Beyond Line-of-Sight UHF Digital Communications with the LoRa Spread Spectrum Waveform

Dan Fay, KG5VBY

Who am I?

- Licensed radio amateur since September 2017, callsign KG5VBY
  - Special event communication
  - Packet radio/digital communications
- Live here in Albuquerque
- Education:
  - B.S. 2004 Computer Engineering, University of Illinois at Urbana-Champaign
  - MS.. 2007 Electrical Engineering, University of Colorado at Boulder
  - Ph.D. 2011 Electrical Engineering, University of Colorado at Boulder

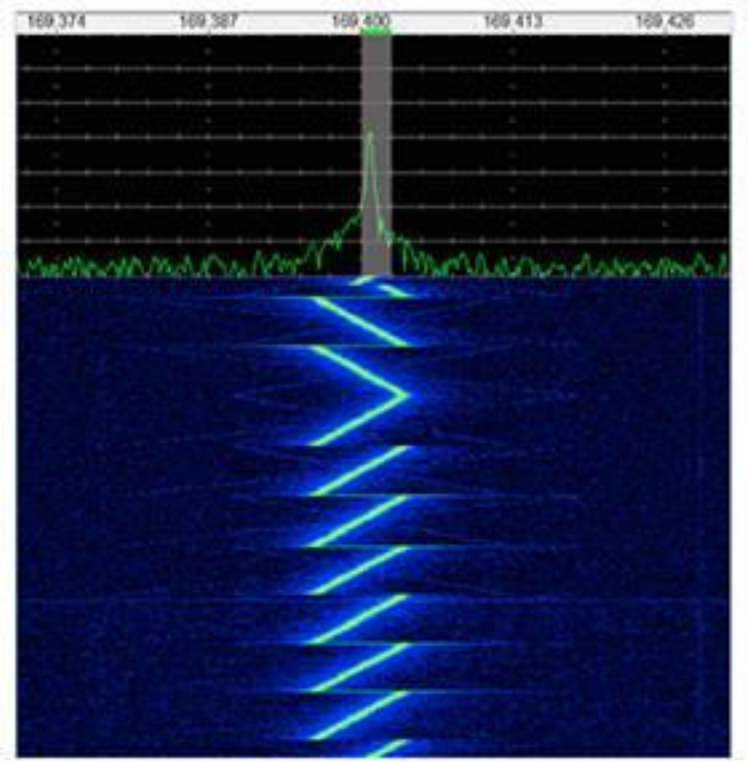
La Luz Trail Run 2018

What did I do?

- I took a low-power, long-range Internet-of-Things spread spectrum wireless modem and applied VHF+ DXing theory and techniques to set a world distance record
  - Increased the power to 25W (LoRa normally operates at 100mW or less)
  - Used much higher antenna gain
  - High link budget of setup allowed for Beyond-Line-of-Sight (BLoS) communication via diffraction and/or troposcatter
- Successfully established IP-based packet radio communications in these conditions

Why LoRa?

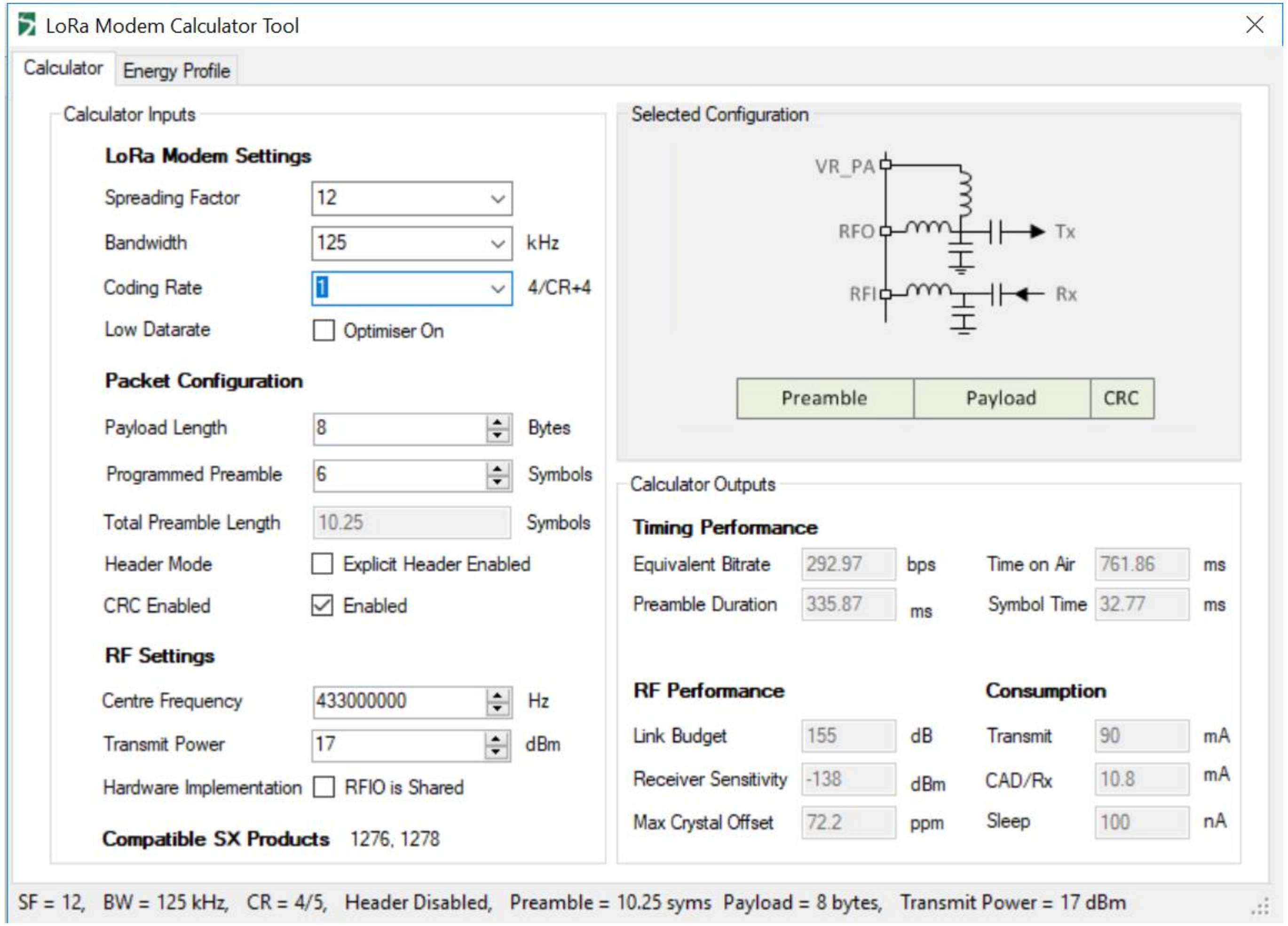
- LoRa is Semtech's proprietary implementation of Chirp Spread Spectrum (CSS)
    - Targets battery-powered, Internet-of-Things (IoT) devices
    - Used to implement LPWAN protocol LoRaWAN
- Benefit: CSS gives large processing gain vs. FSK/OOK
    - LoRa@300bps: -138dBm Rx sensitivity on 70cm
    - FSK@1200bps: -123dBm Rx sensitivity on 70cm (LoRa @1200bps is -132dBm)
    - LoRa supports bitrates up to 37500bps
- Highest sensitivity rate possible for LoRa is -150dBm
    - Not used much because it requires a TCXO to function well
    - Low data rate -- 18bps at this sensitivity
- LoRa is becoming increasingly popular, so products are easy to find
    - 33cm and 70cm easy to find
    - LoRa chipsets support 137MHz through 1GHz
- *LoRa provides large coding gain (9dB or more) vs. FSK along with better multipath fading resistance*



Source: [*https://www.digikey.com/en/articles/techzone/2016/nov/lorawan-part-1-15-km-wireless-10-year-battery-life-iot*](https://www.digikey.com/en/articles/techzone/2016/nov/lorawan-part-1-15-km-wireless-10-year-battery-life-iot)

LoRa Parameters

- LoRa is like an *m-ary* FSK
  - A chirp comprises many *chips*
  - Each chip is like a very short FSK tone
- Spreading Factor (SF)
  - 2^SF = number of chips/symbol
  - Higher SF gives higher Rx sensitivity in exchange for lower data rates
- Bandwidth – how “wide” the chirp is
  - Wider bandwidth gives higher data rates at expense of Rx sensitivity
  - 500KHz, 250KHz, and 125KHz are typically used
- Coding rate specifies the FEC



Other LoRa Features Useful to Hams

- Semtech’s chipsets collectively support 2m and 1.25m bands
  - Need someone to actually design boards for those frequencies
  - NOTE: 250KHz and 500KHz bandwidths are *not* supported on 2m!
- Ham designs could support
  - Higher Tx power – Semtech’s chipsets max out at 200mW
  - Higher Rx sensitivity via better LNA – noise factor is 6dB on SX1276
  - TCXO to enable narrower bandwidths
- GNU Radio supports LoRa
  - Useful for debugging; Rx sensitivity is not as good as Semtech’s chipsets
  - While no complaints yet, unknown if there’s any IP/patent issues with this

