Analysis and Evaluation of Register Transfer Logic Software Defined Radio Performance

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MQP Final Presentation

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LINCOLN LABORATORY
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WPI

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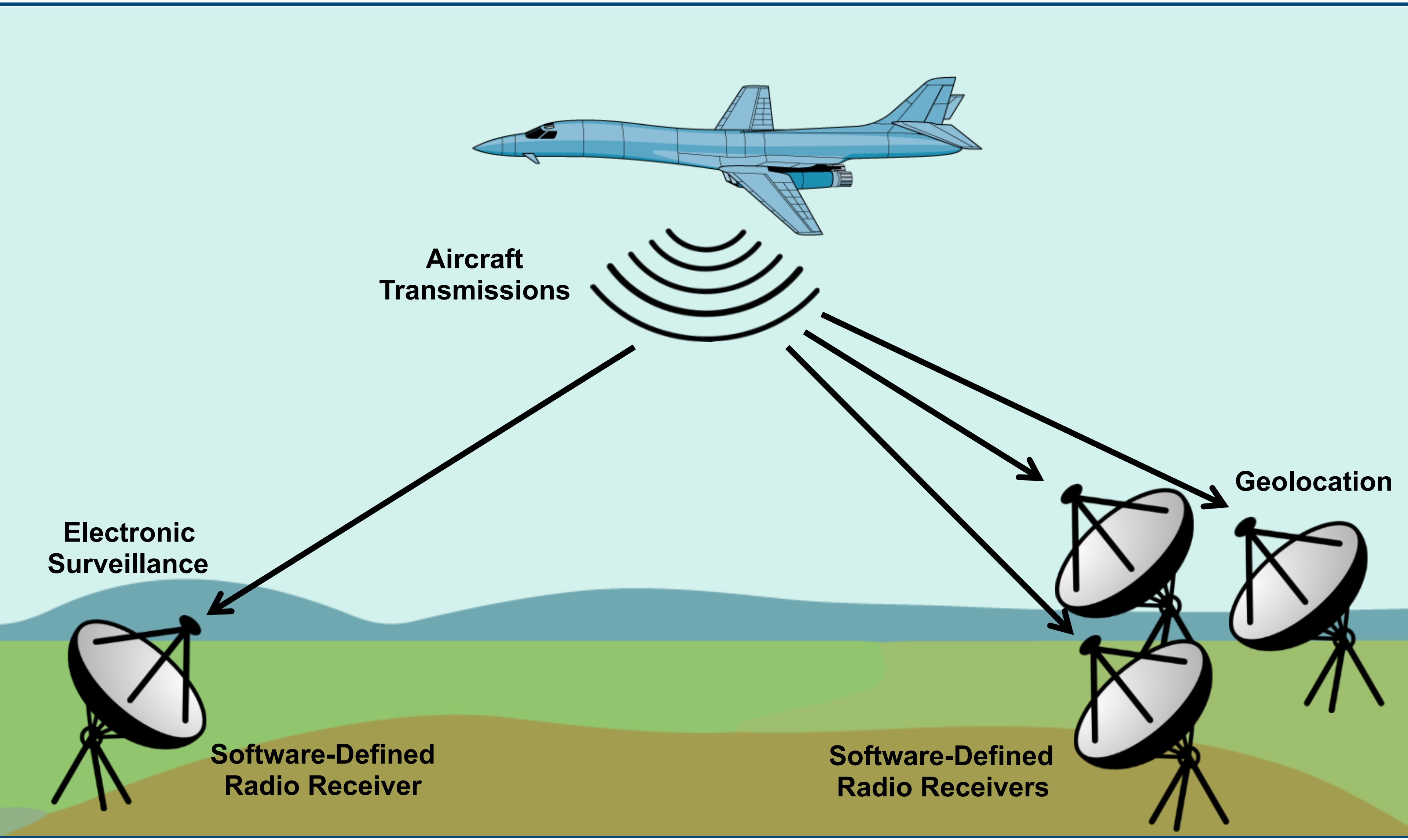
Software-Defined Radio (SDR)

- **Modern radio with some hardware controlled by software**
  - **Software implementations of filters, modulators, amplifiers, etc.**
- **Easily reprogrammable to adjust parameters**
  - **Center frequency, input gain, modulation, etc.**
- **Can be used for various purposes**
  - **Communication systems**
  - **Signal transmission**
  - **Message reception**

Image Sources:
http://www.rtl-sdr.com/
https://www.ettus.com/
http://www.nooelec.com/
http://www.sqdeal.com/

SDR Aircraft Application



Software-Defined Radio Comparison

	Military-Grade	Commercial	Hobbyist
Performance	High	Moderate	?
Availability	Export-Controlled	COTS	COTS
Price	High	Medium	Low

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Focus of this brief

Outline

- Introduction
- Background
  - The USRP and the RTL-SDR
  - USRP and RTL-SDR Comparison
  - Multi-Channel RTL-SDR System
- Standalone SDR Performance Testing
- Multi-Channel RTL-SDR System
- Conclusion

The USRP and the RTL-SDR

USRP

- Commercial grade SDR
- Supported by Ettus Research and National Instruments
- Relatively expensive compared to RTL-SDR

RTL-SDR

- DVB-T television tuner and other hardware on USB dongle
- SDR receiver supported by open-source community
- Inexpensive alternative for hobbyist radio users

Ettus USRP

RTL-SDR

USRP and RTL-SDR Comparison

	Commercial	Hobbyist
	USRP X310 w/ UBX-160	**RTL-SDR R820T2**
Frequency Range	10 – 6000 MHz	
Rx Bandwidth	160 MHz	
ADC Resolution	14 bits	
Transmitter?	Yes	
Price	~$6000	

USRP and RTL-SDR Comparison

	Commercial	Hobbyist
	USRP X310 w/ UBX-160	**RTL-SDR R820T2**
Frequency Range	10 – 6000 MHz	24 – 1766 MHz
Rx Bandwidth	160 MHz	3.2 MHz
ADC Resolution	14 bits	8 bits
Transmitter?	Yes	No
Price	~$6000	~$20

USRP and RTL-SDR Comparison

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The hobbyist RTL-SDR was compared against the commercial USRP.

