# Journal of Visualized Experiments

## Continuous-Wave Propagation Channel-Sounding Measurement System—Testing, Verification, and Measurements

--Manuscript Draft--

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|---|---|
| **Article Type:** | Invited Methods Article - JoVE Produced Video |
| **Manuscript Number:** | JoVE62124R1 |
| **Full Title:** | Continuous-Wave Propagation Channel-Sounding Measurement System—Testing, Verification, and Measurements |
| **Corresponding Author:** | Chriss Hammerschmidt<br>National Telecommunications and Information Administration<br>Boulder, CO UNITED STATES |
| **Corresponding Author's Institution:** | National Telecommunications and Information Administration |
| **Corresponding Author E-Mail:** | chammerschmidt@ntia.gov |
| **Order of Authors:** | Chriss Hammerschmidt |
| | Robert Johnk |
| | Savio Tran |
| | Mike Chang |
| **Additional Information:** | |
| **Question** | **Response** |
| Please specify the section of the submitted manuscript. | Engineering |
| Please indicate whether this article will be Standard Access or Open Access. | Open Access (US$4,200) |
| Please indicate the **city, state/province, and country** where this article will be **filmed**. Please do not use abbreviations. | Boulder, CO, USA |
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**TITLE:**

# Continuous-Wave Propagation Channel-Sounding Measurement System—Testing, Verification, and Measurements

**AUTHORS AND AFFILIATIONS:**
Chriss A. Hammerschmidt, Robert T. Johnk, Savio Tran, Mike Chang
National Telecommunications and Information Administration, Institute for Telecommunication Sciences, Boulder, CO, USA

**Email addresses of co-authors:**
Robert T. Johnk (rjohnk@ntia.gov)
Savio Tran (stran@ntia.gov)
Mike Chang (mchang@ntia.gov)

**Corresponding author:**
Chriss A. Hammerschmidt (chammerschmidt@ntia.gov)

**KEYWORDS:**
Continuous-Wave, Measurements, Radio Propagation, Testing, Validation, System Verification

**SUMMARY:**
This report describes the setup, validation and verification, and results from propagation measurements using a continuous-wave, radio frequency channel-sounding measurement system.

**ABSTRACT:**
Channel sounders are used to measure channel characteristics for radio systems. There are several types of channel sounders used today: continuous-wave (CW), direct pulse, frequency domain using a vector network analyzer (VNA), correlation-based, and swept-time delay cross-correlator. Each of these has unique advantages and disadvantages. CW systems have a larger dynamic range than other systems with a signal that can propagate further into the environment. As the audio sampling rates allow smaller file sizes than other systems, data collection can be continuous and last for several hours. This article discusses a CW-channel sounder system, which has been used to make numerous propagation loss measurements in various cities in the United States of America. Such propagation measurements should be accurate, reproducible, and free of artifacts or biases. This article shows how to set up the measurement, how to validate and verify that the system is making reliable measurements, and finally, it shows results from some of the measurement campaigns such as repeatability measurements, clutter loss measurements (where clutter loss is defined as the excess loss from free-space transmission loss), and reciprocity measurements.

## INTRODUCTION:

The Institute for Telecommunication Sciences (ITS) is the research laboratory of the National Telecommunications and Information Administration (NTIA), an agency of the U.S. Department of Commerce. ITS has a long history of conducting accurate, well-regarded radio frequency (RF) propagation measurements. The increase in spectrum-sharing has been accompanied by the need for accurate, reproducible measurements that provide a better understanding of the radio environment that multiple services will have to share. For the past few years, the military services have been developing spectrum-sharing arrangements with commercial wireless carriers in the Advanced Wireless Services (AWS)-3 band (1755–1780 MHz)[1]. This will allow commercial wireless carriers to use the AWS-3 band prior to phasing military services out of the band. The use of the band will be coordinated by both isolating systems geographically and by modeling frequency interference scenarios. To share this band of spectrum, propagation measurements are necessary to develop and improve propagation models for the evaluation of RF interference between the military and commercial wireless systems within the band.

The Defense Spectrum Organization (DSO) is responsible for the management of the AWS-3 transition and has tasked ITS and others with performing a series of channel-sounding measurements. These measurements will be used to build new models for the calculation of the impact of foliage and man-made structures in the environment (collectively known as clutter). Improved propagation modeling that accounts for clutter could lead to fewer restrictions on commercial transmitters in the vicinity of military systems. The CW-channel-sounder system discussed in this article has been used for the past five years to collect radio propagation measurement data and calculate the clutter attenuation. This measurement system produces accurate, repeatable, and unbiased results, and DSO encouraged ITS to share its institutional knowledge—including best measurement practices for the measurement and processing of RF propagation data—with the wider technical community.

Best measurement practices require understanding a system from the component level to the assembled-system level. These best measurement practices have been documented in the recently published NTIA Technical Memorandum TM-19-535[2] that describes a set of best practices for the preparation and verification of radio propagation measurement systems. ITS recently completed a JoVE article on calibrating a VNA used to measure component losses and identify bad components for this measurement system[3]. This article is a continuation in documenting these best measurement practices for the wider community. Although best practices are discussed in this article for a CW-channel sounder, these same techniques can be used to verify other channel sounder systems: VNA systems; CW systems; full-bandwidth, correlation-based systems; direct pulse systems; and sliding correlator-based systems[4-6].

This article describes in detail how to setup a CW-channel sounder measurement system using a vector signal analyzer (VSA), a spectrum analyzer (SA), two rubidium oscillators, a power meter, a vector signal generator (VSG), and various filters and power dividers for measurements in an outdoor measurement environment[7,8]. The transmitting side of the system consists of the VSG, which generates a CW signal that is boosted by a power amplifier. This is then split by a directional couple to divert some of the signal to the power meter, which allows the user to monitor the system output. The rest of the signal is sent to the receiving side of the system via the propagation channel. The receiving side consists of a low-pass filter to reduce interference and harmonics produced by the power amplifier. The filtered signal is split in a power divider and fed into the

SA for monitoring during the measurement along with a time stamp and Global Positioning System (GPS) location. The other half of the signal is sent to the VSA to be downconverted into in-phase quadrature (I-Q) data in the range of 1–5 kHz. The sampling rate is determined by the instrument span[9] and is guided by the expected Doppler spectrum shifts, which are a function of the speed of the vehicle. The resulting time series is then transferred to a computer for postprocessing and data analysis.

Rubidium clocks are used at both the transmitter and receiver to provide highly accurate measurements and highly stable frequencies. The rubidium clock at the receiving end has a fine frequency adjustment for the precise alignment of the transmitting and receiving frequencies. Typically, the frequencies are adjusted to be within 0.1 Hz of each other for testing. Rubidium clocks are essential for high-accuracy CW propagation measurements. They ensure precise time base accuracy over the course of the measurements and prevent frequency drift of the transmitter and receiver. This article also details how to validate and verify that a system is making accurate measurements in a laboratory setting, both with and without an antenna, prior to making measurements in an outdoor environment. The system has been used for an extensive series of outdoor and indoor tests at frequencies ranging from 430 MHz to 5.5 GHz and for many different transmitting powers[7,8,10].

**PROTOCOL:**

NOTE: The ITS channel sounder system is shown in **Figure 1** and **Figure 2**, and a benchtop evaluation setup is shown in **Figure 3**. Reference these figures while setting up the CW-channel sounder to ensure all components are properly configured. The following sections explain how to verify and validate a system prior to making measurements.

**1. Measurement system setup**

NOTE: This section describes how a system is set up for field measurements. First, system losses in both the transmitting and the receiving side of the system must be accounted for and measured separately before the full system is assembled. Then, the full system is assembled, and individual instruments are configured, calibrated, and synchronized to prepare for lab verification and validation.

1.1. Measure the S-parameters, using a VNA[2], for individual system components before assembling the system: cables, attenuators, power splitters, directional couplers, and low-pass filters.

NOTE: This will characterize losses and identify broken cables, or a device out of specification.

1.2. Assemble the Type N cable at the output of the power amplifier, the directional coupler, the bandpass filter, and the Type N cable that will be connected to the antenna, and use the VNA to measure the component chain.

NOTE: This measurement will include internal reflections that are not seen by measuring individual components with a VNA.

1.3. Record the $S_{21}$ value, which will be a negative number, and will be used as the transmitting system losses. Use these values to correct the received signal level discussed in the representative results section.

1.4. Transmitting system setup

1.4.1. Plug in all devices to a power source: either an uninterruptible power supply (UPS) or a surge-protected set of outlets. Make sure that all instruments are in a powered off state while hooking components together.

1.4.2. Assemble the transmitting equipment (**Figure 1**).

1.4.2.1. Connect the 10 MHz output of the rubidium oscillator to the **Ref IN** port of the VSG using a Bayonet-Neill-Concelman (BNC) cable. Connect **RF OUT** port of the VSG to the input of the directional coupler **IN** port using a Type N cable.

1.4.2.2. Connect the **OUT** port of the directional coupler to the input port appropriate bandpass filter (if needed) using a Type N female to female connector.

1.5. Assemble the Type N cable that will be connected to the receiving antenna, the filter, the cable between the filter and the power splitter, and the Type N cable that will be connected to the VSA; use the VNA to measure this system of components.

1.6. Make the same measurement, but through the same components connected to the SA. Record the $S_{21}$ values, which will be used as the receiving system losses on the VSA side of the power splitter and the SA side of the power splitter. Use these values to correct the received signal level discussed in the representative results section.

1.7. Receiving system setup

1.7.1. Plug in all devices to a power source: either a UPS or a surge-protected set of outlets. Make sure all instruments are in a powered off state while hooking components together.

1.7.2. Assemble the receiving equipment (**Figure 2**).

1.7.2.1. Connect a Type N cable to the input of the bandpass filter**.** Connect the output of the bandpass filter to the input of the power divider (port 1).

1.7.2.2. Connect port 2 of the power divider to the **RF IN** port on the VSA**.** Connect port 3 of the power divider to the **RF IN** port on the SA**.**

1.7.2.3. Using a BNC to banana plug cord, connect the **Frequency Adj** of the rubidium oscillator to the **DC OUT** of the direct-current (DC) power supply**.**

1.7.2.4. Connect a 10 MHz output of the rubidium oscillator to the **Ext Ref In** port on the VSA using a BNC cable**.** Connect a 10 MHz output of the rubidium oscillator to the **Ext Trig/Ref In** port on the spectrum analyzer**.**

1.8. Power on the VSG and ensure that it is set to **RF OFF**. Power on the power meter. Turn all instruments on, and allow the instruments to warm up for an hour before making any measurements.

