# SWS HF Receiver Hardware Requirements Overview

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# Background

- Citizen Science: HF receiver / magnetometer network for Widespread citizen contribution to Ionospheric science.
  - Multi-channel receiver with precision timestamping.
  - 24 hour data collection, retrieval by central site.
  - Very low cost, easy to deploy.
- Key parameters changing as of early March 2019.
  - Impacts not fully analyzed.
- This presentation is refocused:
  - Look at key parameters and general receiver impacts.

# Key Parameters

- Range Resolution – many things depend on this requirement.
  - System bandwidth, ADC sample clock rate, data storage capacity, receiver data interfaces, clock phase noise.
- Timing Resolution and Accuracy
  - GPS timing accuracy, oscillator smoothing and stability, phase noise.
- HW Issues with lesser impacts:
  - Sensitivity, dynamic range, channel isolation, etc.
- Metadata

# Resolution vs. System bandwidth

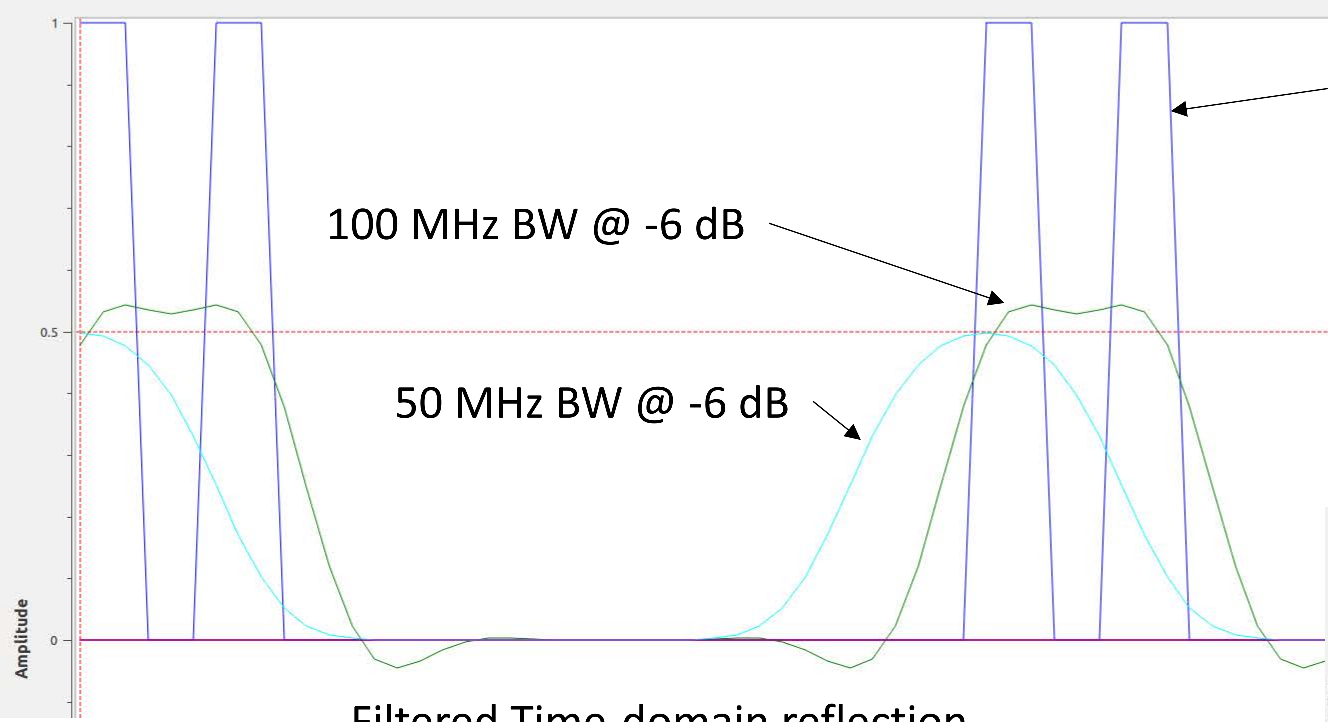
- Classic Oscilloscope approximation:
  - BW = 0.35 / rise time

| Rise time | Bandwidth needed |
|---|---|
| 3.5 nanoseconds | 100 MHz |
| 35 nanoseconds | 10 MHz |
| 350 nanoseconds | 1 MHz |