Multi-Channel RTL-SDR System

- **Implement clock-synchronized RTL-SDRs in multi-tuner system**
  - **System clock oscillators physically connected**
  - **Increases possible reception bandwidth**
  - **Allows for simultaneous signal analysis through multiple channels**

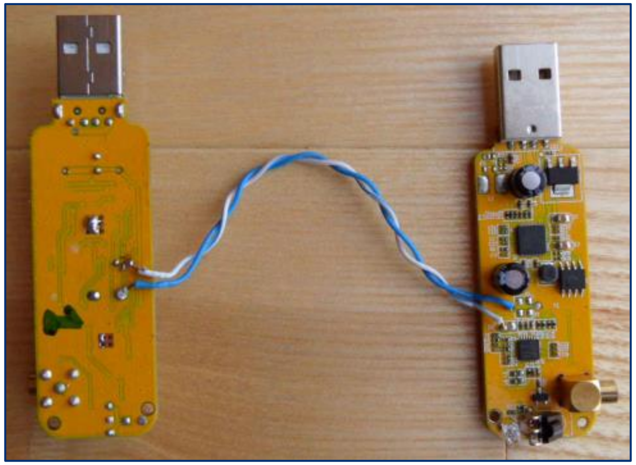


Image Source: https://ptrkrysik.github.io/

Outline

- Introduction
- Background
- Standalone SDR Performance Testing
  - Received Sample Ratio
  - Noise Floor
  - Frequency Coverage
  - Frequency Response
- Multi-channel RTL-SDR System
- Conclusion

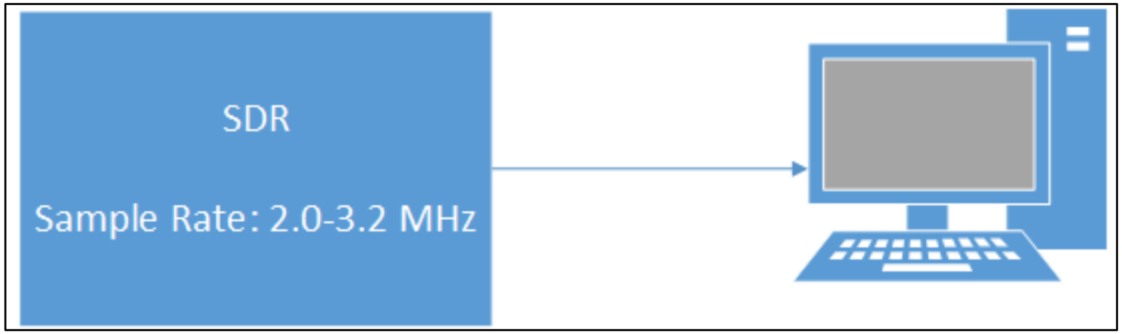
Performance Testing

- **Compare RTL-SDR performance with commercial SDR**
  - **Hobbyist: NooElec, SQdeal, and RTL-SDR Blog RTL-SDRs**
  - **Commercial: Ettus USRP X310 with UBX-160 daughterboard**
- **Test performance characteristics**
  - **Received sample ratio**
  - **Noise floor**
  - **Frequency coverage**
  - **Frequency response**

RTL-SDRs

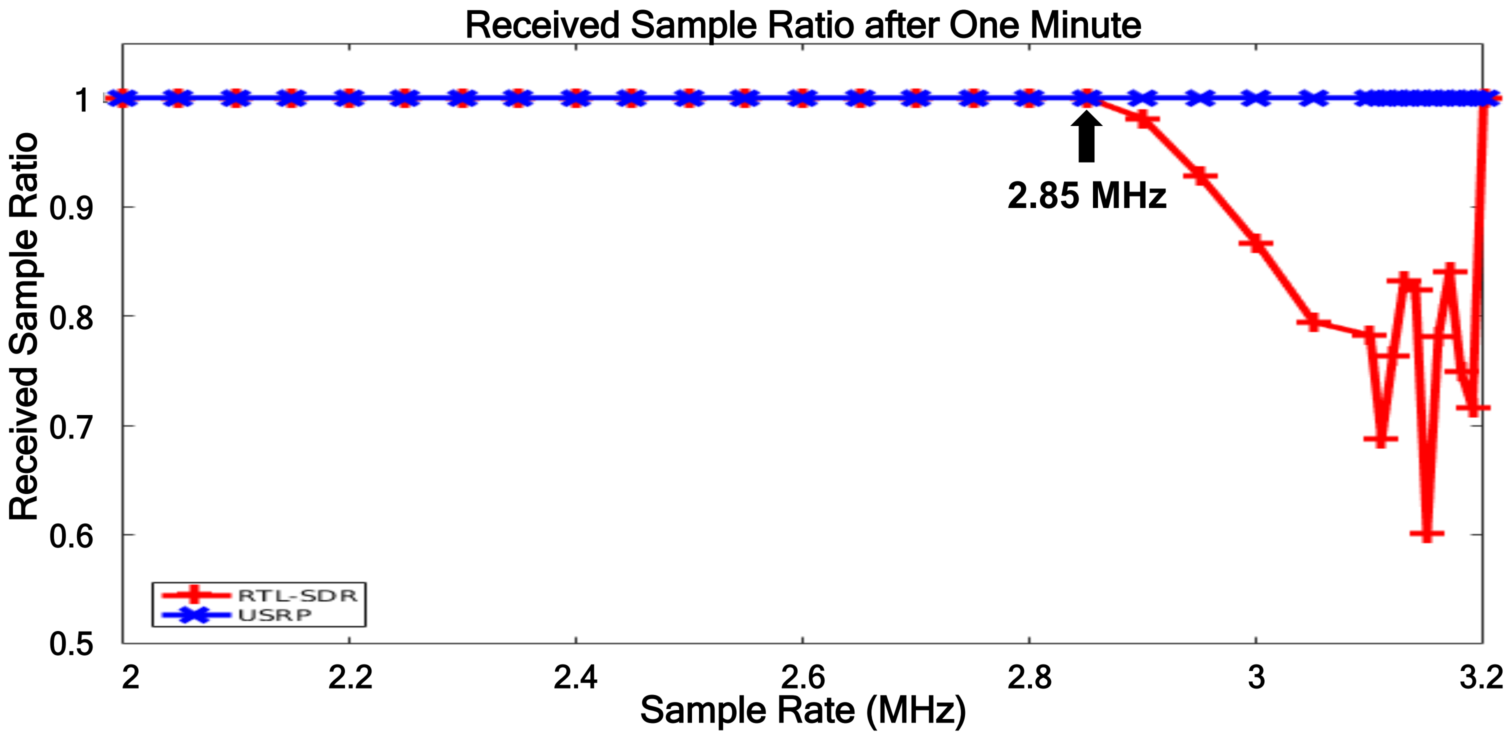
Universal Software Radio Peripheral (USRP)

Received Sample Ratio Test



- **Run RTL and USRP test scripts on RTL-SDRs and USRP**
  - **Test at various sample rates from 2.0 MHz to 3.2 MHz**
  - **Record number of dropped samples per number of total samples**
- **Perform calculations and plotting in MATLAB**
  - **Calculate received sample ratio**
  - **Plot received sample ratio of SDRs across sample rate range**