1.9. Configure the VSA in VSA 89601B mode. While in VSA mode, set the center frequency to the CW frequency of interest. Finally, select the number of points taken with the desired length of the overall measurement in mind.

NOTE: Although the system operates using a CW, the span must be set to capture any Doppler shifts and fading. The resolution bandwidth determines the filter used by the VSA to measure power as it sweeps across the frequency span, so selecting a low-resolution bandwidth allows a more precise measurement. As a tradeoff, a lower resolution bandwidth takes a greater time per point.

1.10. Configure the VSA with the following settings: select VSA 89601B mode; center Frequency: **Freq MHz** (e.g., 1770 MHz); span: 3 kHz; TimeLen: 1 s; ResBW: 3.81938 Hz; NumPts: max (491026 pts, 409601 pts)—depends on VSA; Rng: -42 dBm; top graph upper scale value: -30 dBm.

1.11. Ensure that the SA is controlled by instrument control software that uses programmable standard commands for programmable instruments (SCPI) commands, so that continuous sweeps can be collected and saved.

1.11.1. Set the SA such that the start and stop frequencies match the VSA center frequency. As the RBW similarly determines the filter size used by the SA, set the RBW to the same value as the span of the VSA measurement.

1.11.2. Set the video bandwidth to the same value as the resolution bandwidth and the detection mode to sample to record unaveraged data. Leave attenuation off, making sure the SA will not be overloaded, and keep the preamp on.

1.11.3. Configure the SA with the following for each sweep: StartFreq: Same center frequency as in the VSA setup (e.g., 1770 MHz); StopFreq: Same center frequency as in the VSA setup (e.g., 1770 MHz); RBW (MHz): 0.003; VBW (MHz): 0.003; detector: sample; sweep time: 500 ms; pts/trace: 461; preamp ON; attenuation: 0; auto attenuation: Off.

1.11.4. On the SA, press **Enter** to access the menus. Enable External Reference by holding the **Shift** button and selecting the **System** button on the spectrum analyzer. Then, select **More | Port Settings | Ext Input | Ref** using the softkeys near the screen.

1.12. Configure the VSG by selecting a CW output.

1.12.1. Set the frequency to 1770 MHz. Following section 1.4.2[3], determine the linear range of the power amplifier.

1.12.2. Set the VSG output amplitude to -4 dBm, the upper limit to the linear range of the power amplifier.

1.13. Calibrate the power meter.

1.13.1. Plug the power meter head into the reference port (channel A or B) and the other end of the power meter into a measurement port.

1.13.2. Set the power meter frequency to 1770 MHz for the reference port used above. Zero and calibrate the power meter. Ensure the power meter reading remains within 0.2 dB of 0 dBm.

1.13.3. Unplug the power meter head from the reference port, and connect the power meter head to the output of the attenuator shown in **Figure 1**.

1.14. Calibrate the VSA: **Utilities | Calibration | Calibration.** Turn **RF ON** the VSG.

NOTE: Make sure there is a signal on the spectrum analyzer. If the signal level drops down to -120 dBm, the external reference is not on. If the signal is too strong, it will overload the receiving system and damage either the VSA or SA. Be aware of maximum input signal levels (usually shown on the front of the instrument), and stay at least 10 dB below this level.

1.15. Synchronize the rubidium oscillators by setting the voltage, but do not exceed the maximum input voltage allowed on the rubidium synchronization port.

1.15.1. Change **TimeLen** on the top graph on the VSA screen to 100 ms. Set the y-axis on the bottom plot to I-Q.

1.15.2. Press **Current/Voltage** on the front panel of the power supply. Change the voltage a little at a time and watch the dot on the VSA screen: if it rotates back and forth, do nothing, the frequencies are aligned. If it rotates in one direction consistently, change the power meter reading (voltage) until the dot on the I-Q plot starts to slow down, and it moves slowly back and forth (pendulum motion) (**Figure 4**).

1.15.3. Set **TimeLen** on the top graph on the VSA screen back to 1 s, and set the y-axis back to Log Magnitude.

1.16. Take 10 records of acquisition on the SA to verify that all parameters have been set correctly, and that the signal level on the SA screen matches the signal level on the VSA lower screen.

## 2. Lab verification and validation

2.1. Without attaching antennas, insert a variable attenuator between the transmitting side of the system and the receiving side of the system (**Figure 5**). Remove the power amplifier from the measurement setup for this verification.

2.2. Set the stepped attenuator attenuation to 0 dB and the number of records on the VSA **Input > Recording** to 120.

NOTE: One record is equal to the **TimeLen** set on the VSA.

2.3. Set the number of sweeps on the SA to 120 records. Change the output amplitude of the VSG to 0 dBm, and press the **RF ON** button on the VSG.

2.4. Set a peak marker to find the value of the signal strength, and verify a signal is seen on the VSA. Start the VSA by hitting the **Record** button at the top of the screen. Start an SA measurement using the instrument control software.

2.5. Change the stepped attenuator to 10 dB, and repeat steps 4–10. Go through all settings of the stepped attenuator and record the values for each attenuation setting.

NOTE: As the attenuator approaches 90 to 110 dB, the signal will get noisier as it approaches the system noise floor of the instrument. Measurement values near the noise floor of the system will be highly variable.

2.6. To verify the VSA received signal levels, calculate a 0.5 s windowed average to the 120 s VSA record, and average each sweep of the SA. Add the VSG output power level, the transmitting side and receiving side system losses, and the stepped attenuator setting.

NOTE: The value of the aforementioned sum in step 2.6 should equal the averaged received signal levels recorded by the VSA and the SA within 0.5 dB, for stepped attenuations less than 80 dB. If they do not, go back and remeasure system losses.

## 3. Field measurements

NOTE: Always test and verify the system before every measurement campaign.

3.1. Complete steps 1.1–1.3 before each new measurement campaign, and set up the transmitting side of the system, as discussed in section 1.4.

NOTE: This is typically housed in a cellular-on-wheels (COW), which remains fixed during measurements.

3.2. Connect the power amplifier between the VSG and the directional coupler, as described in step 1.4.2.1.

3.2.1. Use a directional coupler that can handle the power levels generated by the power amplifier. Add a 50 dB attenuator to the directional coupler at the coupled port to stay within the specified input power levels of the power meter, and attach the power meter to this port. Connect the output Type N cable from the directional coupler to the transmitting antenna.

3.2.2. Set up the receiving side of the system, as discussed in steps 1.5–1.6, inside a mobile vehicle. Connect the receiving antenna to the Type N cable connected to the filter.

3.2.3. In addition to the SA setup steps 1.11.3–1.11.4, the GPS antenna needs to be set up in the SA.

3.2.3.1. Enable the GPS record: **Meas Settings** | **Enable GPS Record** | **Standard GPS**.

3.2.3.2. Enable GPS on the spectrum analyzer by holding the **Shift** button and selecting the **System** button on the spectrum analyzer. Then, select **More | GPS | GPS-ON** & **GPS Info-ON** using the softkeys near the screen.

3.2.3.4. Place the GPS antenna on the roof of the receiver measurement vehicle. Ensure that the measurement software also reads in NMEA strings from the GPS for each sweep.

3.3. Continue the setup as discussed in steps 1.11–1.17, and set the number of records on the VSA **Input | Recording** based on estimated measurement time. Set the number of SA records to the number of VSA records plus about 300 records, noting that the SA sweeps slower than the VSA.

3.4. Begin the measurement by first staring the VSA by pressing the **Record** button at the top of the screen. Initiate the spectrum analyzer measurement.

3.5. After the measurement, save the VSA recording file **| Save | Save Recording**. **Save Options | Save Headers with Data**. When saving the file, append a **_VSA** to the end of the file. Change the name of the data file for the spectrum analyzer to match the filename of the VSA, but append **_SA** for the spectrum analyzer.

**REPRESENTATIVE RESULTS:**

The following results were obtained during a field verification of the presented system. The transmitter was located on the Kohler Mesa behind the Department of Commerce Boulder Laboratories in Boulder, Colorado. The receiver was driven through Boulder, Colorado, in a specially designed measurement vehicle (see **Figure 6**), and continuous measurements were taken. The SA stores the swept data as log magnitude format in an event data structure, while the GPS data are stored in a separate event data structure within in the same file. An example of data for one sweep is shown in **Figure 7**. The stored data are converted to linear power in Watts; a mean is computed for all points in that sweep and then converted back to log magnitude. The GPS information is assigned to this mean value for the sweep shown by the red X at a value of −71.5 dBm. This process is done for every sweep in the file.

Next, the baseband I–Q data from the VSA are processed as shown in equation 1. The power in dBm is calculated for every I-Q sample. The VSA collects peak data, which must be converted to dBm, during this step.

$$P_{RMS\_dBm} = 10 \cdot \log_{10}\left(\frac{{V_{peak}}^2}{2 \times 50 \times 10^{-3}}\right) \quad (1)$$

During the measurement, the baseband I–Q data are stored in a temporary file. No GPS information is acquired by the VSA. The length of the file is chosen such that the number of records requested is equal to the number of seconds of drive time. Once the measurement has finished, the data are written to a file whose structure is preprogrammed by the VSA software developers. Data saved into this file include the time difference between measurement samples, the frequency, and the complex data samples. The processing step involves the smoothing of the magnitude of the baseband I–Q data over a 500 ms window for the entire data set to approximate a 40-wavelength driving distance. **Figure 8** shows how the smoothed mean power compares to the raw data for a larger portion of a drive test. The raw data are shown by the blue trace, and the smoothed mean power is shown by the red trace.