Overview of Troposcatter and Diffraction

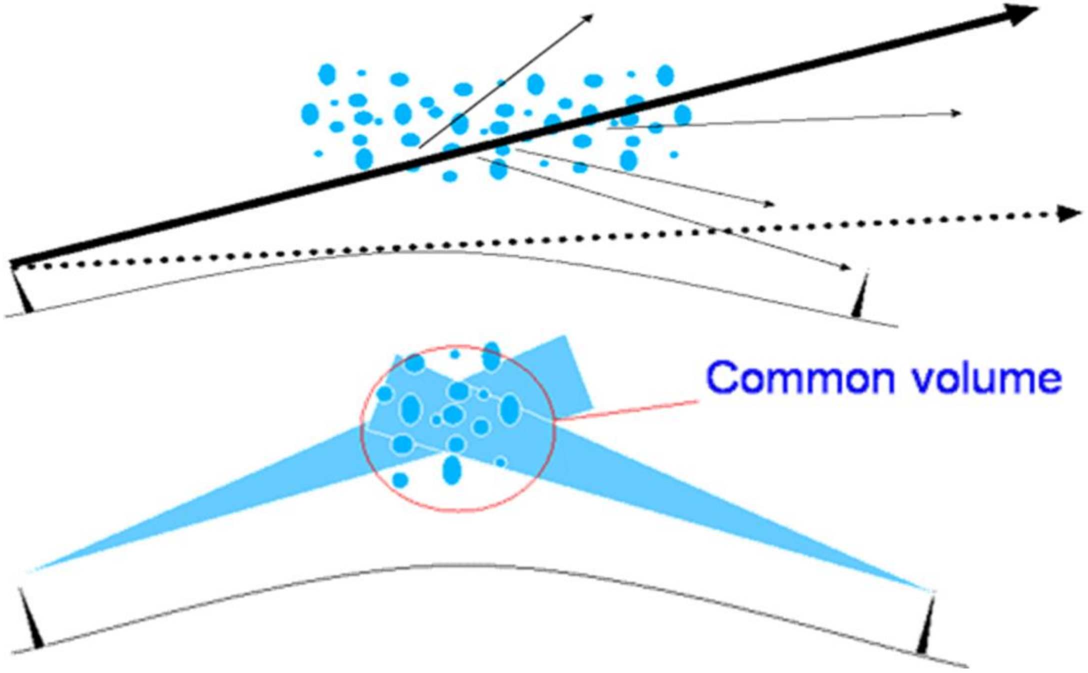
- VHF+ typically limited to Line-of-Sight (LoS), with some exceptions
    - **Sporadic E** – unpredictable, limited to 6m and 2m
    - **Tropospheric ducting** – based on uncommon weather conditions
    - **Airplane scatter** – needs a plane flying overhead
    - **Precipitation scatter** – weather-dependent, mainly microwave frequencies
- Troposcatter and diffraction provide more reliable communications past the LoS
    - **Knife-edge diffraction** – diffraction around “sharp” terrain features
    - **Smooth-earth diffraction** – diffraction around the surface of the earth
    - **Troposcatter** – RF scattering in the upper troposphere

Diffraction

- Two main types
  - Knife-edge diffraction
  - Smooth-Earth diffraction
- Knife-edge diffraction occurs over relatively “sharp” terrain features like mountain peaks and buildings
- Smooth Earth diffraction occurs over the surface of the earth
  - Similar physics to the diffraction of groundwaves on MF, LF, VLF, ELF
  - Much weaker effect due to the short wavelength
- Diffraction is typically useful for medium BLoS distances (10’s of miles)

Troposcatter

- James Duffey KK6MC has an excellent presentation on troposcatter
- Tropospheric scattering involves scattering RF off of irregularities in density in the upper troposphere
- Longer range than diffraction (potentially hundreds of miles)
- Fairly reliable propagation method, but does suffer some fading issues
- Challenging to use
  - Need a low angle of radiation
  - High path losses (160dB+)



Source: KK6MC's presentation in 51st Central States VHF Society Conference

Hypothesis

If we increase the power and antenna gain of LoRa devices, we can achieve long-distance, Beyond Line-of-Sight packet radio communication on 70cm UHF

Experimental Setup

Spread Spectrum Rules for USA Hams

- FCC used to require Automatic Power Control (APC) for any serious power level
- Now, it's limited to 10W PEP, but without any antenna gain limits
- Obtained a Special Temporary Authorization to transmit LoRa at up to 50W
    - STA File Number 0721-EX-ST-2018 with callsign WM9XPW allowed for up to 50W LoRa Tx from my house
    - May try to get two-way mobile communications at 25W approved if I renew the STA for further experiments

LoRa Products

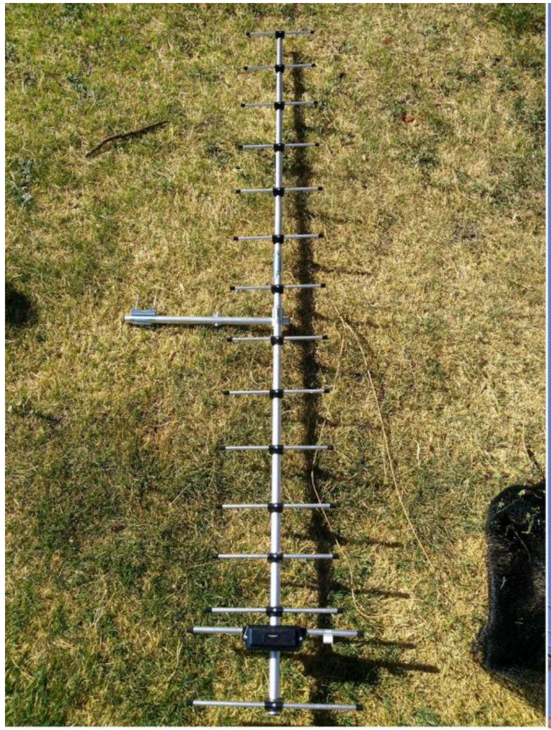
- LoRa is used in the growing Low-Power Wide-Area Network (LPWAN) world to provide low datarate communications
  - LoRaWAN – IoT protocol built on top of LoRa
  - Mainly operates in unlicensed ISM bands (i.e., 868MHz/915MHz)
  - Comcast MachineQ, and The Things Network (TTN) use LoRaWAN
- Different companies implement complete LoRa modules
  - HopeRF – “Low-level” implementation of LoRa modules via SPI bus
  - Microchip – provides a higher-level UART interface with AT commands
  - CDEBytes – makes a variety of “transparent bridge” devices that create a half-duplex UART abstraction for ease of use

CDEBytes LoRa-based Products

- Chengdu Ebyte Electronic Technology Company
  - Produces various wireless modules
  - Mainly sells for Chinese Domestic Market and Asia
  - Sells to Americans via Aliexpress and eBay
- LoRa-based transparent bridges
  - Configure over UART interface
  - Once configured, use like a half-duplex UART
  - 1W module product – uses a TTL-UART interface
  - 1W/5W DTU product – supplies RS-485 and RS-232 interfaces
- *The DTU products were convenient to use and were instrumental in getting this study done*

