equation:

$$0.2993 \text{ mm of delay} = 1 \text{ picoseconds}$$

In other words, if you add a cable between an antenna and an antenna port which has exactly 1 meter of delay, then you should increase the value of the antenna delay for that antenna port by 3341ps.

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 34**.

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** shows the relationship between PII (Pulse Integration Index) and data throughput.

PII	Bytes sent using Code Channel 2	
	100	1000
	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: 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. Users limited to the legal maximum transmit power and with no antenna flexibility should half the numbers shown in **Table 3**.

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 35** below).

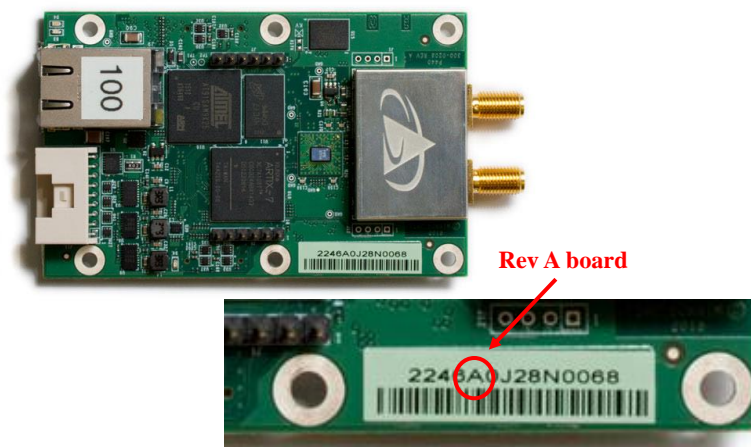


Fig. 35: P440 Version indicated in bar code. Unit shown is a Rev A board.

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 service.

P440 Rev B

- Ethernet through the mezzanine connector is not supported.

7 Broadspec Antenna

The P440 is designed to operate with the Broadspec antennas shown in **Figure 36**. 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" (3.0 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 36**.

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

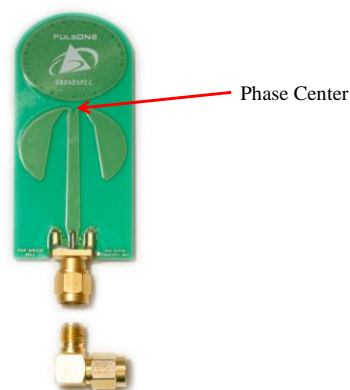


Fig. 36: Broadspec antenna with phase center indicated

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 antenna is currently in the process of being certified in the US as a standalone device. This certification is expected late in 2015.

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 37**. (**Note: This certification is currently in process with formal certification expected in late 2015.**)

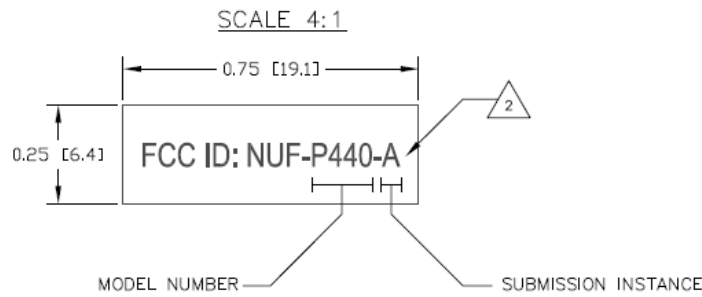


Figure 37: FCC ID number

This label is located on the back or bottom side of the P440. See **Figure 38**.