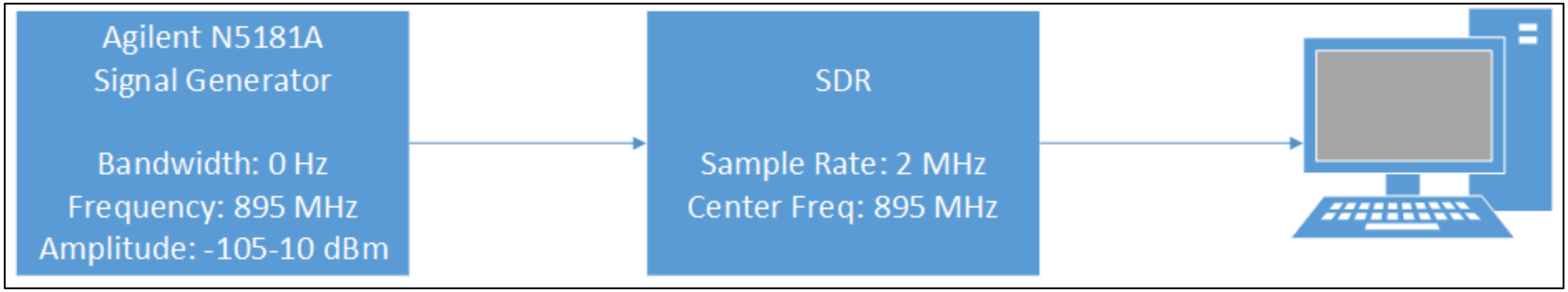
Received Sample Ratio Results



- **All RTL-SDRs have nearly identical performance**
- **RTL-SDRs maintain perfect performance through 2.85 MHz**
- **USRP maintains perfect received sample ratio**

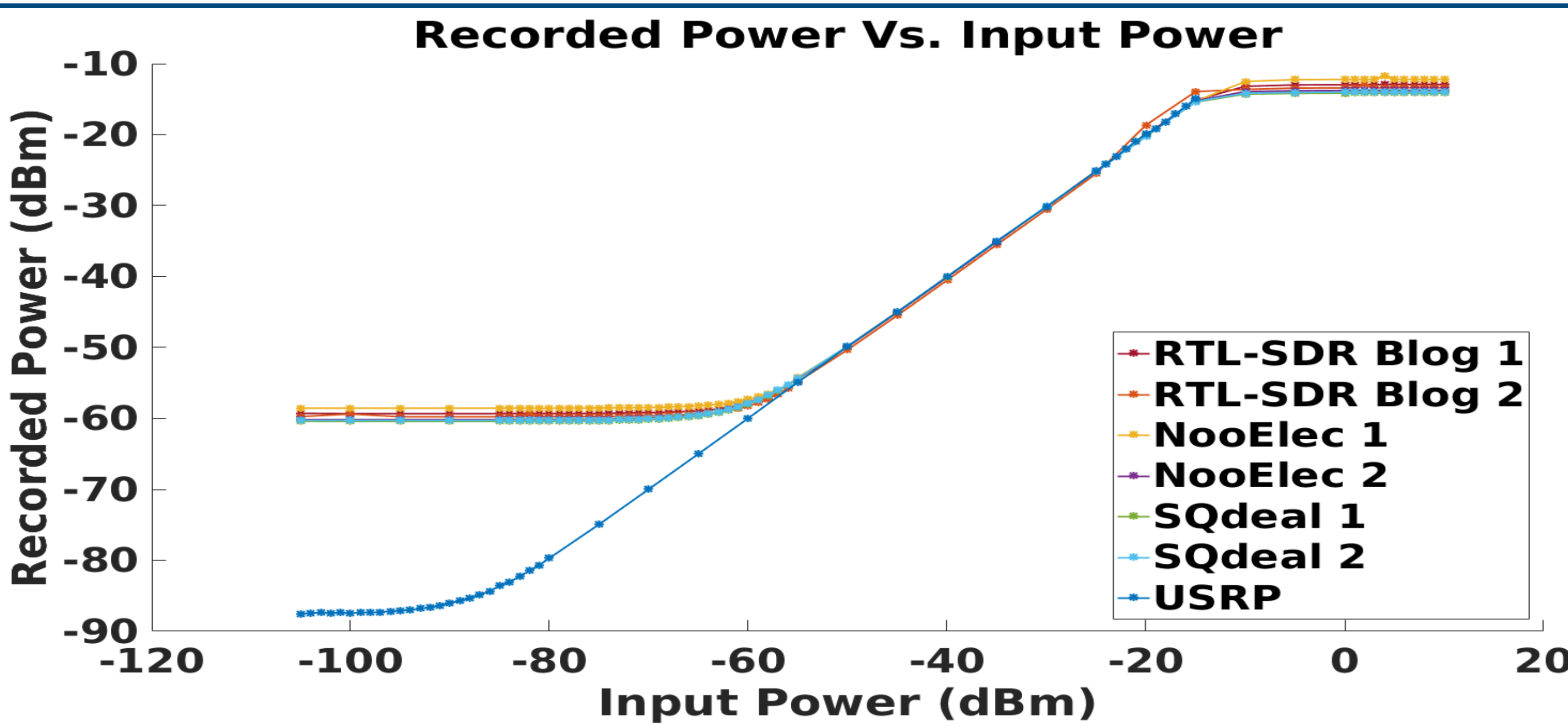
RTL-SDR matches USRP received sample ratio performance through sample rate of 2.85 MHz.

Noise Floor Test



- **Collect magnitude data from SDRs through GNU Radio**
  - **Collect CW input from signal generator**
  - **Test at constant sample rate of 2.0 MHz and frequency of 895 MHz**
  - **Store calibration data to file at amplitudes from -105-10 dBm**
- **Perform calculations and plotting in MATLAB**
  - **Calculate mean recorded magnitude from each data file in dBm**
  - **Plot mean recorded magnitude from SDRs versus input magnitude**

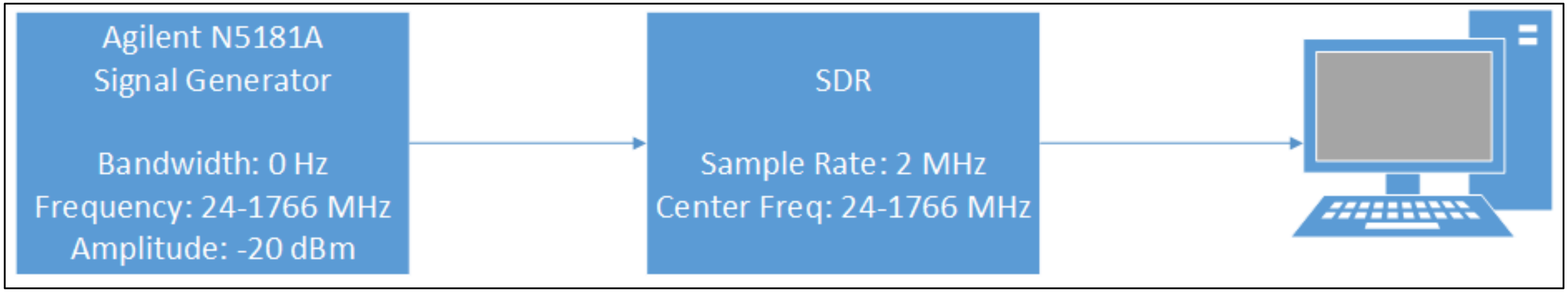
Noise Floor Results



- RTL-SDRs noise floors about -60 dBm
- USRP noise floor lower at about -85 dBm
- Theoretical noise floor N = kTB = -111 dBm
  - Recorded noise floors much higher due to lack of LNA