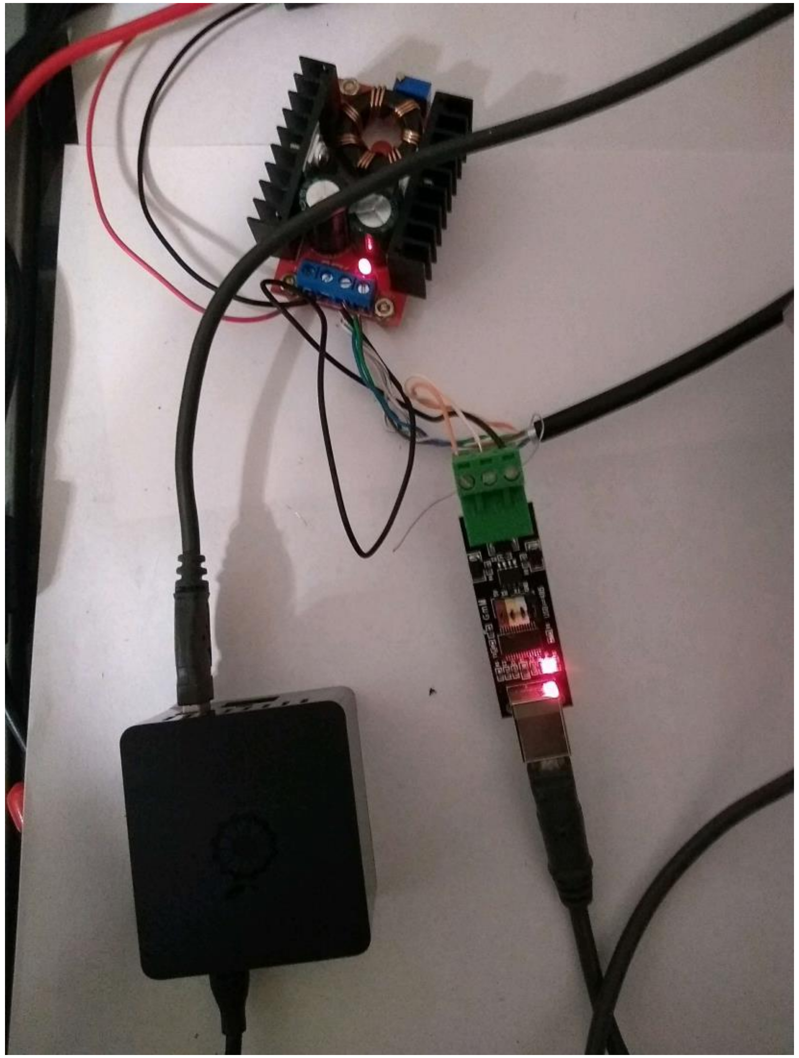
Base Station Antenna

- Elevated roughly 20’ above the ground
  - Lowest angle of radiation requires elevation of 7-10 wavelengths above ground
  - For the 70cm band, that means at least 16’ above the ground
- Diamond 430S15
  - 15-element Yagi-Uda antenna
  - Gain is specified at 14.8 dBi
  - Mounted to chimney on my house using straps holding a 10’ length of 1” EMT conduit



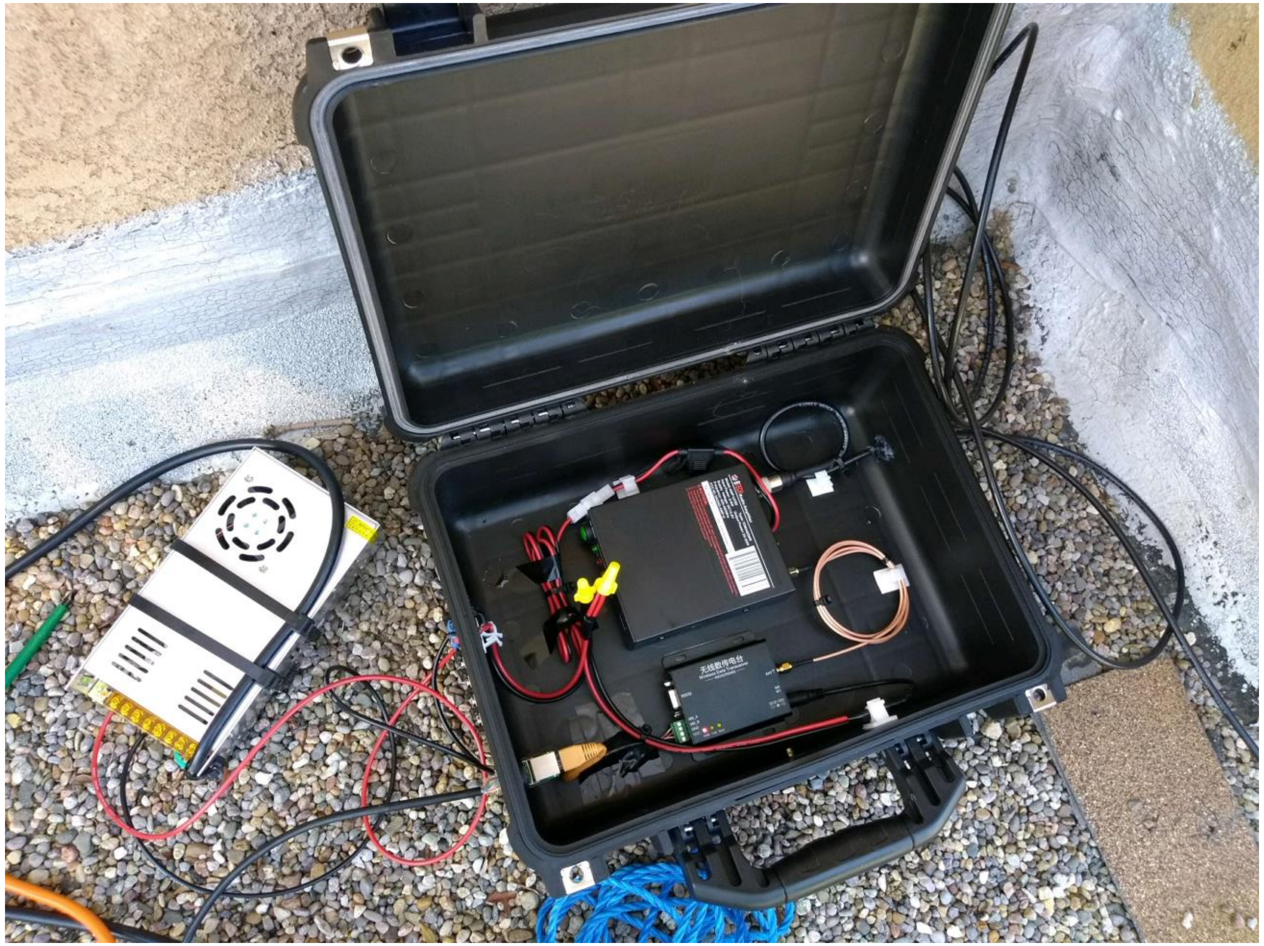

Base station Setup (inside shack)

- Sends data (and power) over Cat 5e cable
- Orange Pi SBC (black cube in lower left) transmits and receives data via USB-RS485 adapter
- USB-RS485 adapter (lower right) sends UART data over a wire pair in the cable
- Boost converter board (top) steps up 12V to ~36V before sending power over remaining three wire pairs in the Cat 5e cable
- Uses LoRa at 300bps (SF=12, BW=125KHz)



Base Station Transmitter (high power)

- 1W CDEBytes device
- Btech AMP-U25D
  - Designed to amplify DMR HT’s
  - Amplifies 1W input to ~25W
- Fed via 12V/13A power supply (on left side)

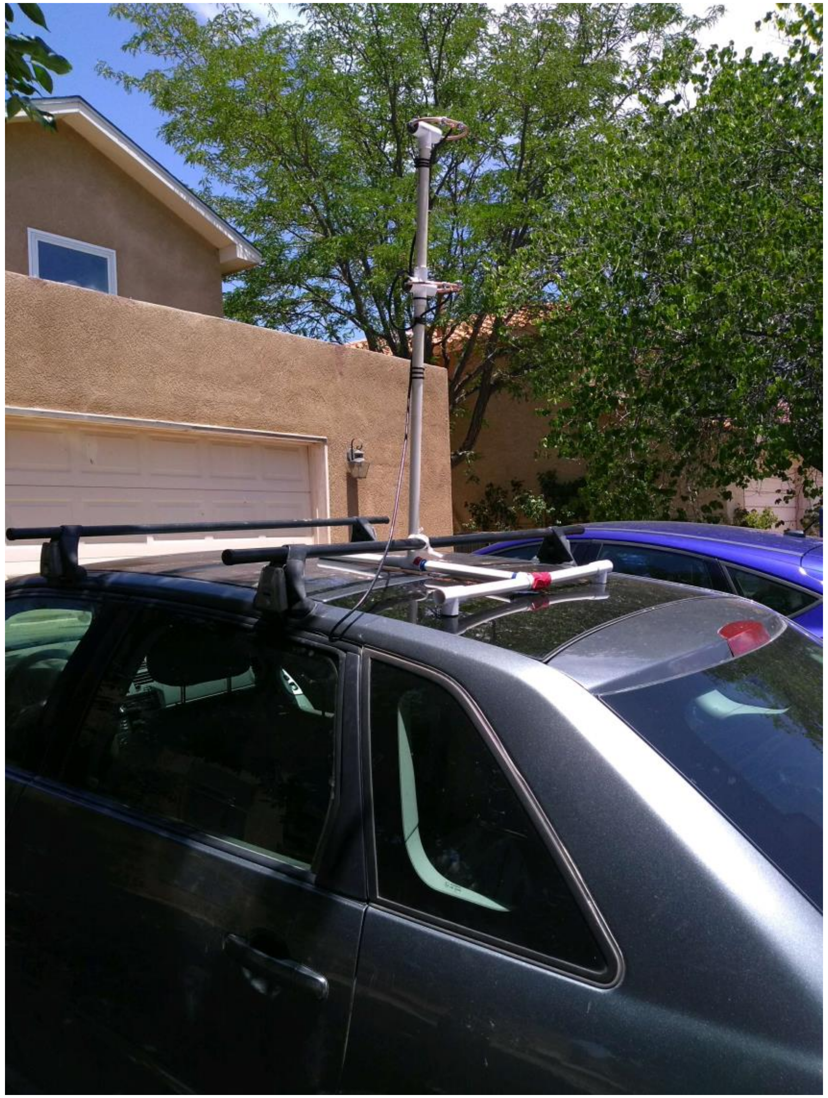


Base Station Transceiver (low power)