The VSA and SA data sets are aligned using a circular convolution. The VSA data point at each second is aligned with the SA samples generated at each second to transfer the GPS coordinates from the SA to the VSA data points. A linear regression model aligns the data by minimizing the residuals between the measured power levels of the two data sets. The aligned data are presented by plotting the SA power in dBm on the x-axis and the VSA power in dBm on the y-axis (**Figure 9**). As the SA system noise floor is higher than the VSA system noise floor, the graph will show a downward curvature at points below approximately -115 dBm for data sets close to the noise floor. **Figure 9** and **Figure 10** show the alignment of the VSA power and the SA power vs. the elapsed time in seconds. The GPS time stamp from the SA mean power is then attached to the first data point of the VSA average-smoothed power data series. The vertical offset between the two data sets is eliminated by correcting for cable loss from the power divider to the SA; however, as only the time-stamped VSA data are used, this extra step is unnecessary. These data are then saved and used in the Longley-Rice/Irregular Terrain Model (ITM)[11,12] to predict terrain losses. The VSA data are corrected by adding system losses and removing system gains to obtain the measured basic transmission loss (BTL) or basic transmission gain (BTG) along the drive route as shown in **Figure 11** and **Figure 12** and given by equation 2.

$$BTL\ (dB) = P_t - P_r + (G_t - L_t) + (G_r - L_r) \quad (2)$$

where, BTL is the basic transmission loss, $P_t$ and $P_r$ are the transmitting and receiving powers in dBm, $G_t$ and $G_r$ are the gains of the transmitting and receiving antennas in dBi, respectively, and $L_t$ and $L_r$ are the system losses for the transmitting system and receiving system in dB, respectively.

In **Figure 11**, the purple star is the transmitting location. The yellow and purple dots represent the highest and lowest received signal levels, respectively. A plot of the measured BTG (black x's), the ITM-modelled BTG (blue +'s), free-space transmission gain (FSTG) (red circles), and the system noise floor (pink dots) is shown in **Figure 12**. When the ITM BTG equals the FSTG, there are no terrain interactions, and all losses can be assumed to come from buildings, foliage, or other interactions with the surrounding environment. This is shown in **Figure 13**, where the black line is the terrain pulled from the USGS terrain database[13], the red, dashed line is the line-of-sight (LOS) line between the transmitting antenna and the receiving antenna, and the blue, dotted and dashed lines are the upper and lower first Fresnel zones[14] where most of the energy is localized.

**FIGURE AND TABLE LEGENDS:**

**Figure 1: Diagram of transmitting components and connections.** Transmitting side of continuous-wave (CW)-channel sounder. Abbreviations: RF = radio frequency; Ref = reference.

**Figure 2: Diagram of receiving components and connections.** Receiving side of continuous-wave (CW) channel sounder. Abbreviations: GPS = Global Positioning System; RF = radio frequency; Ext Ref = external reference; GPS Ant = GPS antenna; Ext Trig/Ref = external Trigger/Reference; TCP/IP = transmission control protocol/internet protocol; Freq Adj = Frequency-adjusted; DC = direct current.

**Figure 3: CW channel sounder system in laboratory.** A benchtop deployment of the Institute for Telecommunication Sciences (ITS) channel sounder for system validation and accuracy testing showing the main components. Abbreviations: VSA = vector signal analyzer; VSG = vector signal generator.

**Figure 4: I-Q display.** Frequency adjustment using in-phase and quadrature (I-Q) plot. Abbreviations: CW = continuous-wave; TimeLen = time length; I-axis = in-phase axis; Q-axis = quadrature axis.

**Figure 5: Verification and validation system setup.** System setup for verification and validation measurements. Abbreviations: I-Q = in-phase quadrature; RF = radio frequency; Ref = reference; GPS = Global Positioning System; Ext Trig/Ref = external trigger/Reference; TCP/IP = transmission control protocol/internet protocol; Freq Adj = frequency adjusted; DC = direct current.

**Figure 3: Cellular-on-wheels (COW) and measurement van.** Photo showing green van used for receiving system and cellular-on-wheels (COW) used to house transmitting system.

**Figure 4: Spectrum analyzer sweep and sweep average.** Single sweep for spectrum analyzer data capture consisting of 461 points over a 0.5 s sweep time. Abbreviation: SA = spectrum analyzer.

**Figure 5: Vector signal analyzer received power and moving average.** In-phase and quadrature (I-Q) magnitude data (blue trace) for a small slice of a larger run compared to the mean power (red trace) calculated over a 0.5 s window.

**Figure 6: VSA and SA signal alignment.** Alignment of vector signal analyzer power and spectrum analyzer power. Abbreviations: VSA = vector signal analyzer; SA = spectrum analyzer.

**Figure 7: VSA and SA received power after signal alignment.** Aligned vector signal analyzer power and spectrum analyzer power vs elapsed time in seconds. Abbreviations: VSA = vector signal analyzer; SA = spectrum analyzer.

**Figure 8: Geolocation of measured basic transmission gain.** Measured basic transmission gain along the drive route.

**Figure 9: Measured and modelled basic transmission gain.** Measured basic transmission gain (blue x's), Irregular-Terrain Model (ITM) basic transmission gain (BTG) (black +'s), free-space transmission gain (red circles), and system noise floor (pink dots) vs. elapsed time along the drive route. Abbreviations: MBTG = Measured basic transmission gain; ITM = Irregular-Terrain Model.

**Figure 10: Terrain profile and first Fresnel zone.** United States Geological Survey terrain profile (black line) for elapsed time 1636.2 s. The upper (first) Fresnel zone (blue, dotted line) and lower (first) Fresnel zone (blue, dashed line) are also plotted along with the line-of-sight line (red, dashed line) between the transmitting antenna and receiving antenna. Abbreviations: USGS = United States Geological Survey; NED = national elevation database.

**DISCUSSION:**

It is very important to test a system as described in this protocol before attempting to make measurements in an outdoor environment. In this way, any bad components or instabilities can be traced and identified in the measurement system and can be resolved. The critical steps in this protocol are to 1) test the individual components first, and verify that they are operating within their specification, 2) assemble transmitting and receiving sides separately and test the chain of components, 3) assemble the transmitting and receiving side by inserting a stepped attenuator and measuring the signal levels as the attenuation is changed to make sure the received signal levels in the VSA and SA are as calculated. Further troubleshooting can be performed by using a VSG, such as the one shown in the **Table of Materials**, that has an option to generate fading simulations, which can be used to test the system using simulated waveforms in various fading environments encountered in real-world propagation environments. Once the measurement system is operating correctly, measurements can be made in an outdoor environment with the confidence that measurements will be accurate.

Another important step is to monitor the transmitting power throughout the measurement to verify that the system is operating correctly. The power amplifier is characterized and tested separately to understand its linearity and out-of-band emissions spectra. The power amplifier may be validated on the benchtop with the rest of the setup, but care must be taken to reduce the signal power below the maximum rated power input to the VSA using appropriately rated attenuators. Neither the GPS antenna nor its settings should be used for lab verification and validation. As the VSA's screen is not capable of providing real-time monitoring of the environment, the addition of an SA as a real-time monitor helps determine the current state of the system. There are several types of channel-sounding measurement systems to capture channel characteristics for radio systems: CW, direct pulse, frequency domain using a VNA, correlation-based, swept-time delay cross-correlator.

One limitation of this system is that a CW signal probing the local environment does not contain time-domain information such as time-delay profiles. A time-delay profile gives information about the timing of source reflections of the signal in the local environment. However, an advantage of using a CW signal is that it is easier to obtain permission to transmit on one frequency in various bands using the narrowband CW signal rather than trying to transmit a wide-band signal. CW systems can have a larger dynamic range than other systems, and the signal can usually propagate further in the environment. A CW signal also has audio sampling rates that result in smaller file sizes than other types of channel-sounding systems. With this system, data collections are continuous and can last for several hours. The CW-channel sounder measurement system discussed in this article can be used at different frequencies, depending on the range of the various assembled components. The system can be used in an outdoor propagation environment or an indoor propagation environment[15].