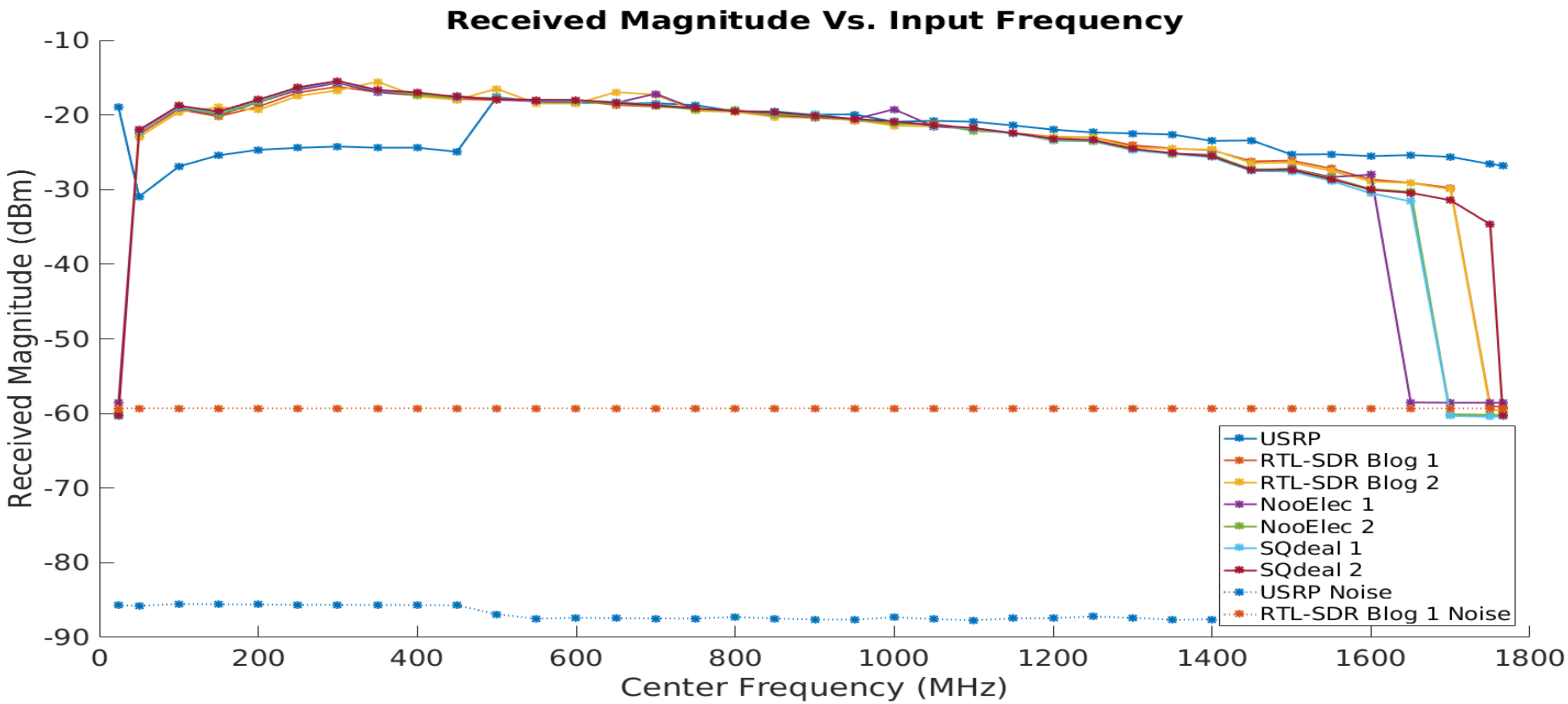
RTL-SDR has noise floor about 25 dB higher than noise floor of USRP.

Frequency Coverage Test



- **Collect magnitude data from SDRs through GNU Radio**
  - **Collect CW input from signal generator**
  - **Test at constant sample rate of 2.0 MHz and amplitude of -20 dBm**
  - **Store data to file at frequencies from 24 MHz to 1766 MHz**
- **Perform calculations and plotting in MATLAB**
  - **Calculate mean recorded magnitude from each data file in dBm**
  - **Plot mean recorded magnitude of SDRs across frequency range**

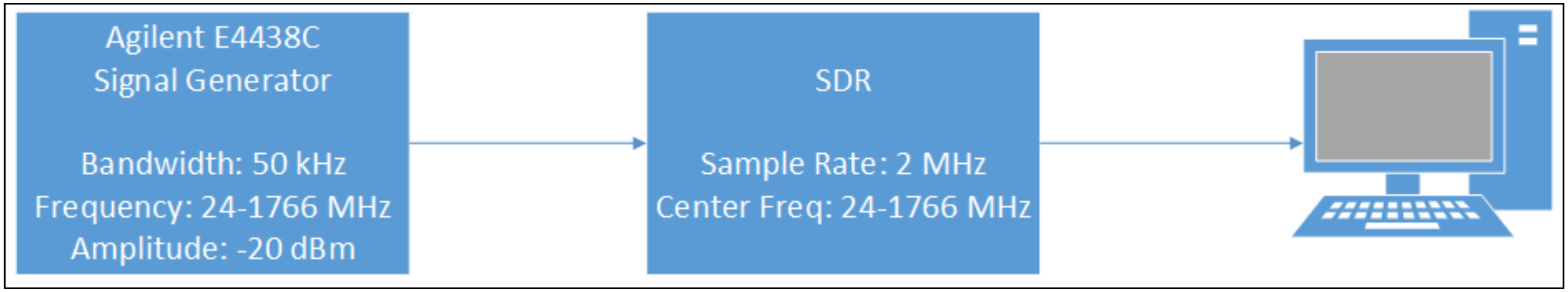
Frequency Coverage Results



- **RTL-SDR signal always above noise floor from 50-1600 MHz**
- **USRP signal well above noise floor across frequency range**
- **RTL-SDR SNR about 30-40 dB, USRP SNR about 55-65 dB**

RTL-SDR can reliably match USRP frequency coverage performance between 50-1600 MHz.