- 5W CDEBytes device
- Gets power from Cat 5e cable
- Boost converter board raises voltage from Cat 5e cable to compensate for line losses

Mobile Antenna

- Dual stacked halo antenna
  - Based on KR1ST's quad-stacked halo antenna
  - Gain is estimated to be 2-3dBi
- ¾" PVC pipe base
- Works well, even while driving on the highway at 75 miles/hour



Mobile Transceiver Setup

- Laptop computer running Linux Mint receives data
- SLIP provides IPv4 connectivity
- Python script receives UDP packets, appends the payload with the GNSS location data, and saves it to a file

Mobile Transceiver Setup

- GNSS (GPS+GLONASS) USB receiver for location information
- 5W CDEBytes transceiver
- USB-to-RS232 adapter
- Power supply
  - 8AA batteries for RX-only
  - 12V/3A power supply for TX/RX
- Tried an external LNA board, it didn’t work (not sure why)

Modeling Propagation

- This work involves a lot of time-consuming driving, so we'd like to minimize the amount of driving we're doing
- We'd like to know whether we can receive the signal at a given location
- It would be good to know the propagation method
  - Are we past the radio horizon?
  - How is the RF propagating? Diffraction or troposcatter?
- We can model propagation by determining the link budget for a given Tx/Rx setup and comparing it to the path losses
- Used Radio Mobile Online to do this

Link Budget

- **Definition**: maximum total path loss allowed for successful communication
- Measured in dB
- **Link budget (dB)** =

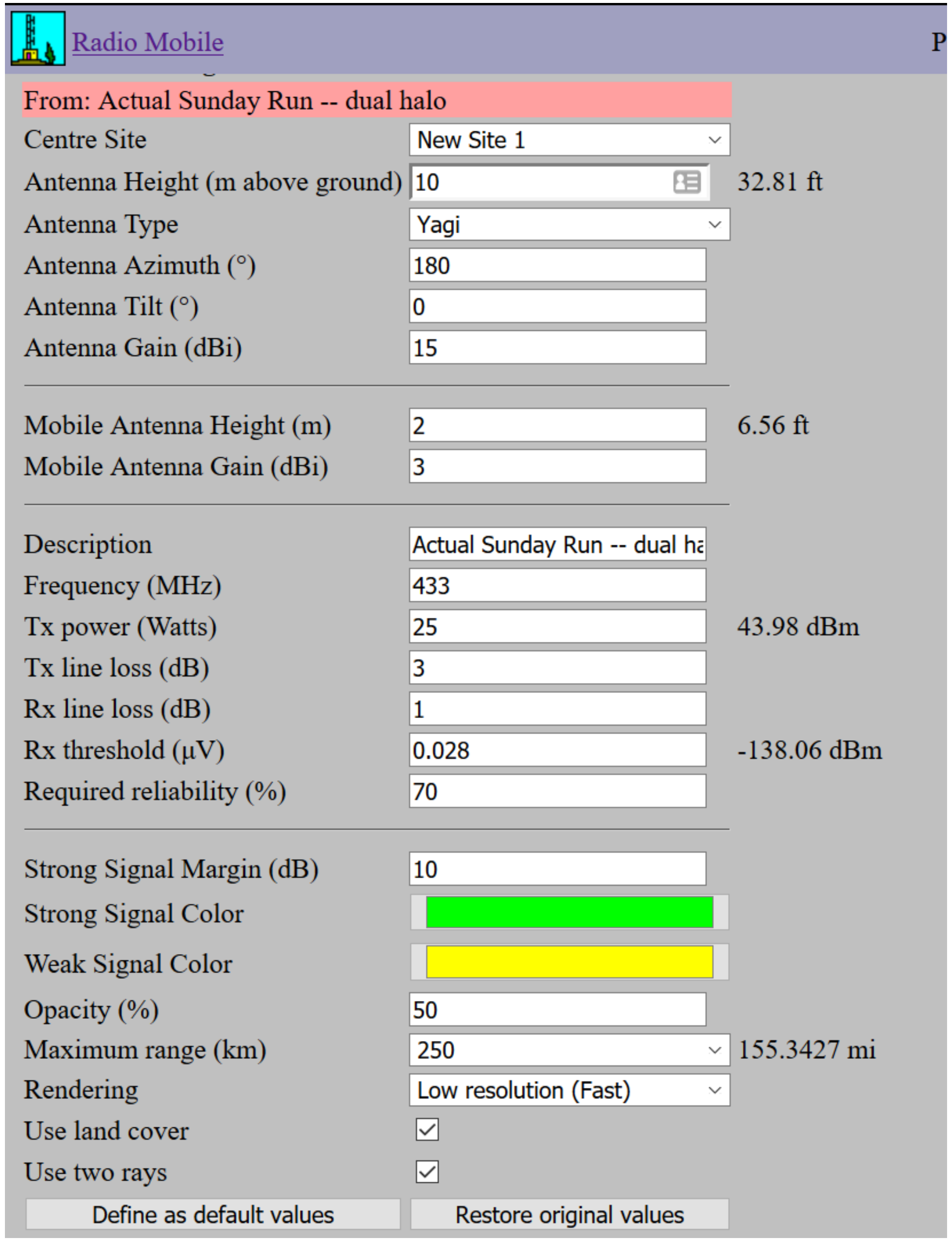
  Tx power (dBm) + Rx sensitivity (dBm) + Tx antenna gain (dBi) + Rx antenna gain (dBi) – feedline losses (dB) – other losses (dB)

Link Budget Calculations

Path Component	Mobile Halo Setup Gain/(Loss)	Dismounted Yagi Setup Gain/(Loss)	Mobile TX/RX Gain/(Loss)
Tx power	44 dBm	44 dBm	37 dBm
Tx antenna gain	14.8 dBi	14.8 dBi	14.8 dBi
Tx feedline loss	(2.3 dB)	(2.3 dB)	(2.2 dB)
Rx sensitivity	-138 dBm	-138 dBm	-138 dBm
Rx antenna gain	2 dBi (estimated)	12.4 dBi	2 dBi
Rx feedline loss	(0.97 dB)	(0.90 dB)	(0.97 dB)
Total Link Budget	193.5 dB	206.0 dB	188.6 dB