**ACKNOWLEDGMENTS:**
Thanks to the Defense Spectrum Office (DSO) for funding the work presented in this article.

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Figure 1

Click here to access/download;Figure;Fig1_TX_Diagram.png

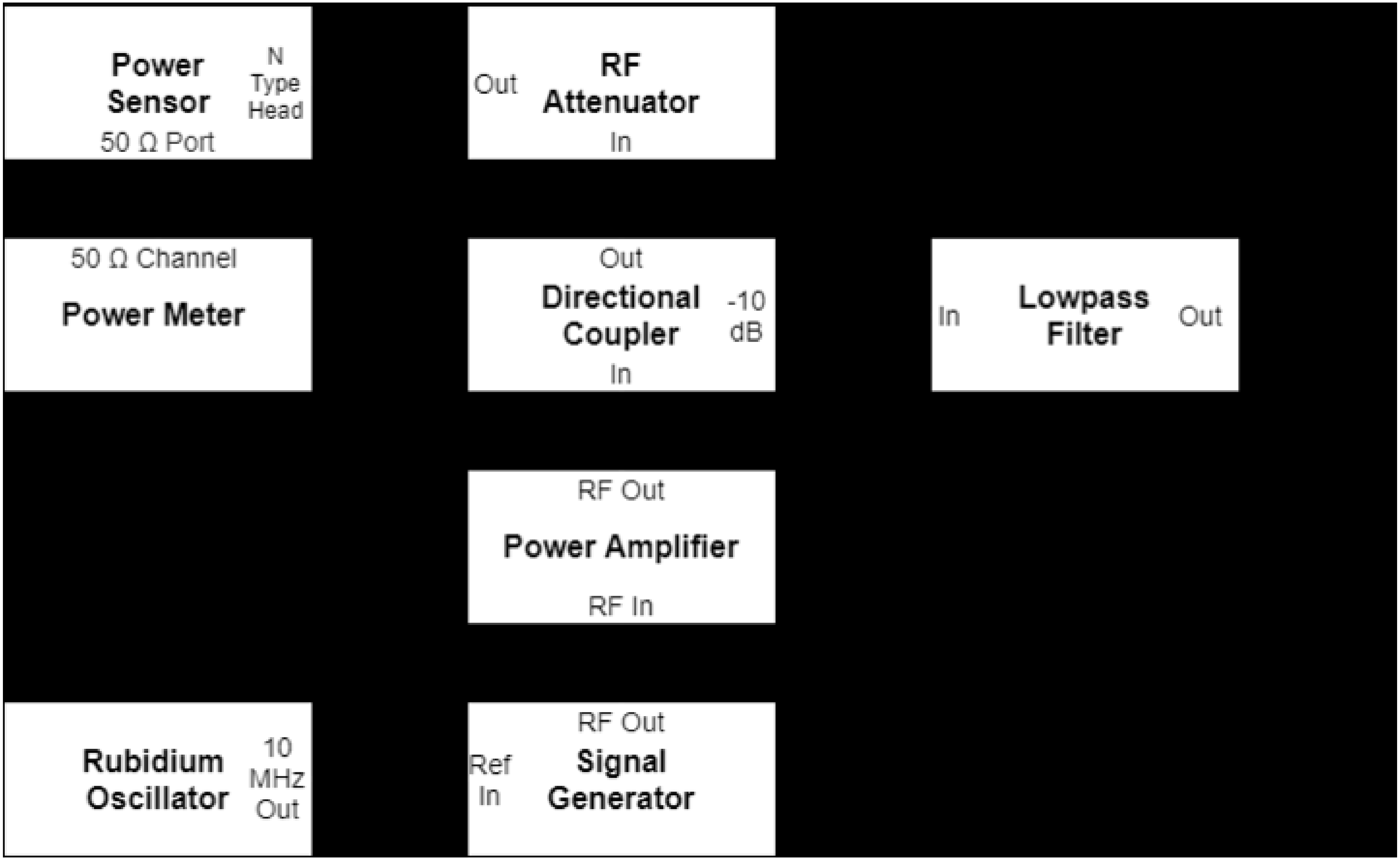


Figure 2

Click here to access/download;Figure;Fig2_RX_Diagram.png

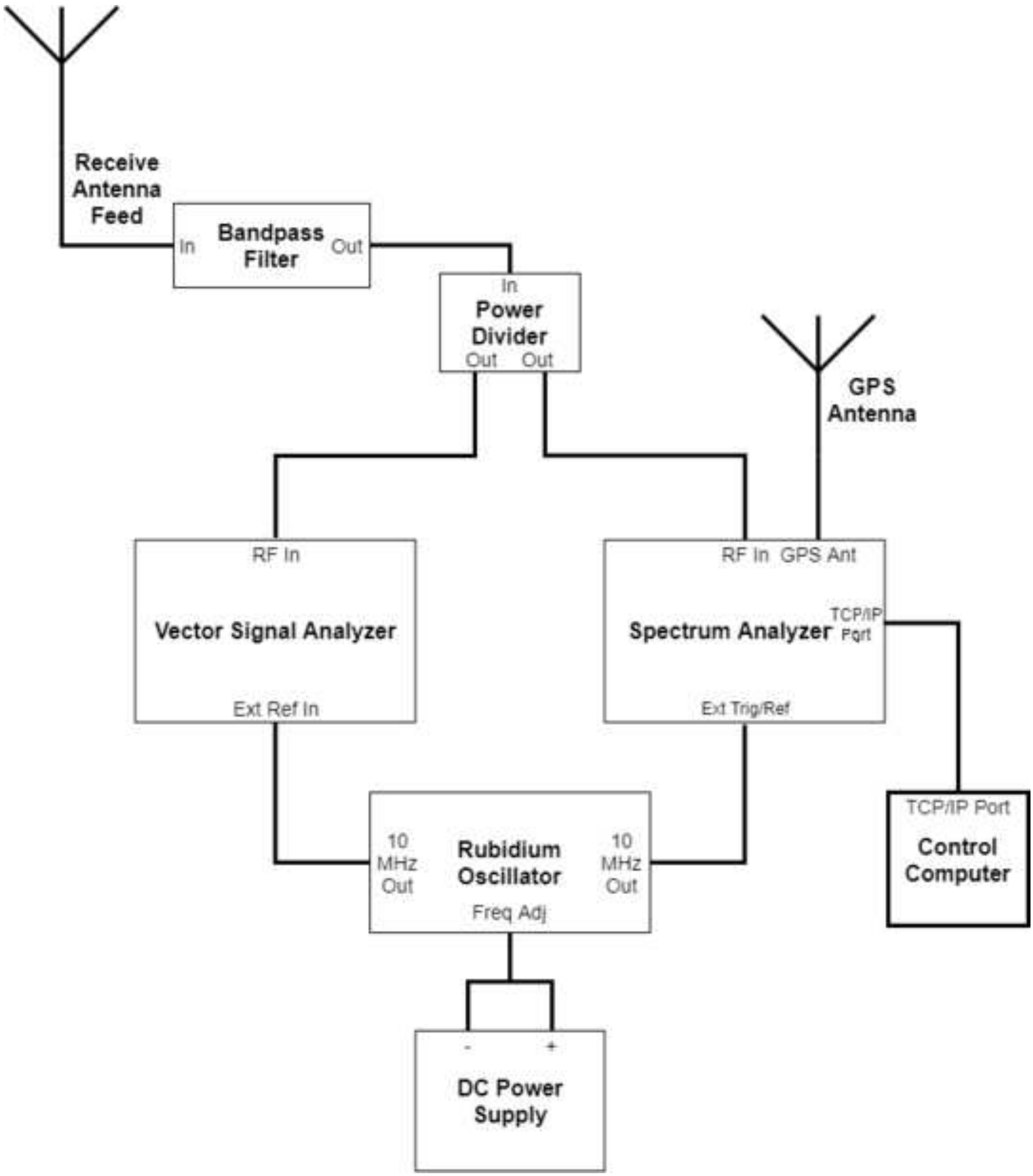
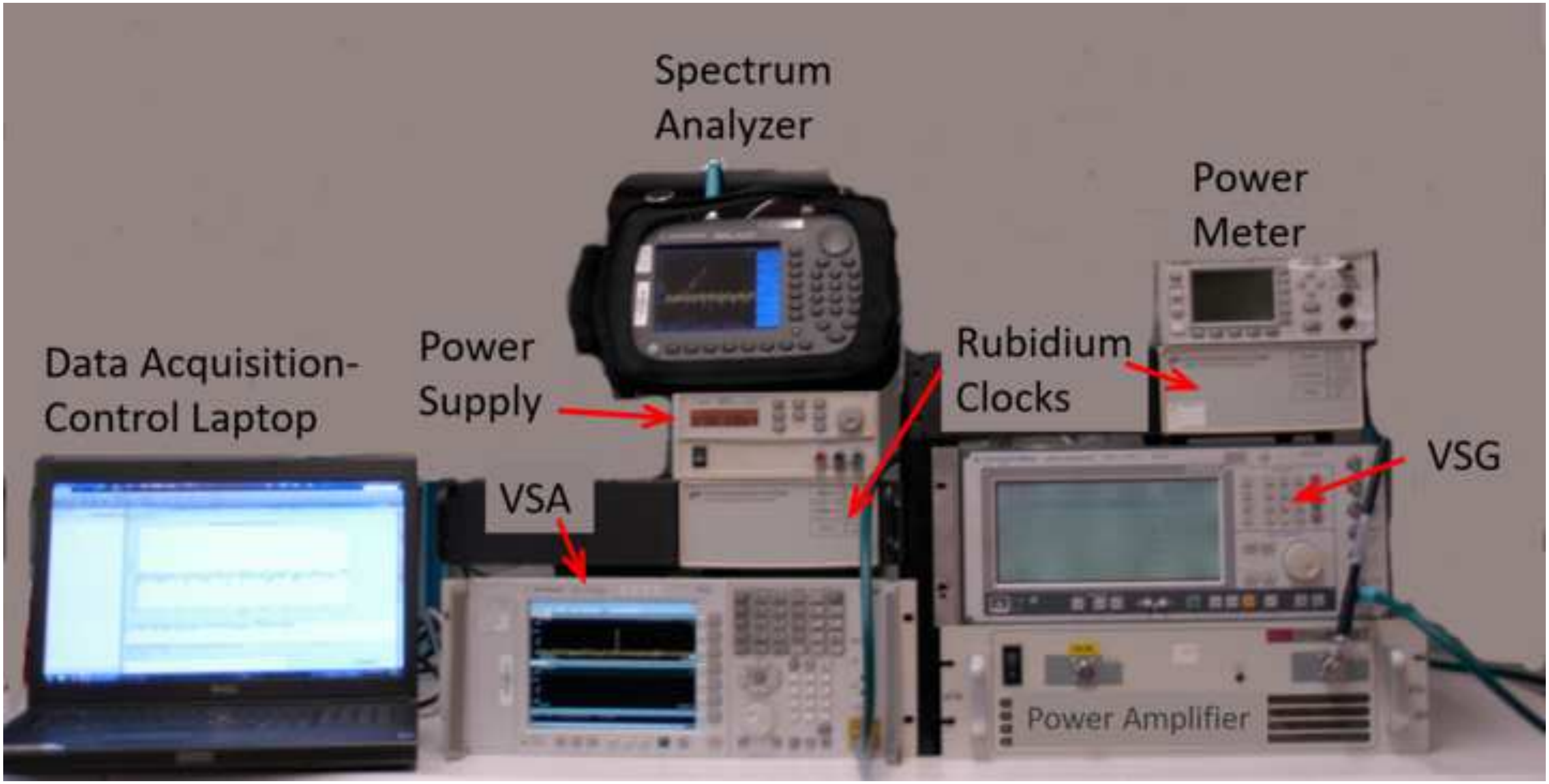


Figure 3





Spectrum Analyzer
Power Meter
Data Acquisition-Control Laptop
Power Supply
Rubidium Clocks
VSA
VSG
Power Amplifier