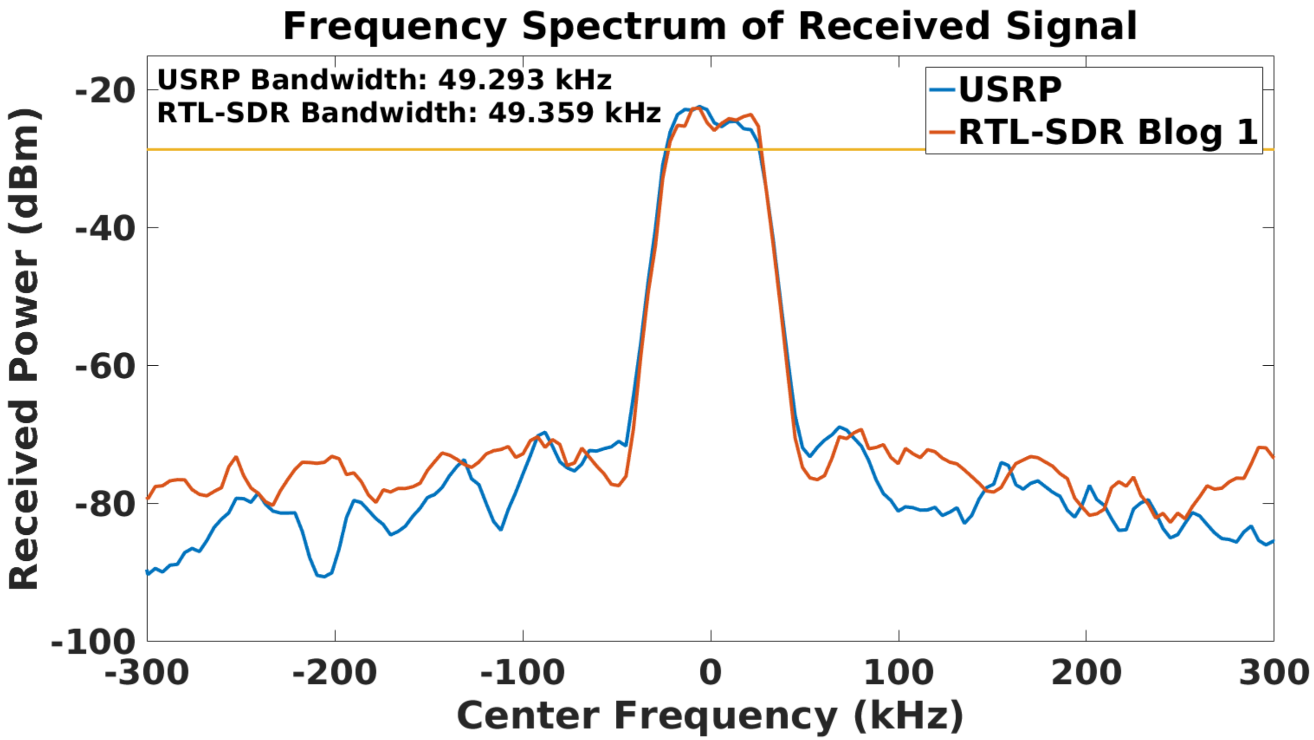
Frequency Response Test



- **Collect IQ data from SDRs through GNU Radio**
  - **Collect 50-kHz-bandwidth input from signal generator**
  - **Test at constant sample rate of 2.0 MHz and amplitude of -20 dBm**
  - **Store data to file at frequencies from 24 MHz to 1766 MHz**
- **Perform calculations and plotting in MATLAB**
  - **Plot Welch periodogram power spectrum estimate of signal**
  - **Determine 3-dB bandwidth**

Frequency Response Results

- **ADS-B: carrier frequency of 1090 MHz, bandwidth of 50 kHz**



- **RTL-SDR 3-dB bandwidth of 49.359 kHz**
- **USRP 3-dB bandwidth of 49.293 kHz**

RTL-SDR frequency response performance comparable to USRP.

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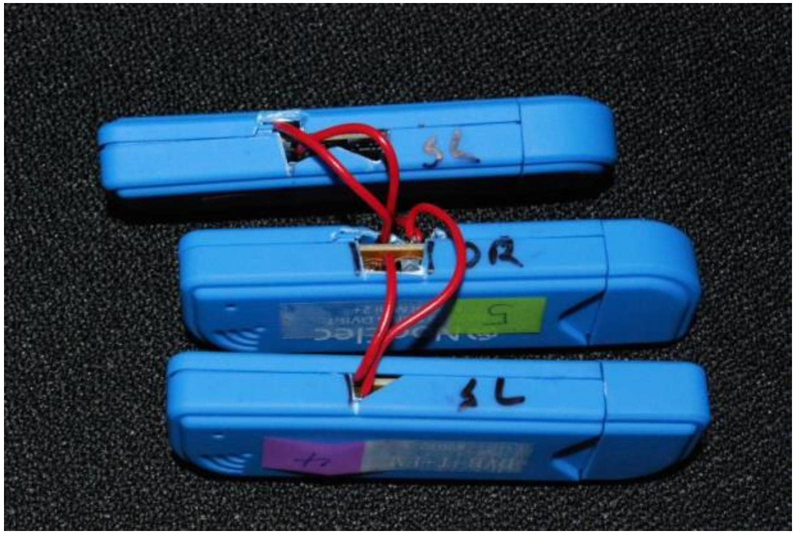
- Standalone SDR Performance Testing
- Multi-Channel RTL-SDR System
  - Multi-Channel Hardware Implementation
  - Rise Time Testing
  - Two-Channel Phase Testing
- Conclusion

Multi-Channel Hardware Implementation

- Successfully built two-channel and three-channel RTL-SDR
- System clock oscillators connected physically
- Verified to work and collect samples