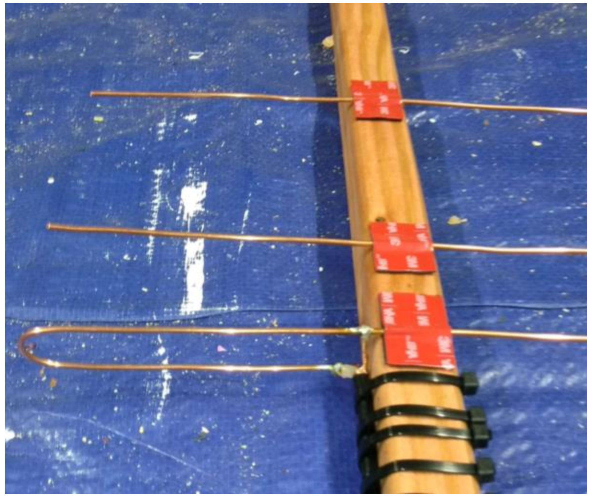
Radio Mobile Online

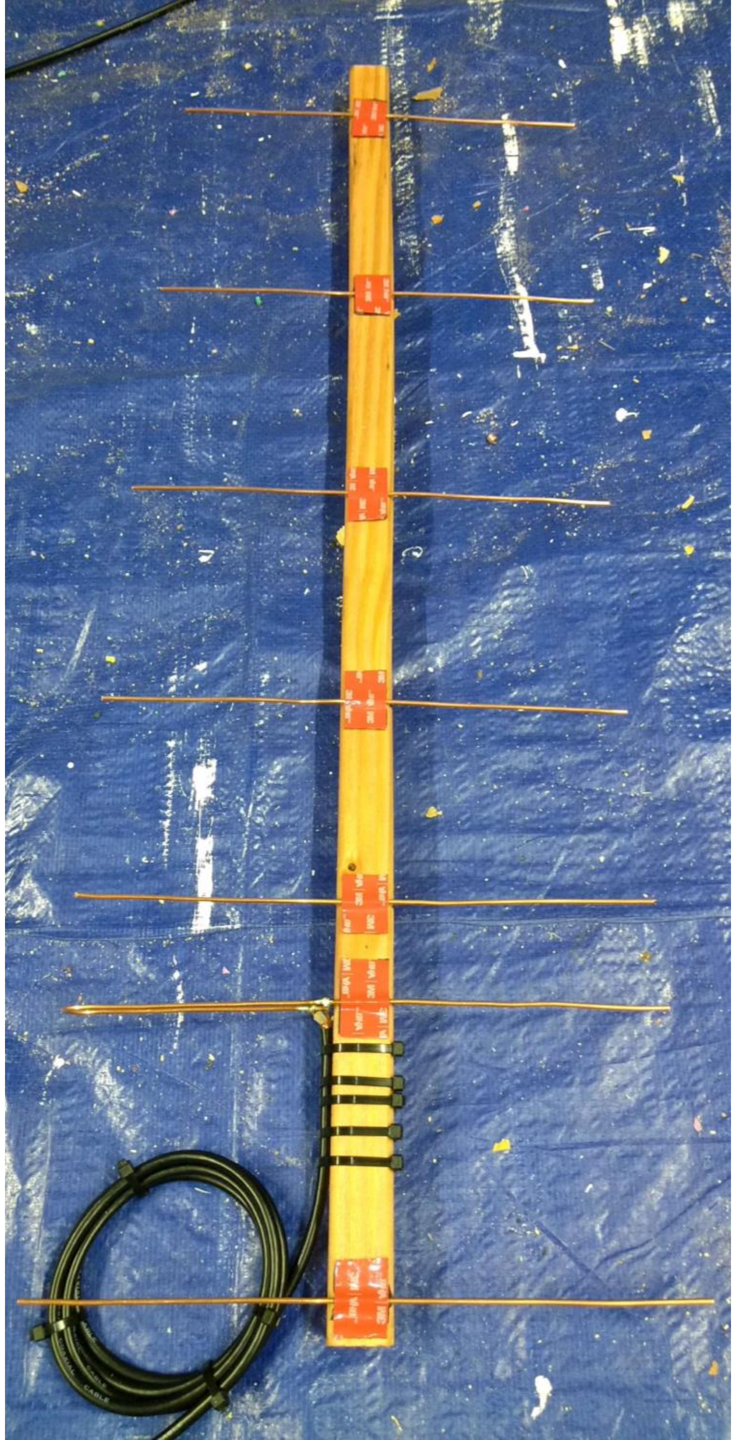
- Website/application that calculates RF coverage
  - Uses real terrain data for calculations
  - Models not only LoS coverage but diffraction and troposcatter as well
- Input key parameters
  - Power output
  - Antenna gain
  - Antenna direction
  - Antenna elevation



Stationary Antenna

- 7-element Yagi-Uda
  - #10 copper wire elements
  - 2’ wood boom
  - RG-8x feedline
- Element size and placement determined using Alexander Frank’s Yagi-Uda antenna calculator
- Folded match is based on WA5VJB’s design
- Estimated gain is 12.4 dBi





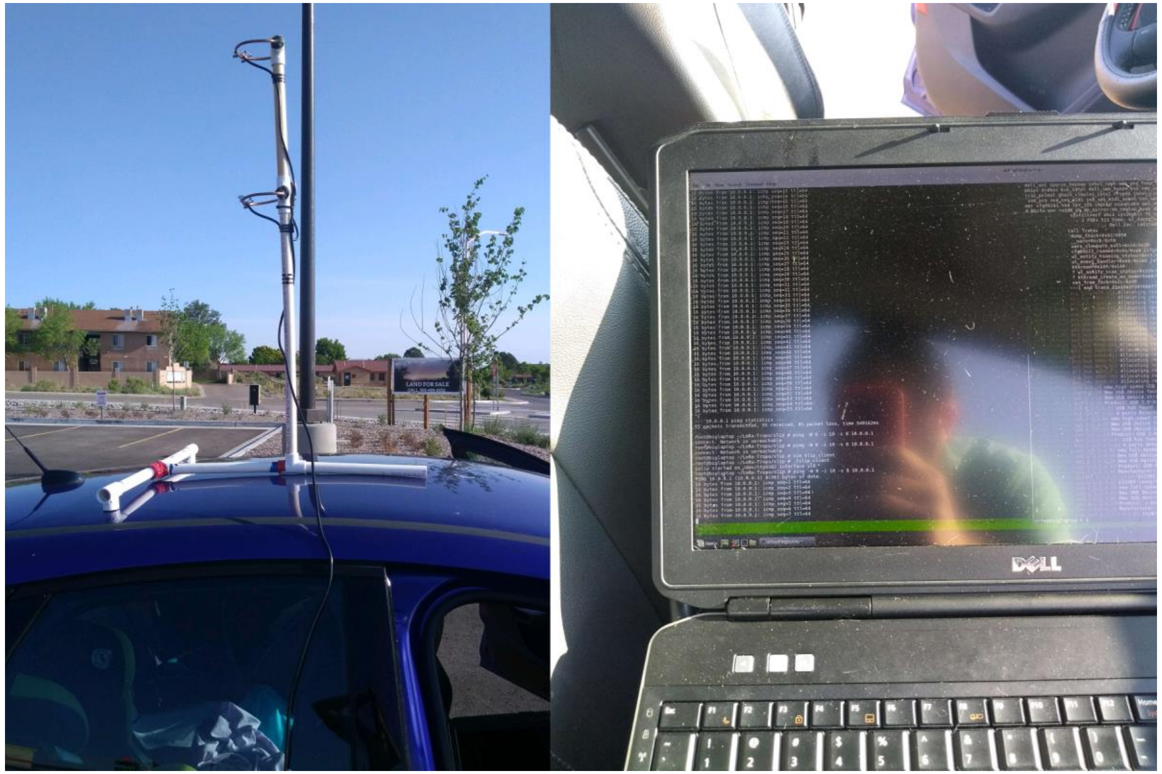
My Assistants

- Key traveling companions on my various LoRa reception surveys
- Middle seat – my 1yr old Lexi
- Passenger side – my 4yr old Sophie

Experimental Results

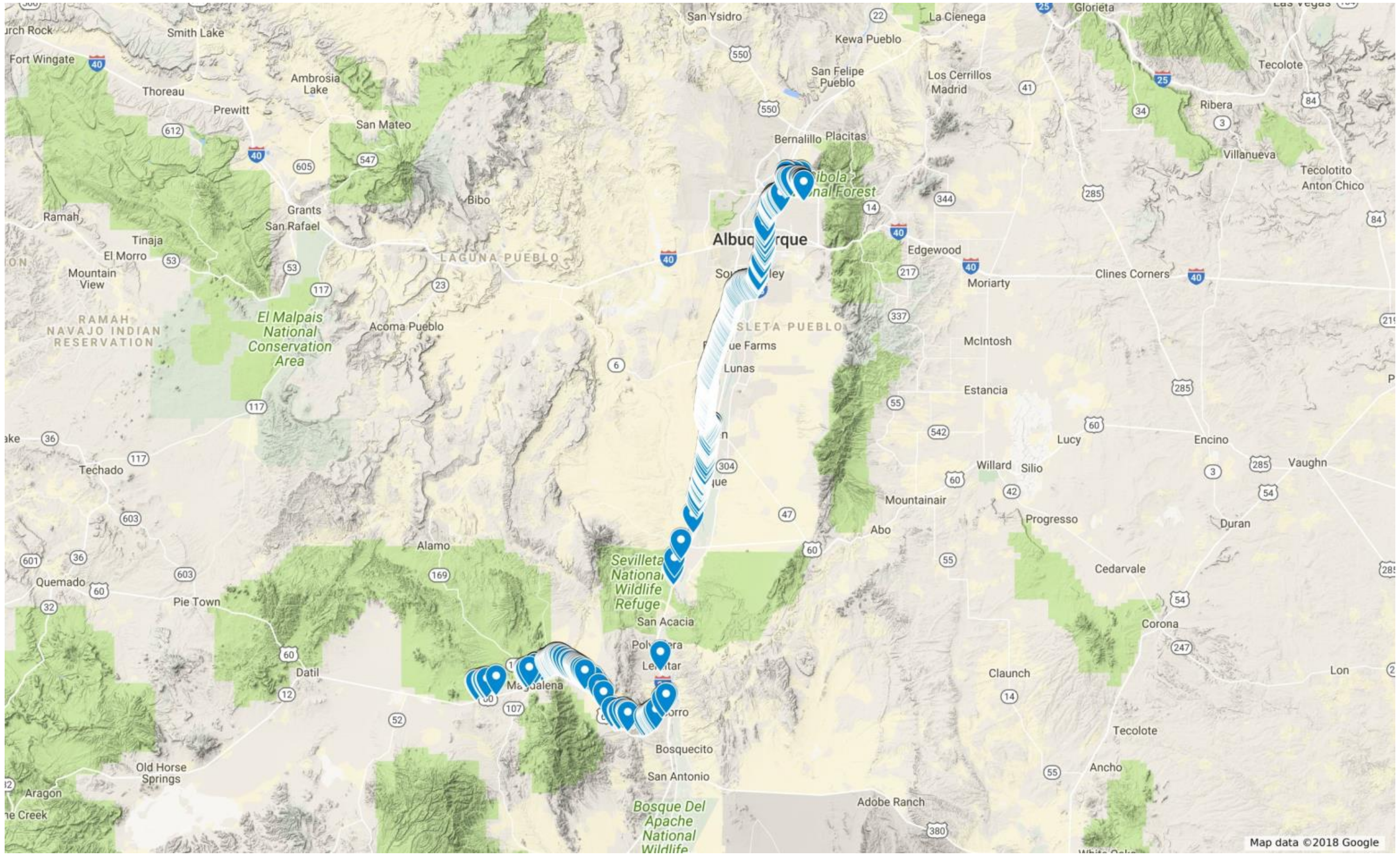
Mobile Tx/Rx Results

- Drove down to Belen, NM
- Attempted two-way communication via the `ping` utility
- Success!