Figure 4



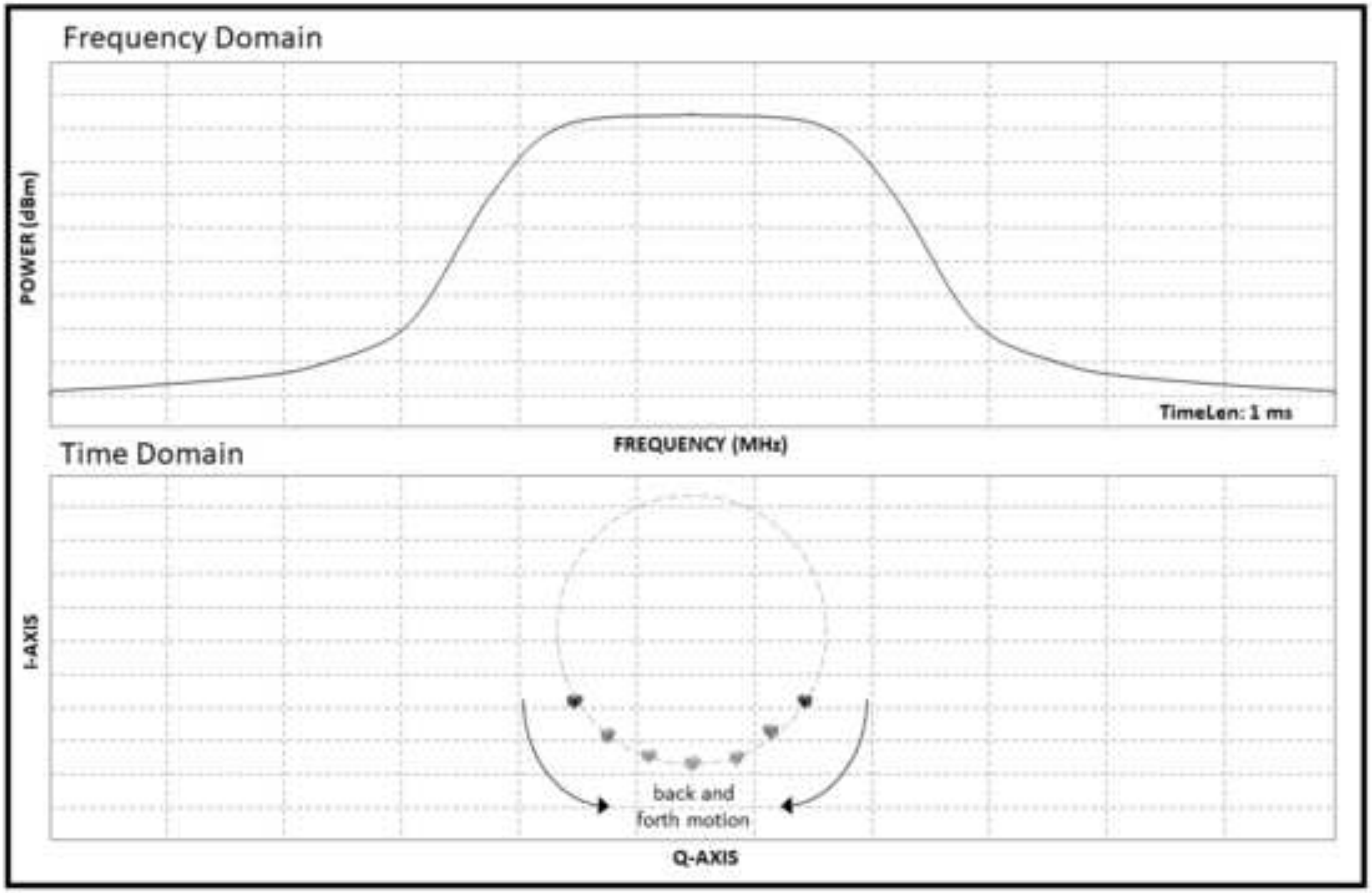

Frequency Domain
POWER (dBm)
TimeLen: 1 ms
FREQUENCY (MHz)
Time Domain
I-AXIS
back and
forth motion
Q-AXIS

Figure 5 Click here to access/download;Figure;Fig5_Validation_Diagram (1).png

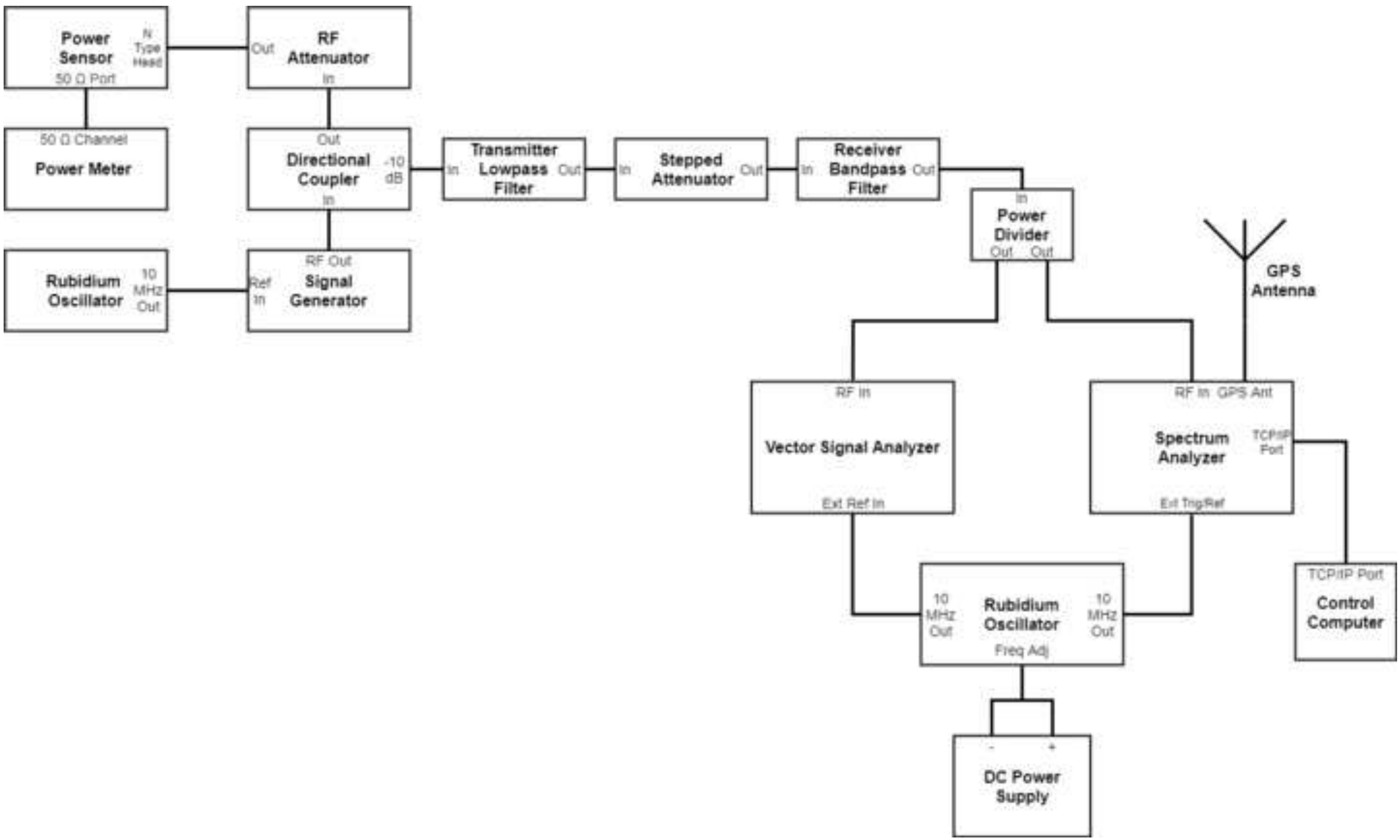
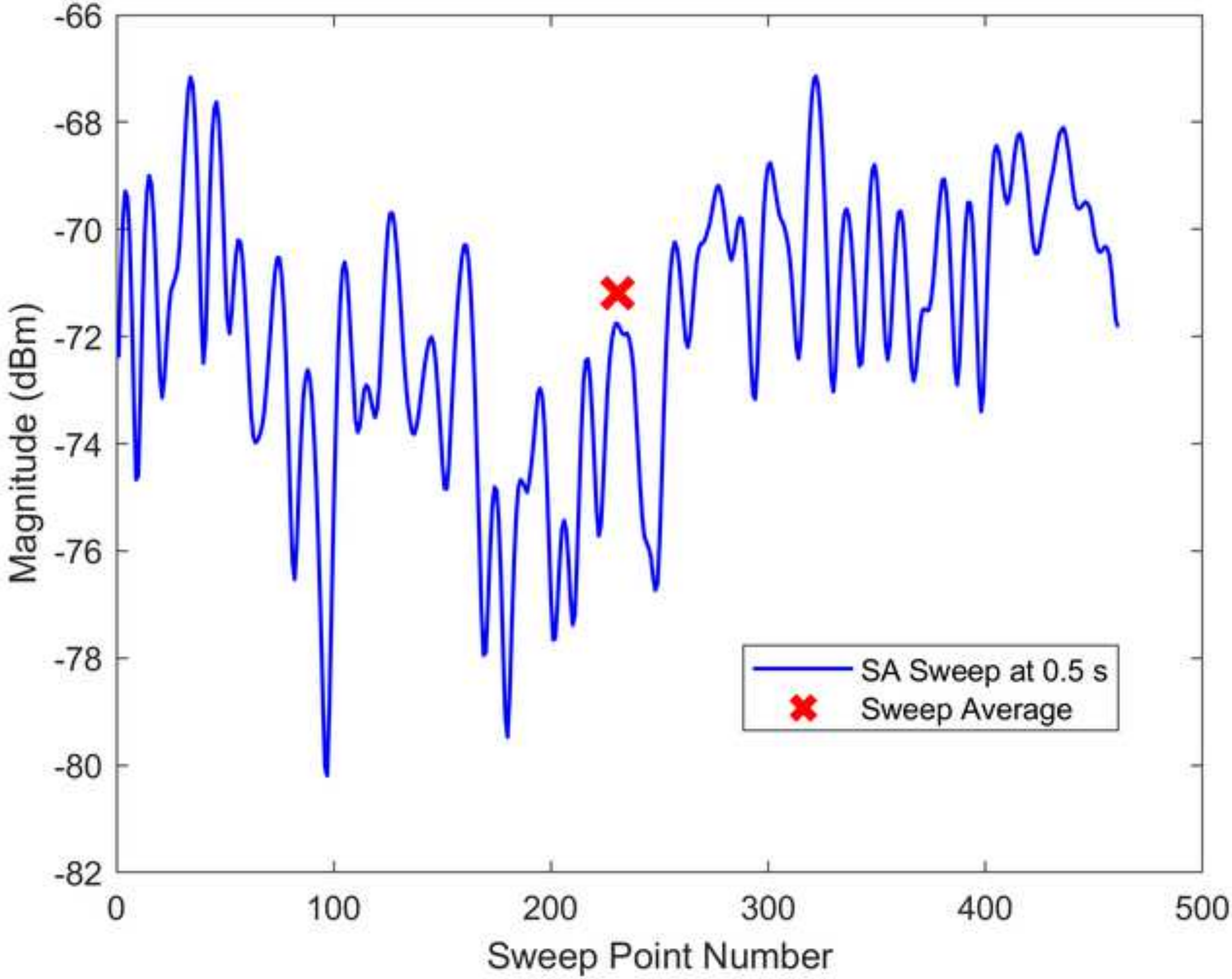