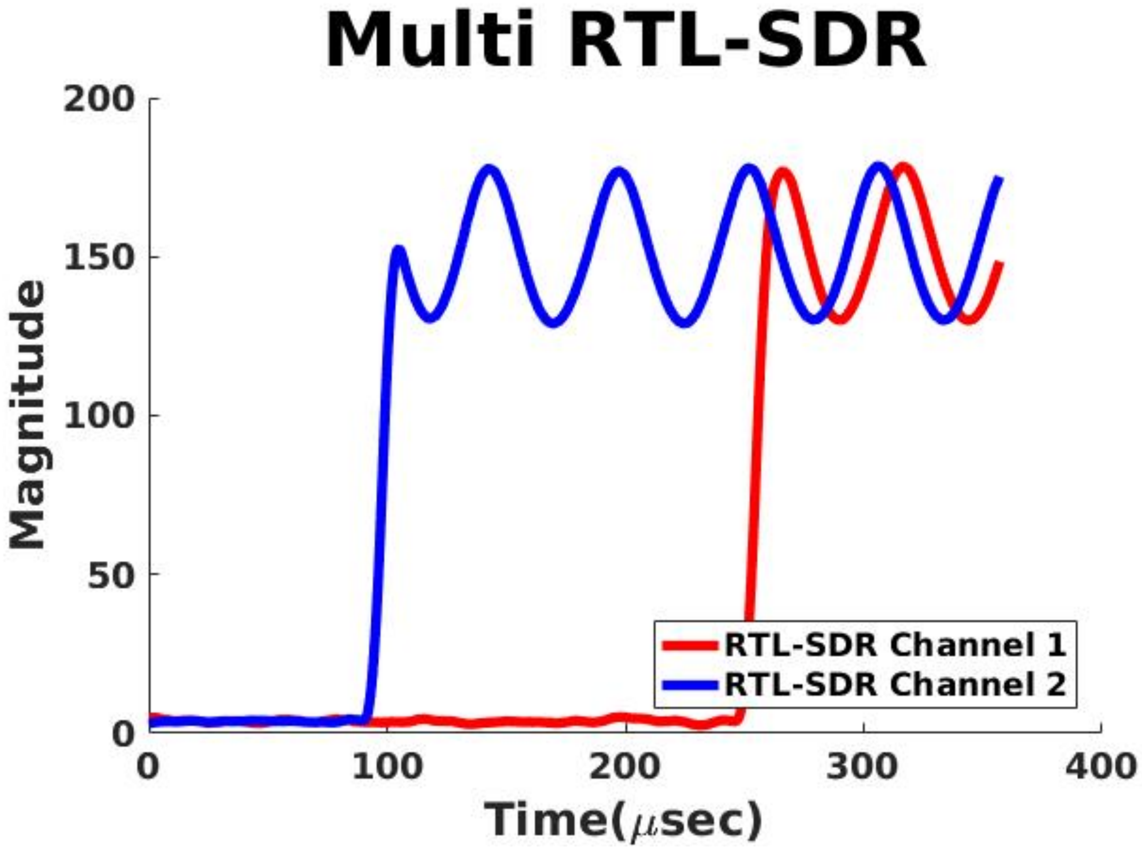
Two-Channel RTL-SDR



Three-Channel RTL-SDR

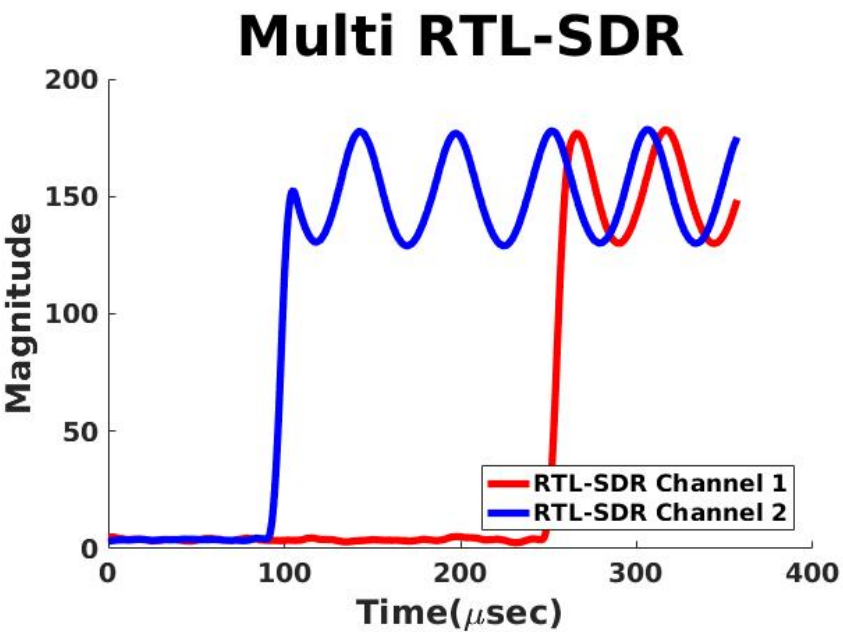
Two-Channel Rise Time

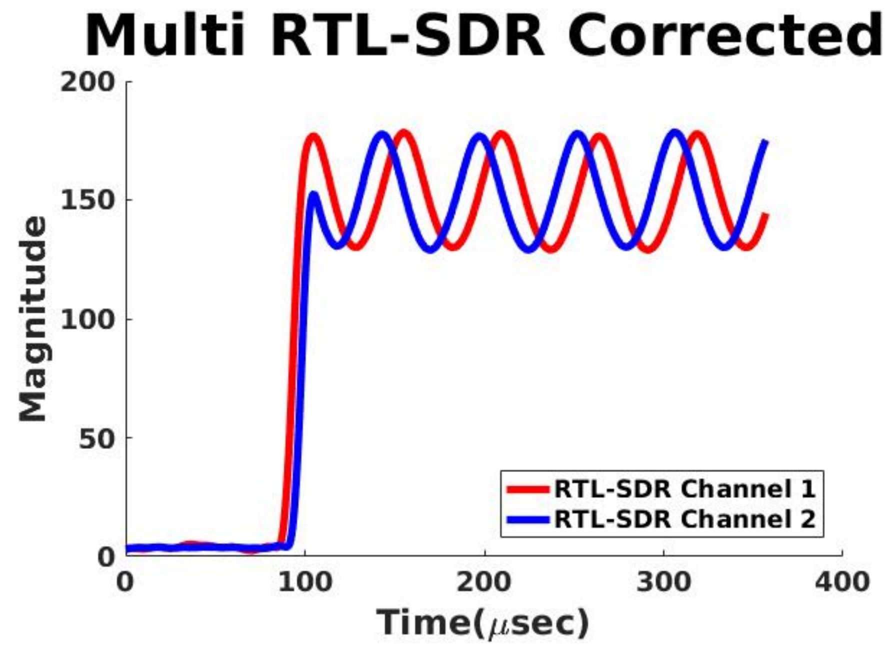
- **Two-channel RTL-SDR system used**
  - **Each RTL-SDR identically configured**
  - **RTL-SDRs turned on to capture data**
  - **Signal generator turned on and then off after 1-2 seconds**



Two-Channel Rise Time Correction

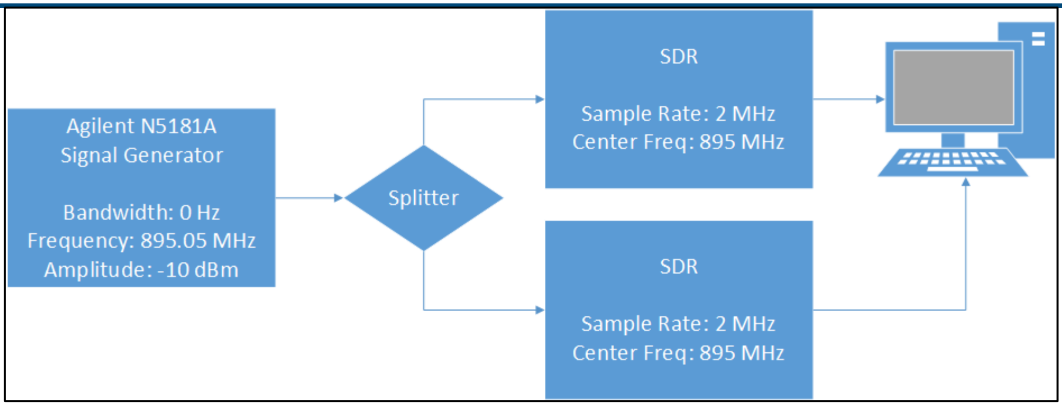
- Record timestamp when first sample was received over USB
- Shift lagging dataset by the time difference (images below)
- Improved results but still inconsistent (.175 ms -> 4.26 ns) (avg: 40 ns)
  - Most likely caused by USB





In order for a multi-channel system to work, a method of synchronization must be used to correlate the two signals.