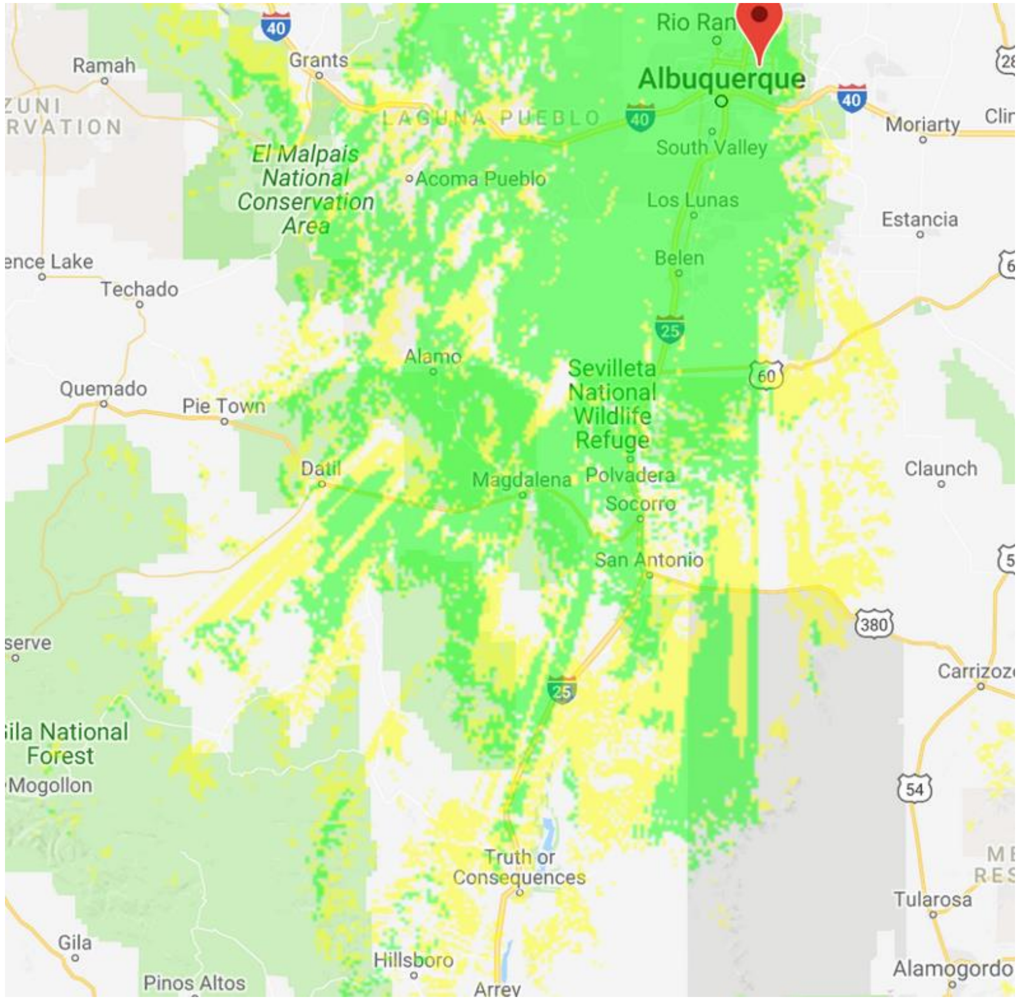


Coverage Map (Halo Rx Antenna)

Mobile Results



Coverage Map (Yagi Rx Antenna)

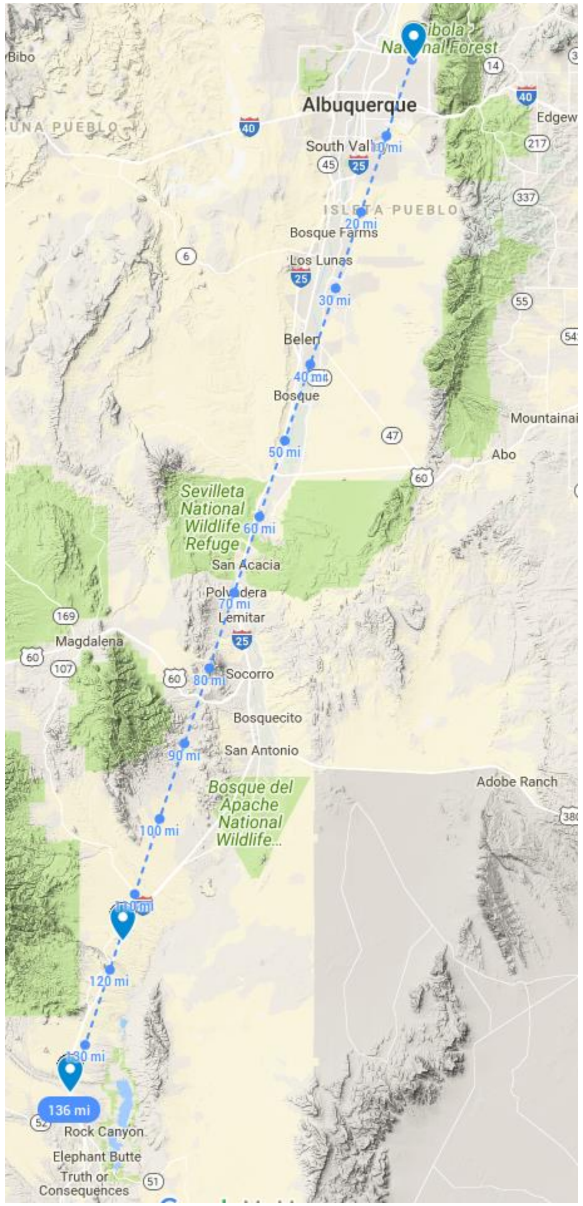


Setting the Distance Record

- Radio Mobile Online's coverage maps were essential
  - Pinpointed exact locations of good coverage
- Good coverage near Elephant Butte
- Pulled off highway into a good flat spot
- Pointed Yagi in direction of mountain-free horizon

Distance Record

- Longest ground-to-ground communication distance with LoRa
- 136 miles (218 km) between house in Albuquerque and Elephant Butte
- Previous distance record was 201km
  - Set by Andreas Spiess in Switzerland
  - Communication between two large mountains

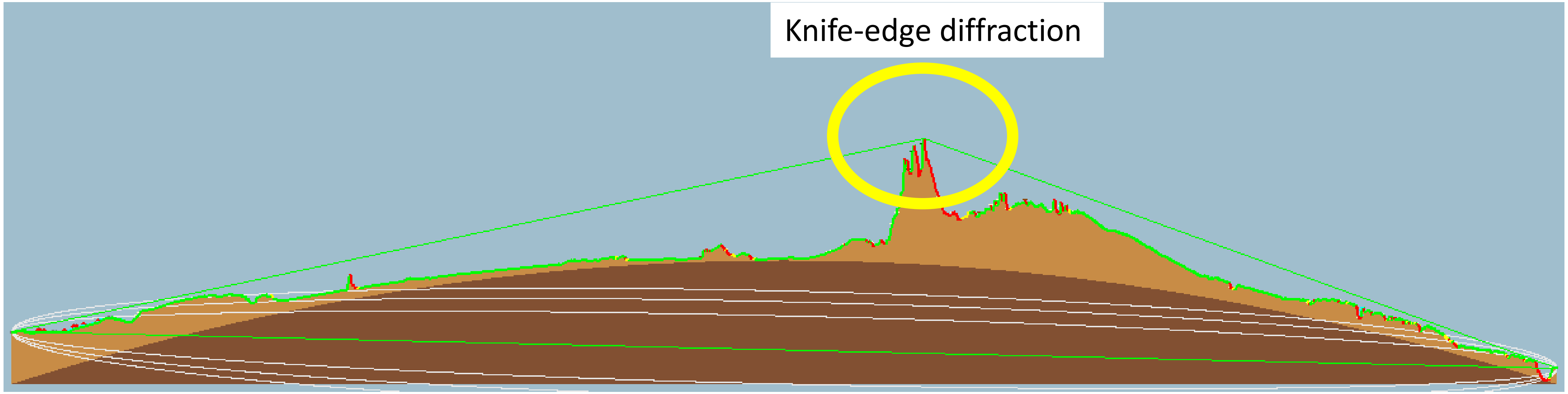


Propagation Analysis

Radio link study 13					
New Site 1 (1)					(2) Record Location
Latitude	35.164157	°	Latitude	33.294216	°
Longitude	-106.535629	°	Longitude	-107.285737	°
Ground elevation	1711.5	m	Ground elevation	1504.8	m
Antenna height	7.0	m	Antenna height	2.0	m
Azimuth	198.56 TN | 190.28 MG	°	Azimuth	18.14 TN | 9.71 MG	°
Tilt	-1.04	°	Tilt	-0.93	°
Radio system					**Propagation**
TX power	43.98	dBm	Free space loss	131.94	dB
TX line loss	3.00	dB	Obstuction loss	44.39	dB
TX antenna gain	15.00	dBi	Forest loss	1.00	dB
RX antenna gain	13.00	dBi	Urban loss	1.00	dB
RX line loss	0.50	dB	Statistical loss	3.53	dB
RX sensitivity	-137.46	dBm	Total path loss	181.86	dB