Figure 6

Click here to access/download;Figure;Fig6_CowandVanPhoto.JPG

Figure 7

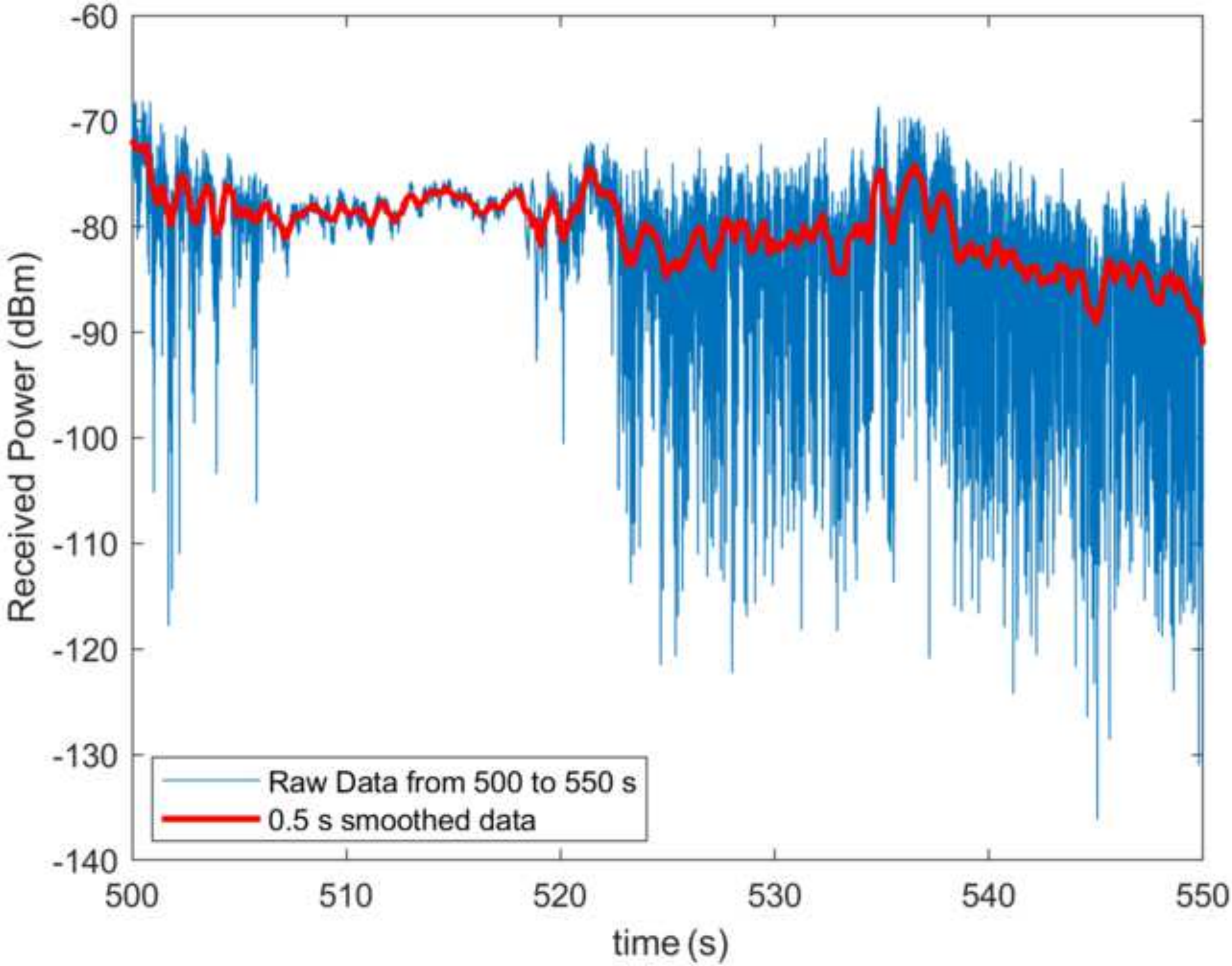




-66
-68
-70
-72
-74
-76
-78
-80
-82
Magnitude (dBm)
0
100
200
300
400
500
Sweep Point Number
SA Sweep at 0.5 s
Sweep Average

Figure 8





-60
-70
-80
-90
-100
-110
-120
-130
-140
Received Power (dBm)
500
510
520
530
540
550
time (s)
Raw Data from 500 to 550 s
0.5 s smoothed data

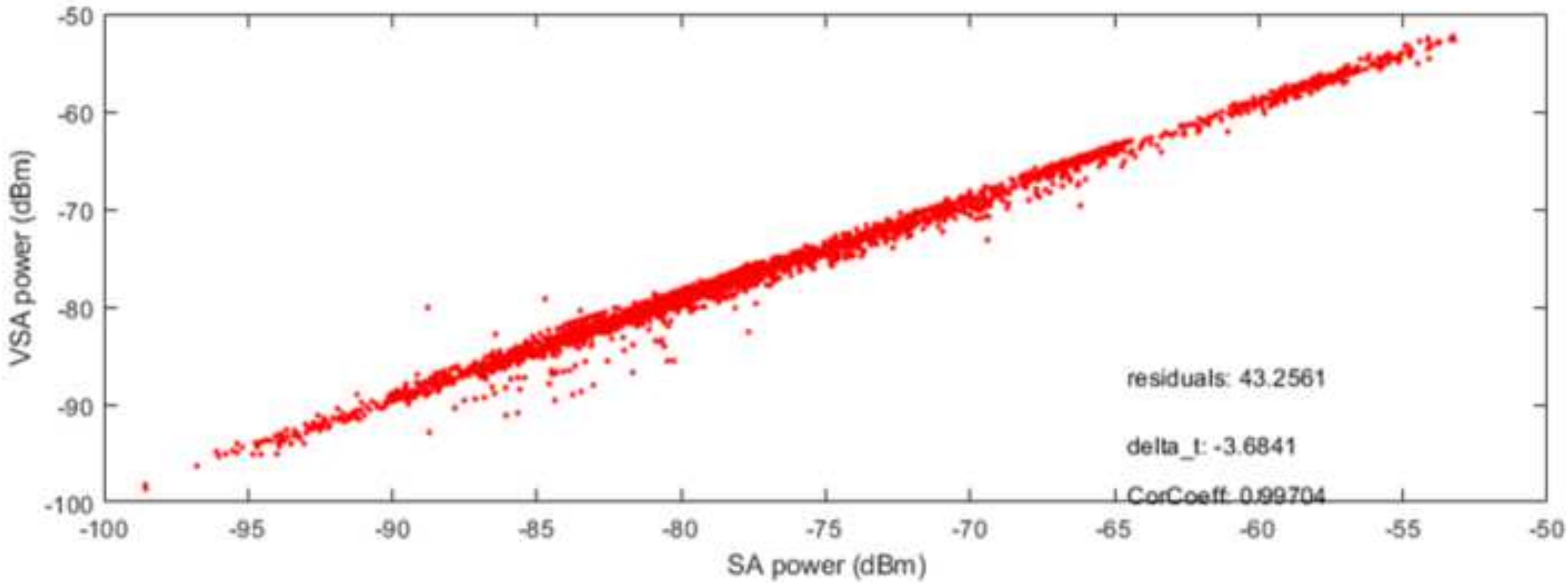

VSA power (dBm)
SA power (dBm)
-50
-60
-70
-80
-90
-100
-100
-95
-90
-85
-80
-75
-70
-65
-60
-55
-50
residuals: 43.2561
delta_t: -3.6841
CorCoeff: 0.99704