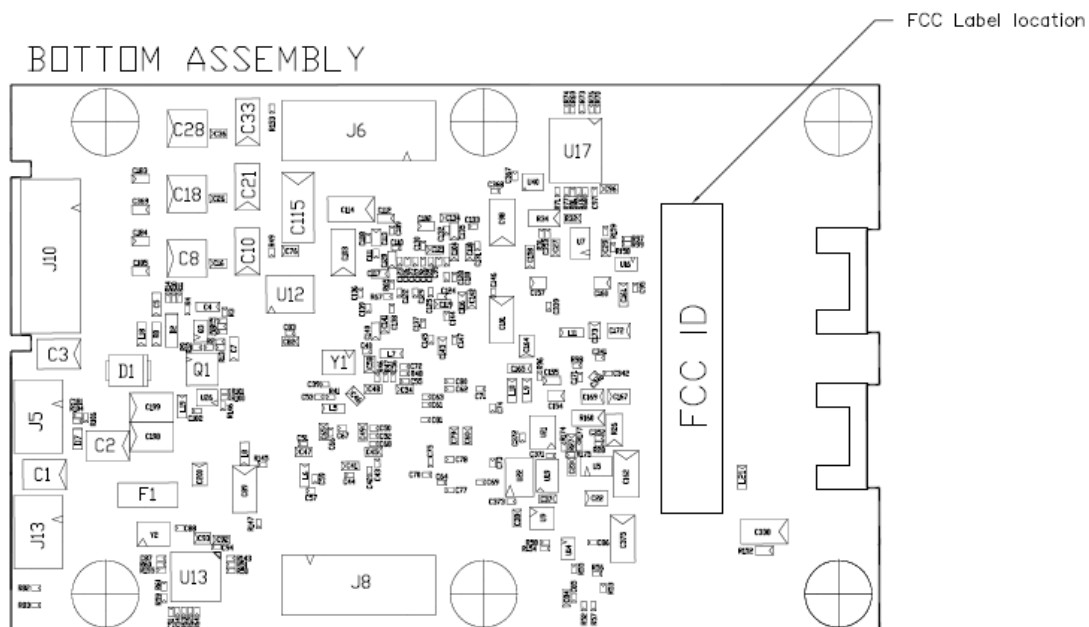


Fig. 38: Location of certification number

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 compliant 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

Time Domain has self-certified the P440 in all its variations under Export Commodity Control Number (ECCN) 5A001b.4 pending formal classification from the U.S. Department of Commerce's Bureau of Industry and Security. This self-certification is based upon the Bureau's previous assignment of ECCN 5A001b.4 to the company's P400 modules. Products falling under ECCN 5A001b.4 are controlled for export purposes pursuant to the Commerce Control List for National Security and Antiterrorism. 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 product to more than a dozen 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. Also Kit modules are powered through the USB connector while Industrial Modules are typically powered through the Locking connector. 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 5.5 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. 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.

The following table provides the name of the configuration, a part number, and 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 <ul style="list-style-type: none"> • 5 P440 modules <ul style="list-style-type: none"> ○ 140RM01 for Region 1 ○ 140RM02 for Region 2 • 5 Broadspec antennas (100ANR3) • 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 <ul style="list-style-type: none"> • 2 P440 modules <ul style="list-style-type: none"> ○ 140RM01 for Region 1 ○ 140RM02 for Region 2 • 4 Broadspec antennas (100ANR3) • 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 <ul style="list-style-type: none"> • 10 P440 modules <ul style="list-style-type: none"> ○ 140RM01 for Region 1 ○ 140RM02 for Region 2 • 20 Broadspec antennas (100ANR3) • 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)

		<ul style="list-style-type: none"> • 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)	<p>Contains</p> <ul style="list-style-type: none"> • 20 P440 modules <ul style="list-style-type: none"> ○ 140RM01 for Region 1 ○ 140RM02 for Region 2 • 40 Broadspec antennas (100ANR3) • 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	100ANR1	Single Time Domain UWB Antenna (3-6 GHz) female SMA connector and right angle SMA connector
Broadspec Antenna	100ANR2	Single Time Domain UWB Antenna (3-6 GHz) male SMA connector
Broadspec Antenna	100ANR3	Single Time Domain UWB Antenna (3-6 GHz) male SMA connector and right angle SMA connector
Accessory Series		
P440 Enclosure	340EN01	Single P440 Enclosure

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 16 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.