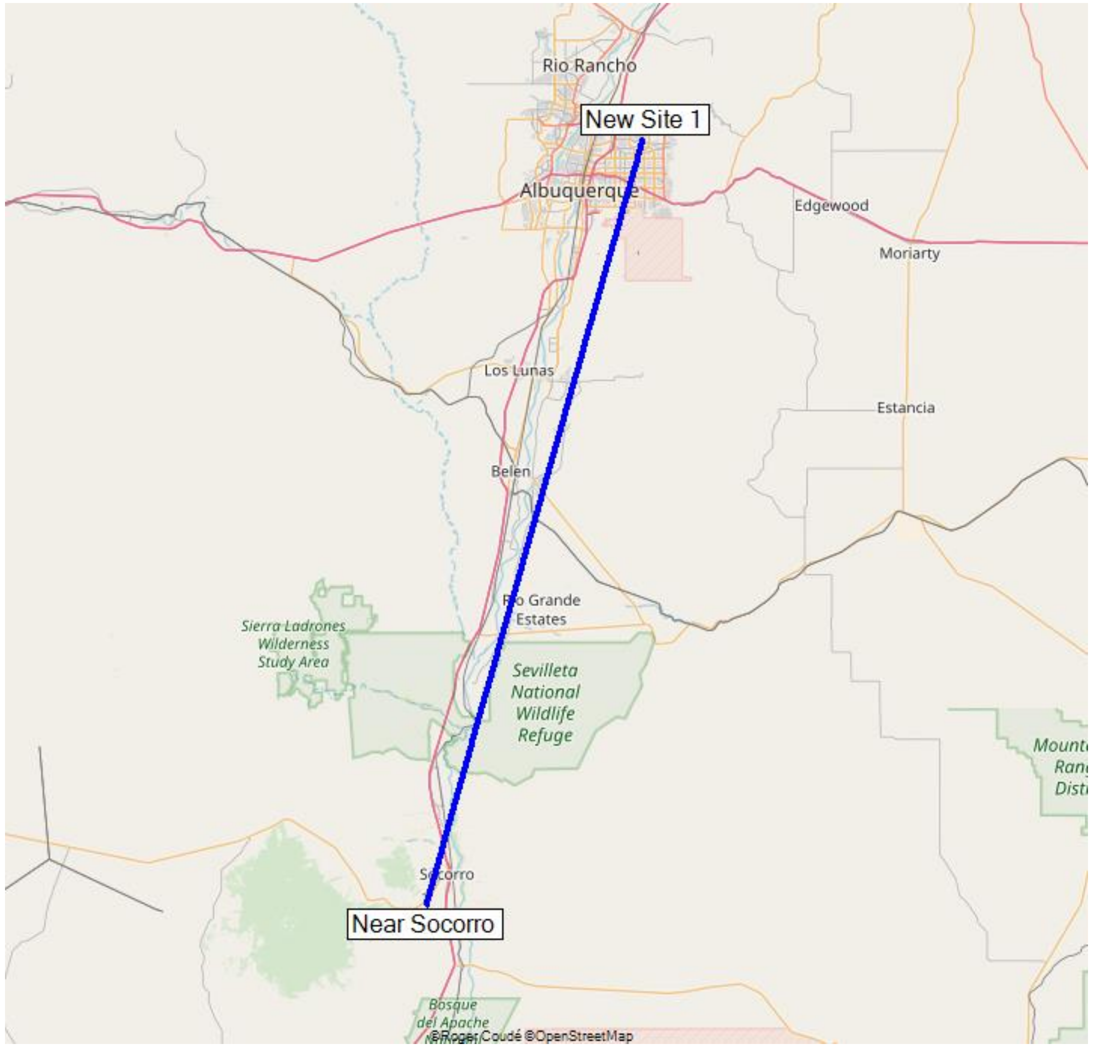
Performance		
Distance	**219.063**	**km**
Precision	109.6	m
Frequency	433.000	MHz
Equivalent Isotropically Radiated Power	396.223	W
System gain	201.50	dB
Required reliability	70.000	%
Received Signal	-113.38	dBm
Received Signal	0.48	µV
Fade Margin	**19.64**	**dB**

Propagation Analysis

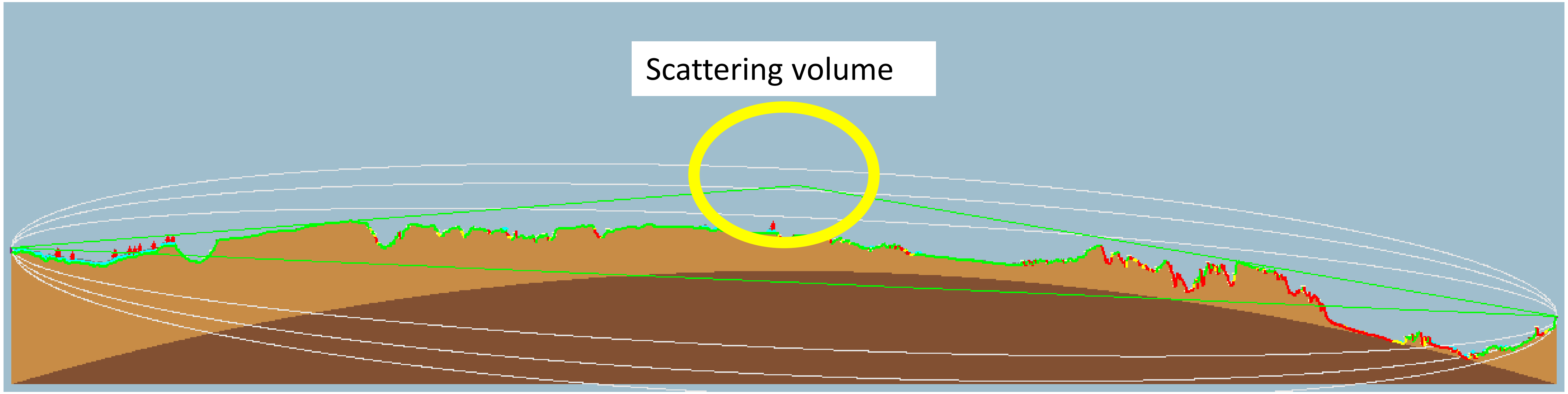


- Mountain (not visible from either Tx or Rx point) induces knife-edge diffraction

Troposcatter Example



Propagation Analysis



- Path is most likely due to troposcatter and not diffraction

Analysis Results

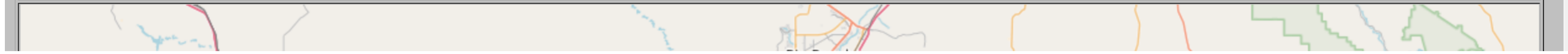
Radio Mobile | Par/By Roger Coudé VE2DBE | Information

Sunday 6-10 Results

New Site 1 (1)		(2) Near Socorro	
Latitude	35.164157 °	Latitude	34.009572 °
Longitude	-106.535629 °	Longitude	-106.932235 °
Ground elevation	1711.5 m	Ground elevation	1560.5 m
Antenna height	10.0 m	Antenna height	2.0 m
Azimuth	195.90 TN | 187.60 MG °	Azimuth	15.68 TN | 7.30 MG °
Tilt	-0.67 °	Tilt	-0.53 °