Figure 10

Click here to access/download;Figure;Fig10_VSA_SA_AlignmentPlots.png

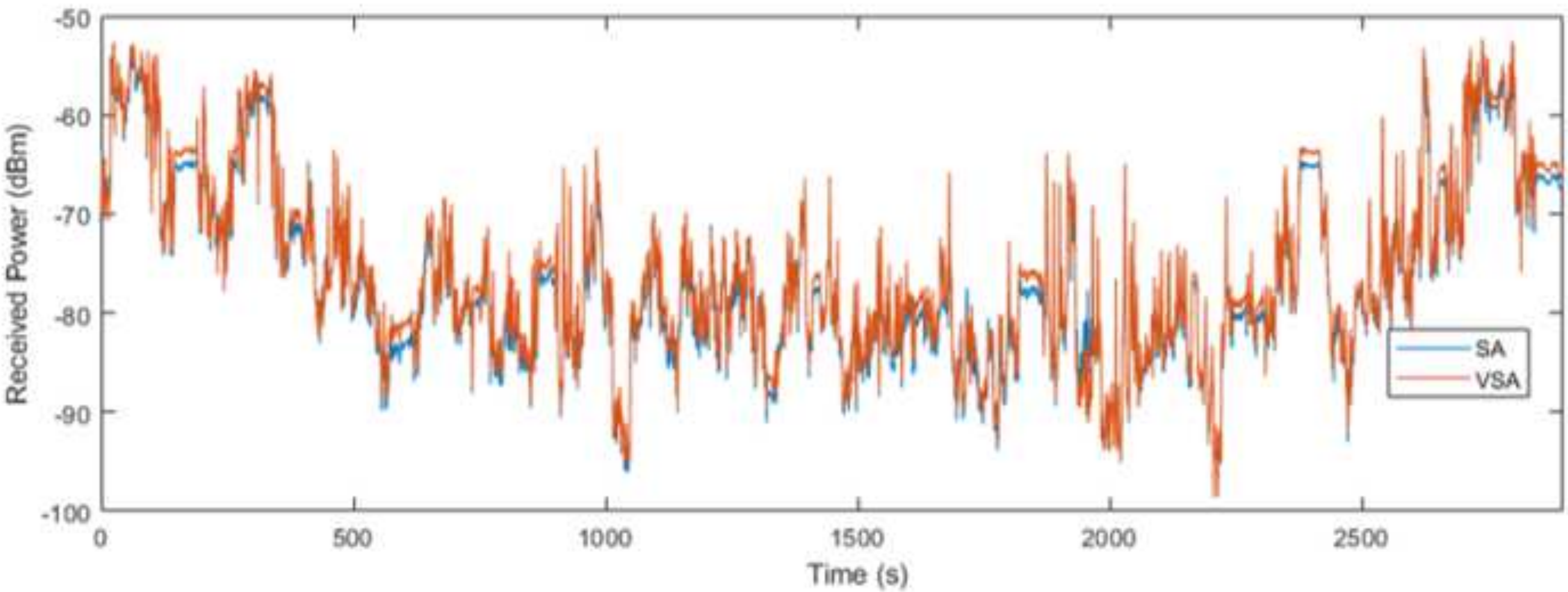


Figure 11

Click here to access/download;Figure;Fig11_MBTGAlongDriveRoute.png

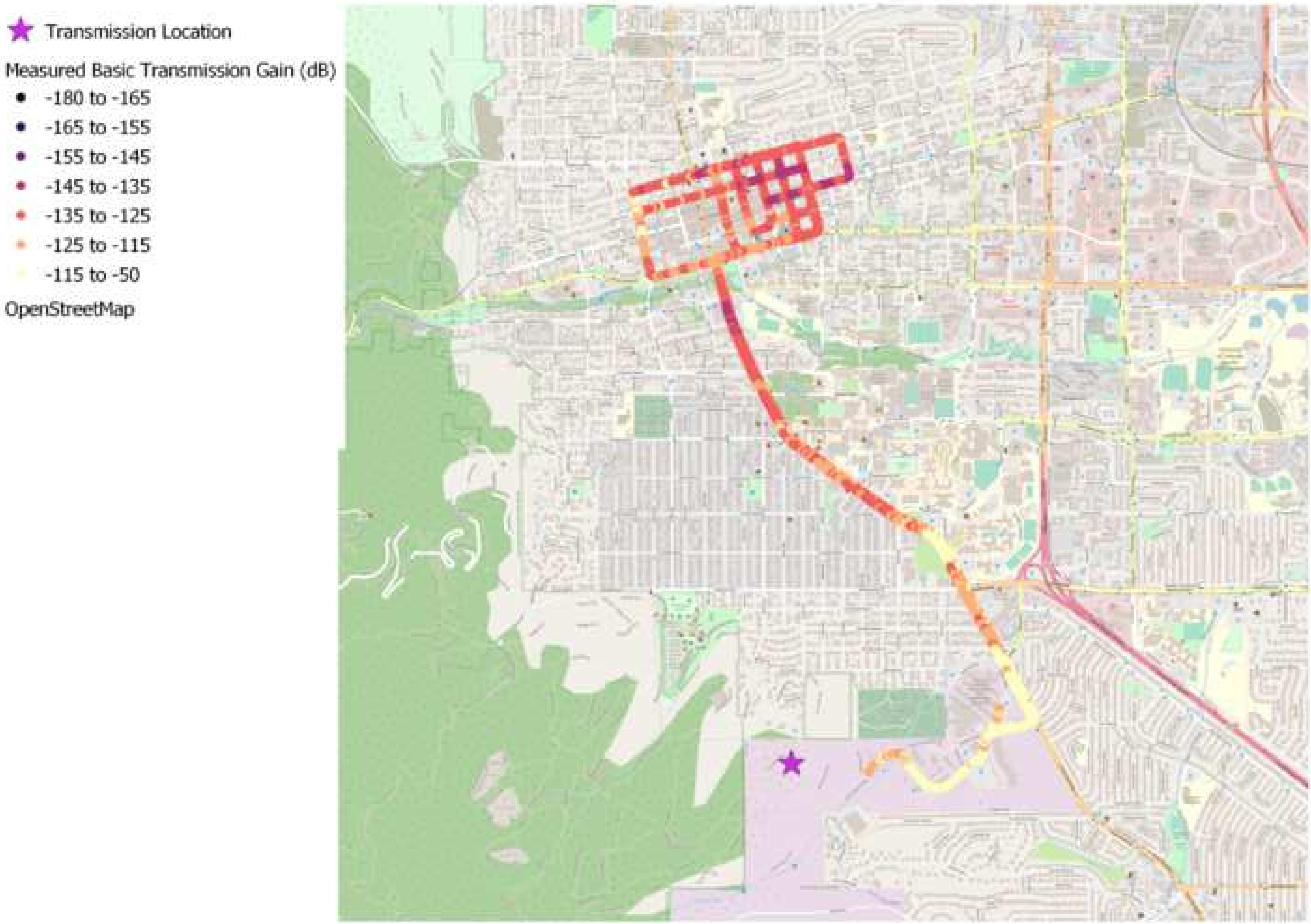


Figure 12



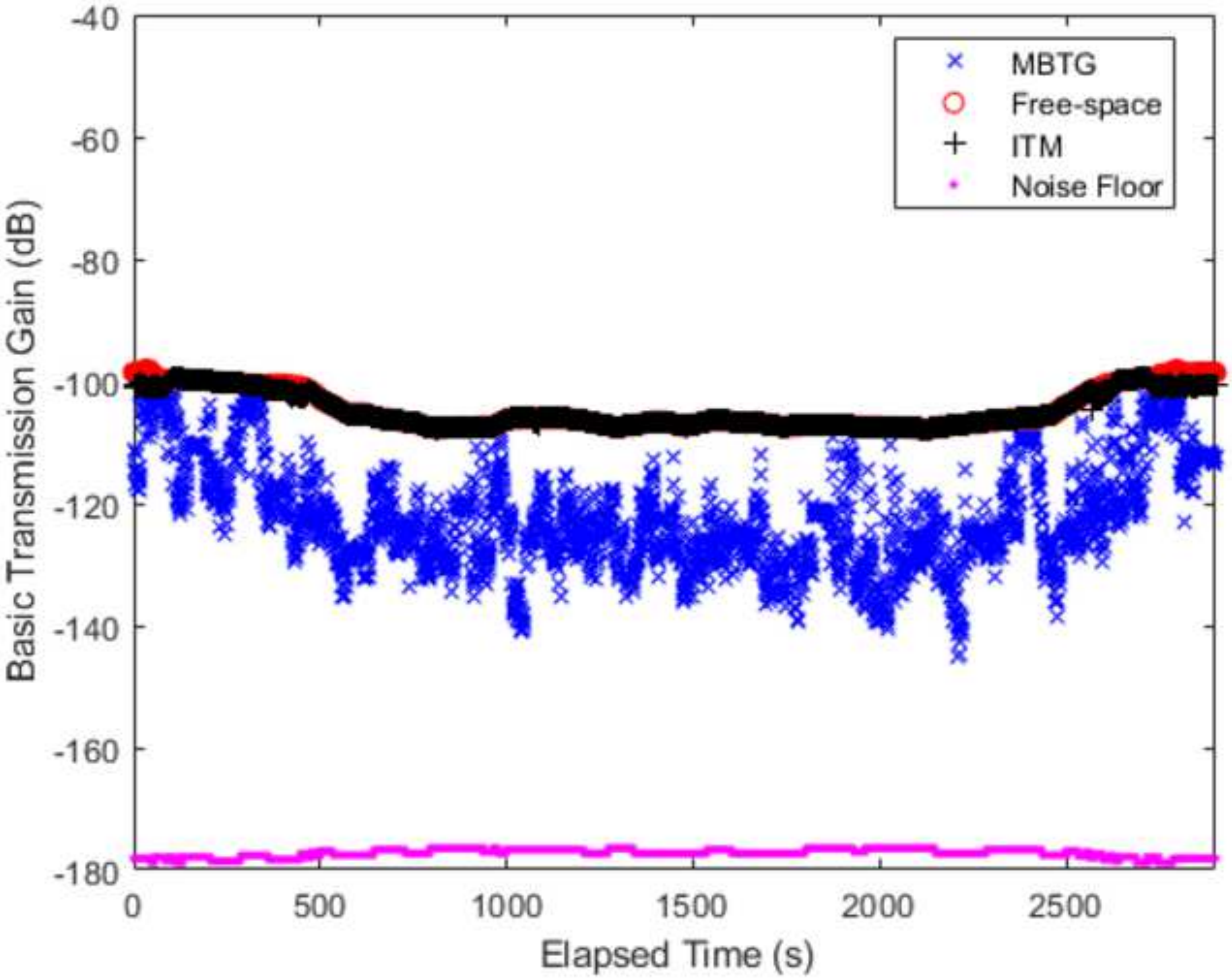
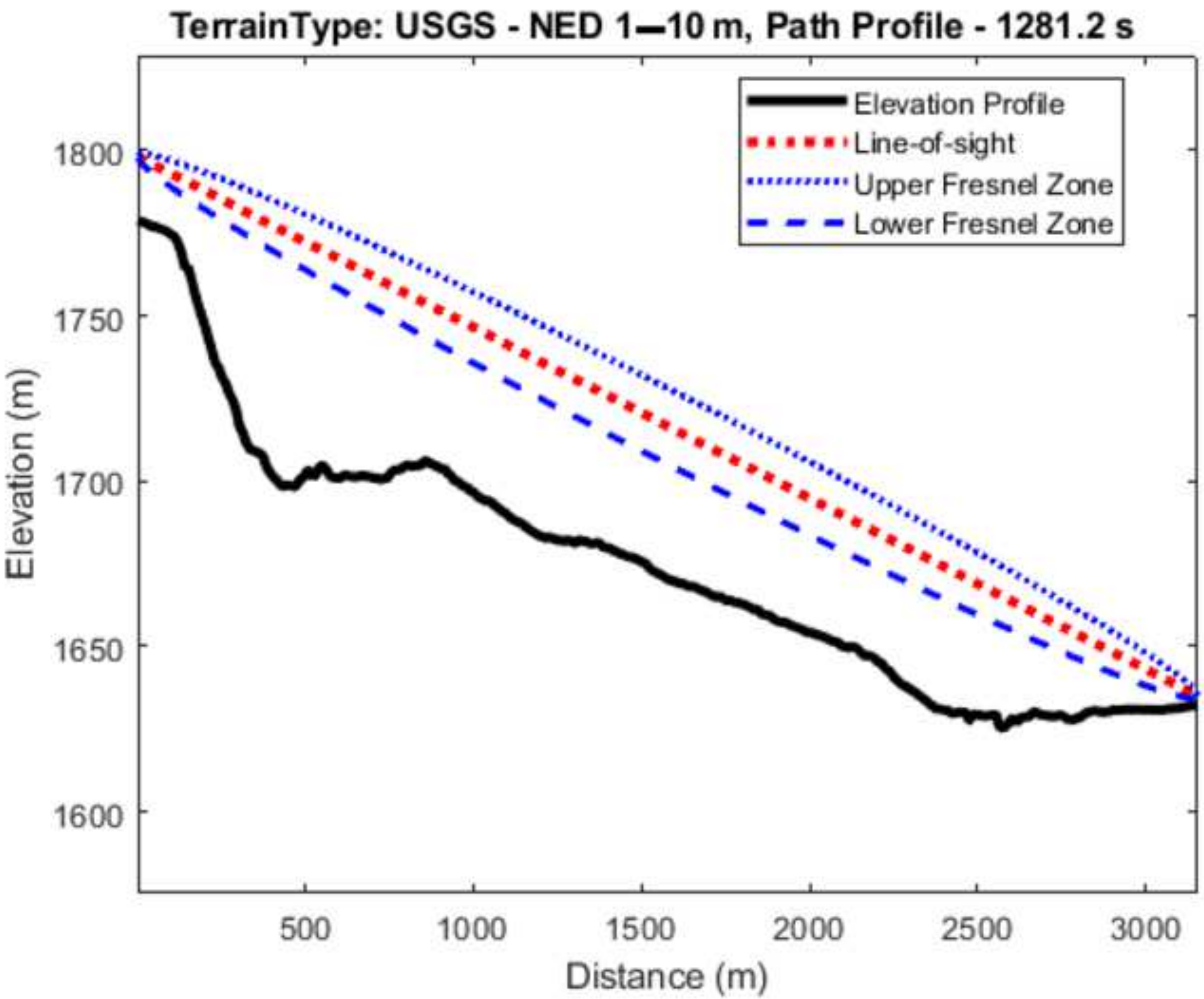