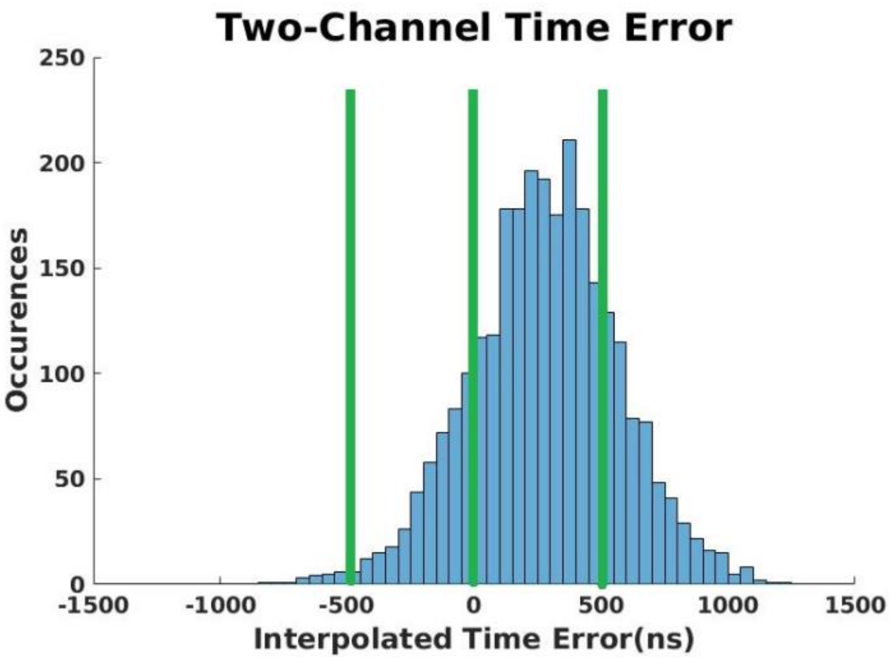
Two-Channel Phase Testing

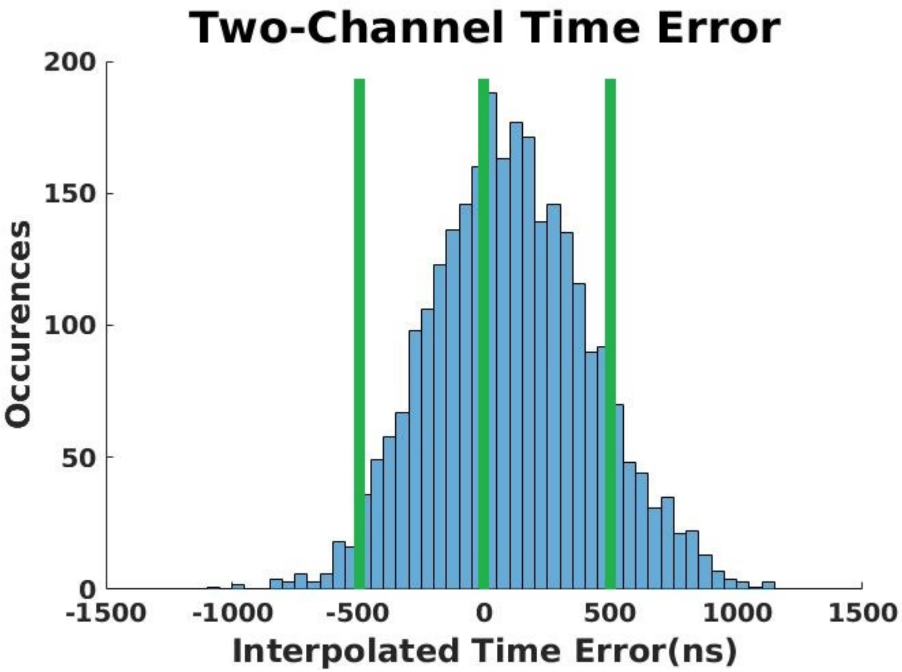


- Identical configuration of two-channels
  - Center Frequency: 895 MHz
  - Sample Rate: 2 MHz
  - Turned on at same time
  - Each collect 5 seconds worth of samples
- Signal Generator
  - Output a 895.05 MHz sine wave (50 kHz sine wave at baseband)
  - Amplitude of -10 dBm
- Find beginning of 50 kHz sine wave in each
  - Band-pass filter w/ Interpolation
  - Find the peaks and see the difference between locations in two signals

Two-Channel Phase Results

- Two-Channel RTL-SDR was within 350 ns for 50 ms
- Standard deviation consistently near 300 ns
- Our peak algorithm was inconsistent at aligning peaks
- Sub-sample standard deviation (interpolated x10)
  – Green bars correspond to one sample





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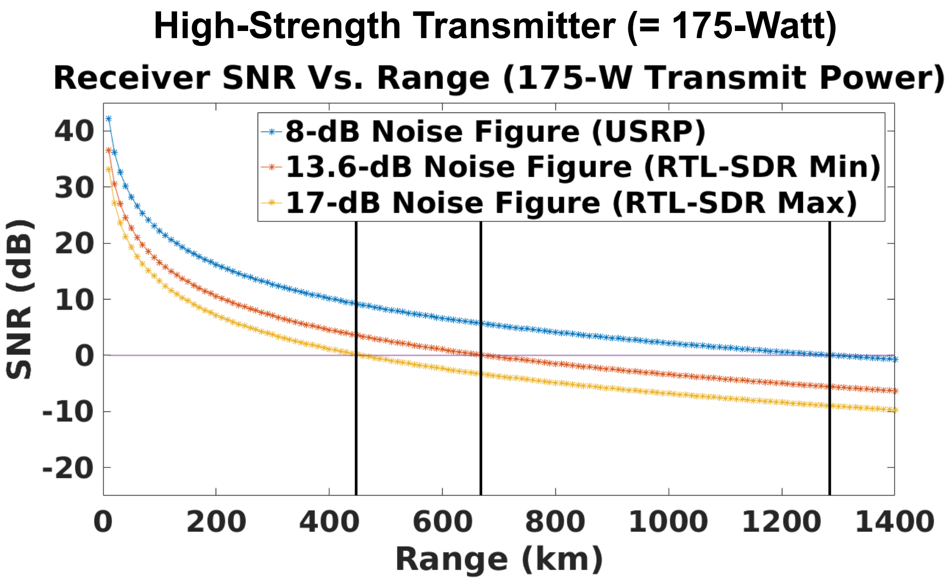
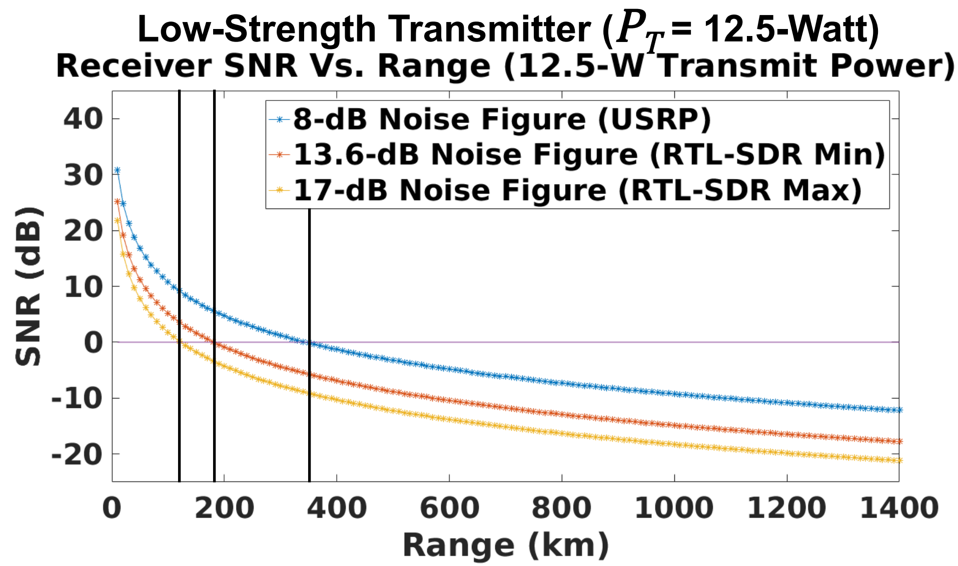
  - ADS-B Reception Example
  - Summary
  - Future Work