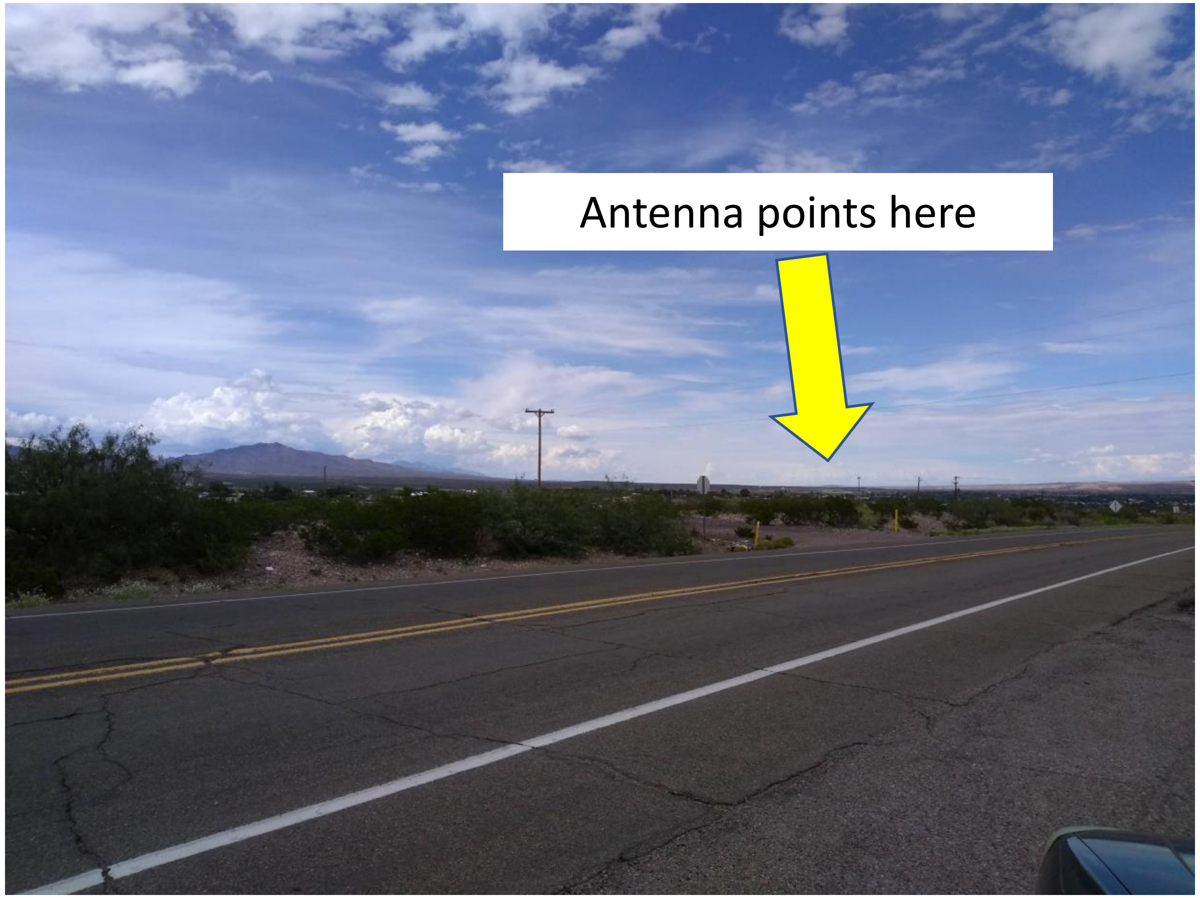
Radio system		**Propagation**	
TX power	36.99 dBm	Free space loss	127.63 dB
TX line loss	1.00 dB	Obstuction loss	35.83 dB
TX antenna gain	15.00 dBi	Forest loss	1.00 dB
RX antenna gain	2.00 dBi	Urban loss	1.85 dB
RX line loss	1.00 dB	Statistical loss	5.03 dB
RX sensitivity	-139.04 dBm	Total path loss	171.35 dB

Performance	
Distance	**133.419 km**
Precision	66.7 m
Frequency	433.000 MHz
Equivalent Isotropically Radiated Power	125.594 W
System gain	185.01 dB
Required reliability	70.000 %
Received Signal	-119.36 dBm
Received Signal	0.24 µV
Fade Margin	**13.67 dB**



Receiving Troposcatter

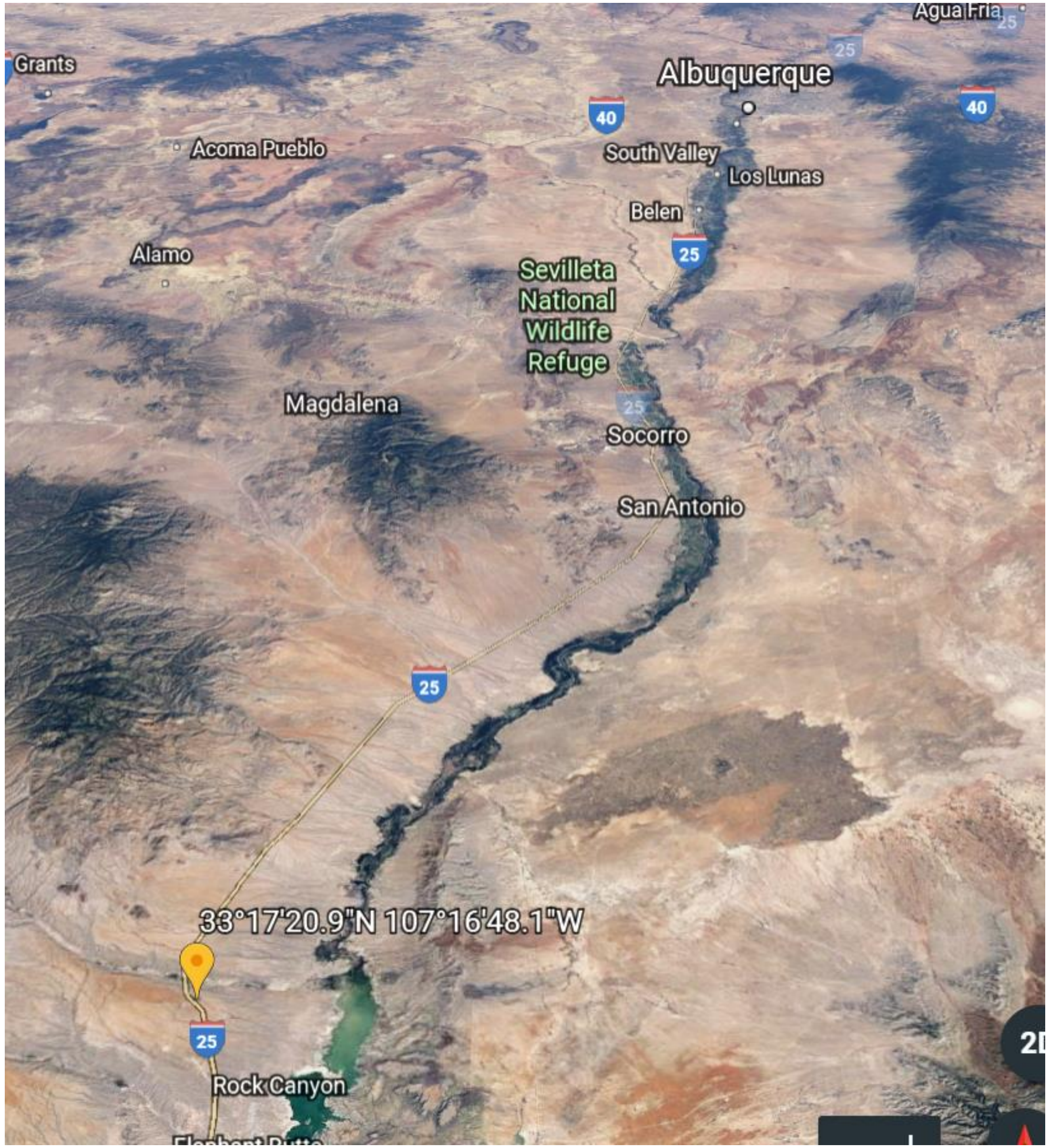
- Central New Mexico's rugged terrain favors diffraction over troposcatter
- The world record was likely knife-edge diffraction
- May be possible to break this record in a flat where long distance troposcatter is possible



Discussion

Discussion

- Central New Mexico’s rugged terrain favors diffraction over troposcatter
- The world record was likely caused by knife-edge diffraction
- May be possible to break this record in a flat area (e.g. Kansas) where long distance troposcatter is possible



Future Work

- “Go West” – look at propagation results for the I-40 corridor going west from Albuquerque
- Study horizontal vs. vertical polarization
- Use 1W HopeRF LoRa modules to access the RSSI information
- Develop a synchronized, flooded mesh network using LoRa
  - Carry codec2-encoded voice as well as data
  - LoRa’s multipath fading resistance may also confer resistance to collisions
  - Could form basis of wide-area mesh network

Contact Info

- **Blog:** https://faydrus.wordpress.com (describes a lot of my radio/maker experiments)
- **E-mail:** Daniel.fay@gmail.com (kg5vby@arrl.net also works)
- **Twitter:** faydrus