MBTG
Free-space
ITM
Noise Floor
Basic Transmission Gain (dB)
Elapsed Time (s)
-40
-60
-80
-100
-120
-140
-160
-180
0
500
1000
1500
2000
2500

Figure 13




TerrainType: USGS - NED 1—10 m, Path Profile - 1281.2 s
Elevation Profile
Line-of-sight
Upper Fresnel Zone
Lower Fresnel Zone
Elevation (m)
1800
1750
1700
1650
1600
500
1000
1500
2000
2500
3000
Distance (m)

| Name of Material/Equipment | Company | Comments/Description |
|---|---|---|
| Cabling | Micro-Coax | Various lengths |
| Directional Coupler | Anatech Electronics, Inc. | AM1650DC833 |
| Filter 1 | K&L Microwave, Inc. | 8FV50-1802-T95-O/O |
| GPS Antenna | Trimble | SMA connection to SA |
| Instrument Control & Processing Software | MATLAB | Used to store and process measurement data |
| Power Amplifier | Ophir RF | 5263-003 |
| Power Divider | Mini-Circuits | ZAPD-20+ |
| Power Meter and Power Sensor | Keysight | E4417A/E4412A |
| Receiving Antenna | Cobham | OA2-0.3-10.0V/1505 |
| Rubidium Frequency Standard | Stanford Research Systems | FS725 |
| SA | Agilent | N9344C |
| Transmitting Antenna | COMTELCO | BS1710XL6 |
| Vector Signal Generator | Rohde & Schwarz | SMIQ |
| VSA | Keysight Technologies | N9030A |

**Editorial comments:**

1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues.
2. Please revise the following lines (40-46, 49-54, 57-74, 79-81,83-85) to avoid previously published work: Calibration of Vector Network Analyzer for Measurements in Radio Frequency Propagation Channels doi: 10.3791/60874 Published: June 2, 2020. Chriss Hammerschmidt1, Robert T. Johnk1, Savio Tran1]

A: We removed these lines and provided additional explanation

3. Please revise the following lines (103-110, 112-116, 121-127,129-136) to avoid previously published work: A high-performance cw mobile channel sounder subtitle as need (aper subtitle) robert johnk, chriss hammerschmidt, irena stange institute for telecommunication sciences (NTIA/ITS) U.S. department of commerce boulder laboratories boulder, colorado 80205, USA. Published in: 2017 IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMCSI)

A: We removed these lines and provided additional explanation

4. Please revise the following lines (346-348,362-367, 372-380) to avoid previously published work: C. Hammerschmidt and R. Johnk, "Extracting clutter metrics from mobile propagation measurements in the 1755–1780 MHz band," MILCOM 2016 - 2016 IEEE Military Communications Conference, Baltimore, MD, 2016, pp. 213-218, doi: 10.1109/MILCOM.2016.7795328.

A: We removed these lines and provided additional explanation

5. The Protocol should contain only action items that direct the reader to do something. Please move the discussion about the protocol to the Introduction, Representative Results, or Discussion. This applies to lines 103-153.

A: We moved the discussion of the system to the introduction.

6. Please consider providing system set-ups (Lines 203-211, 216- 225) as Tables in separate .xls or .xlsx files uploaded to your Editorial Manager account. These tables can then be referenced in the protocol text.

A: Added .xlsx files for SA and VSA setups

7. Please highlight up to 3 pages of the Protocol (including headings and spacing) that identifies the essential steps of the protocol for the video, i.e., the steps that should be visualized to tell the most cohesive story of the Protocol. Remember that non-highlighted Protocol steps will remain in the manuscript, and therefore will still be available to the reader.

8. Please use abbreviated forms for durations of less than one day when the unit is preceded by a numeral (“sec” must be replaced as “s”).

A: Changed to s

9. Please include a title and a description of each figure and/or table. All figures and/or tables showing data must include measurement definitions (if applicable). Please include all the Figure Legends together at the end of the Representative Results in the manuscript text.

A: Done, and defined abbreviations

10. Please ensure that each Figure Legend has a title and a short description of the data presented in the Figure and relevant symbols.

A: Done

11. Please remove the embedded figure(s) from the manuscript. All figures should be uploaded separately to your Editorial Manager account. Each figure must be accompanied by a title and a description after the Representative Results of the manuscript text.

A: Done

12. Please remove the embedded Table from the manuscript. All tables should be uploaded separately to your Editorial Manager account in the form of an .xls or .xlsx file. Each table must be accompanied by a title and a description after the Representative Results of the manuscript text.

A: Done

13. Figure 3: Please define the X and Y-axis.

A: Done

14. Figure 7: Please define “#” represented in the X-axis

A: Done

15. Figure 8 and Figure 12: Please use abbreviated forms for time units in the X-axis. (“time(sec)” must be revised as “time (s)”

A: changed them to “time (s)”

16. As we are a methods journal, please revise the Discussion to explicitly cover the following in detail in 3-6 paragraphs with citations:
a) Critical steps within the protocol

b) Any modifications and troubleshooting of the technique
c) Any limitations of the technique

Power and link budget

Distance

Range

Time delay profiles

d) The significance with respect to existing methods

longer distance measurements

local scattering

e) Any future applications of the technique

A: I think addressed all of these points in the discussion.

17. Please revise the text to avoid the use of any personal pronouns (e.g., "we", "you", "our" etc.).

A: Removed personal pronouns

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**Reviewers' comments:**
**Reviewer #1:**
Manuscript Summary:
This paper presents a measurement platform for the characterization of wireless propagation. The organization of the document is clear, and it presents a detailed description of the processes for conducting a measurement campaign. The authors clearly describe lists of steps to set up the equipment and assemble the components, which enables the reproducibility of their proposal. The presented results validate the measurement platform and emphasize the features that can be analyzed for the characterization of wireless channels.

Major Concerns:
The introduction of the document does not present a big picture of the problem. Instead, the authors discuss the tasks of their agency related to the development of the measurement platform. I suggest writing a paragraph describing a more general picture of the problem.

A: We added this to the introduction in lines 80 to 106.

Minor Concerns:
The authors present lists of steps that should be conducted to set up and assemble the measurement platform. The reasons for the realization of these steps are not discussed. My suggestion is to add some paragraphs introducing the actions to be done before presenting the corresponding lists. This can help readers to understand why a component is used and how they can reproduce the experiments if they do not own similar components.

A: I think we addressed this in the Introduction lines 80 to 106. If there is something they are looking for they will have to be more specific.

**Commented [VI1]:** JoVE format does not permit introduction of descriptive paragraphs in the protocol section. However, this information could be added in the introduction or discussion sections.

Also, consider splitting the list of steps in the Measurement System Setup section. The authors could split the list into smaller lists that present the subprocesses more clearly.
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

The particular parameters used in the platform can be presented in tables so readers can refer easily to them.
Figure 5 shows the benchtop version of the measurement platform. Here, the signal generator is referred to as CW source/Fading simulator, which is not consistent with the text.

A: I will try to find the original photo and change the text. If not I'll go into the lab and take another photo.

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**Reviewer #2:**
Manuscript Summary:
The manuscript introduces a continuous-wave channel sounding system that proves to be reliable and could make accurate and unbiased propagation loss measurement result. This sounding system focus on AWS-3 band and could support other frequencies according to the manuscript, which might be quite interesting to other measurement campaign. A very good instruction on how to setup the system step by step with details, with a full list of needed technical equipment. Multiple measuremnt results are presented with graphs. However, I think this manuscript could have some improvements as listed in the confidential comments.

Line 52-54: "These arrangements will allow commercial wireless carriers to enter the AWS-3 band prior to completing the transition of military services out of the band." This seems unclear to me. Does this means commercial carriers can enter AWS-3 band if military services is not working in this band?

A: added the sentence "The use of the band will be coordinated by both isolating systems geographically and by modeling frequency interference scenarios" so hopefully this makes it clearer.

Line 90: "continusous wave (CW)". This abbreviation has already appeared in the previous Abstract section. All later texts should not repeat this.

A: deleted in later references, kept them in the figure captions because I read this is what the editor wanted, if not it needs to be clarified.

Line 185: Repeated abbreviation "UPS".

A: deleted the second instance, line 166

Line 246: Could damage the device if following steo by step (turnning on VSG before reading the warning). Should put the "Warning" before "Turn RF On of VSG".

A: Vidhya: Did you add this in lines 246-248?

Line 250 and 251: Similarly, warnings should come first or in the step of 16.1.

A: Vidhya: Did you want this in a Note?

Line 257 : Adding graph to show how is the rotation like on IQ plot if the frequencies are alligned.

A: This is what we tried to show in the figure and in the text, that is would swing back and forth. If you need further clarification, maybe you can suggest a better way to do this. I see the text was removed about how to synchronize the rubidiums, do you want me to put this back in. This step is important

Line 388: Adding equation for BTG, since this parameter is shown in Figure 11 and 12.
Figure 5: The figure is blurred.

**Commented [VI2]:** Since this has been also given in the text, I removed these tables.

**Commented [VI3]:** NOTES are usually used to provide such warnings and special points that readers should be aware of.

**Commented [VI4]:** Added; lines 245-248.

**Commented [VI5]:** Nothing has been deleted. Only reframed to appear as numbered points or moved into notes between these points. Do points 1.15 (1.15.1-1.15.3) not describe this? Please check.

**Commented [VI6]:** Equation for BTL added
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

A: Changed the figure by taking a new photograph and changing the fading simulator to VSG

Figure 13: Two blue dotted lines couldn't be easily distinguished.

A: Discussed in the test and the legend.

**Commented [VI7]:** Well, they can be distinguished, but you have not discussed the lower Fresnel zone at all in the legend (and referred to the upper one as the first one).