ADS-B Reception Example





- **Idealized Radar Range Equation for SDR Receiver**
  - $SNR = 10*\log_{10}((P_T*c^2) / ((4\pi)^2*f_0^2*R^2*k*T_0*B*F_n))$ dB
  - $C = 3 * 10^8$ m/s, $k = 1.38*10^{-23}$ J/K, $T_0 = 290$ K
  - f_0 **is ADS-B signal carrier frequency (1090 MHz)**
  - B **is bandwidth of receiver (2 MHz)**
  - F_n **is receiver noise figure (8 dB for USRP, 13.6-17 dB for RTL-SDR)**
  - R **is radar range,** SNR **is signal-to-noise ratio at receiver**

Summary

- **Tested standalone performance of RTL-SDR Vs. USRP**

	USRP	RTL-SDR
Perfect Received Sample Ratio	2.0-3.2 MHz, at Least	2.0-2.85 MHz
Noise Floor	~85 dBm	~60 dBm
Frequency Coverage	24-1766 MHz	50-1600 MHz
Frequency Response	Accurate Bandwidth	Accurate Bandwidth

- **Developed and tested multi-channel RTL-SDR systems**
  - **Built two-channel and three-channel clock-synchronized systems**
  - **Developed rise time delay correction procedure**
  - **Determined phase delay deviation between channels**

Future Work

- More advanced signal processing for phase testing
- Wideband reception through multi-channel RTL-SDR system
- Over-the-air reception through multi-channel RTL-SDR system
- Geolocation with three-channel RTL-SDR system
- Implementation of larger multi-channel RTL-SDR system

Acknowledgements

- Group 108
  - Lisa Basile
  - Matt Beals
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  - Josh Erling
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  - Professor Clancy

Thank You

Questions?

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Clock Stability Testing

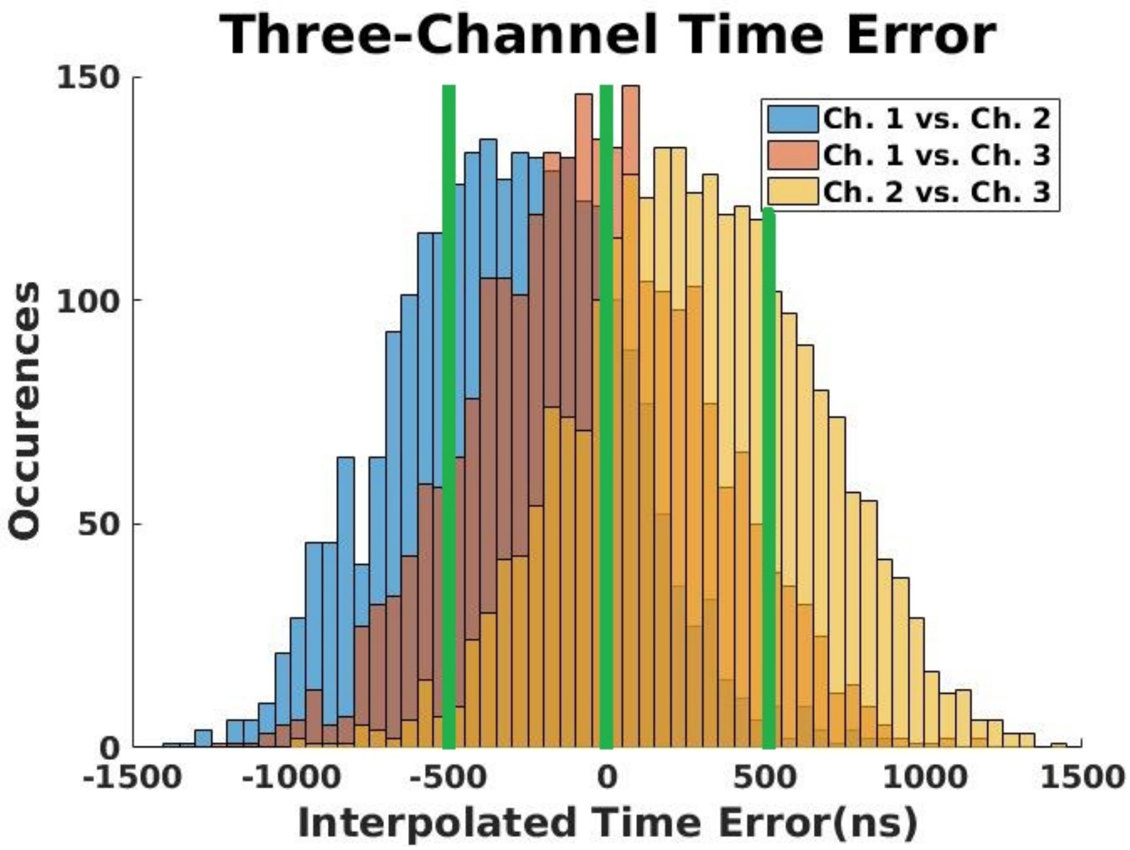
- Tested NooElec RTL-SDR and SQdeal Mini USB RTL-SDR
  - Found time interval error
  - Analyzed frequency of oscillator
- NooElec showed better performance due to temperature controlled oscillator
  - For time interval test the time variance was around half of SQdeal
  - Frequency yielded NooElec's range was around half of SQdeal

Time Interval Error Results

Oscillator	Std Dev	Max Lag	Max Lead
NooElec NESDR Mini 2+	56.00ps	193.33ps	180.00ps
SQdeal Mini USB RTL-SDR	98.71ps	315.00ps	382.50ps

NooElec oscillator chosen as source for three-channel RTL-SDR system.

Three-Channel Time Histogram



Two-Channel RTL-SDR System

Group Picture