- Radar range resolution rule of thumb:
  - Rr = c /2B
  - (c is the speed of light, B is the bandwidth)
  - Just barely resolves an object.

| Range resolution | Bandwidth needed |
|---|---|
| 1 meter | 50 MHz |
| 10 meters | 5 MHz |
| 100 meters | 0.5 MHz |

# Range Resolution Simulation

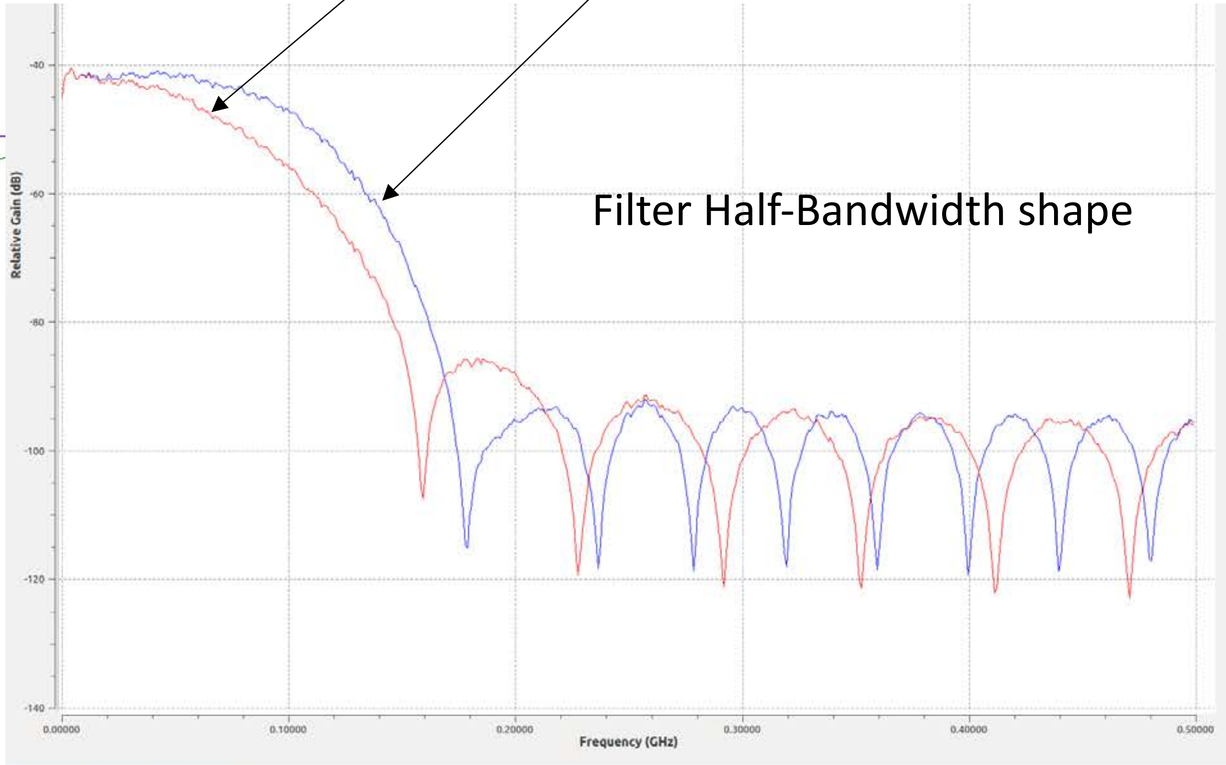


Two 1 meter targets separated by 1 meter

100 MHz BW @ -6 dB

50 MHz BW @ -6 dB

Filtered Time-domain reflection



50 MHz BW @ -6 dB

100 MHz BW @ -6 dB

Filter Half-Bandwidth shape

(Filter shape also impacts resolution.)

Gnuradio simulation: 1 Gsps.
(Doesn't change at 2 Gsps)

# Phase Noise → Jitter (down-conversion)

$$B(t) = R(t)\, e^{i(-\omega t + \varphi(t))}$$

$$B(t) = \underbrace{R(t)\, e^{-i\omega t}}_{\text{Down conversion with clean oscillator}}\ \underbrace{e^{i\varphi(t)}}_{\text{Phase noise Imprinted onto baseband signal}}$$

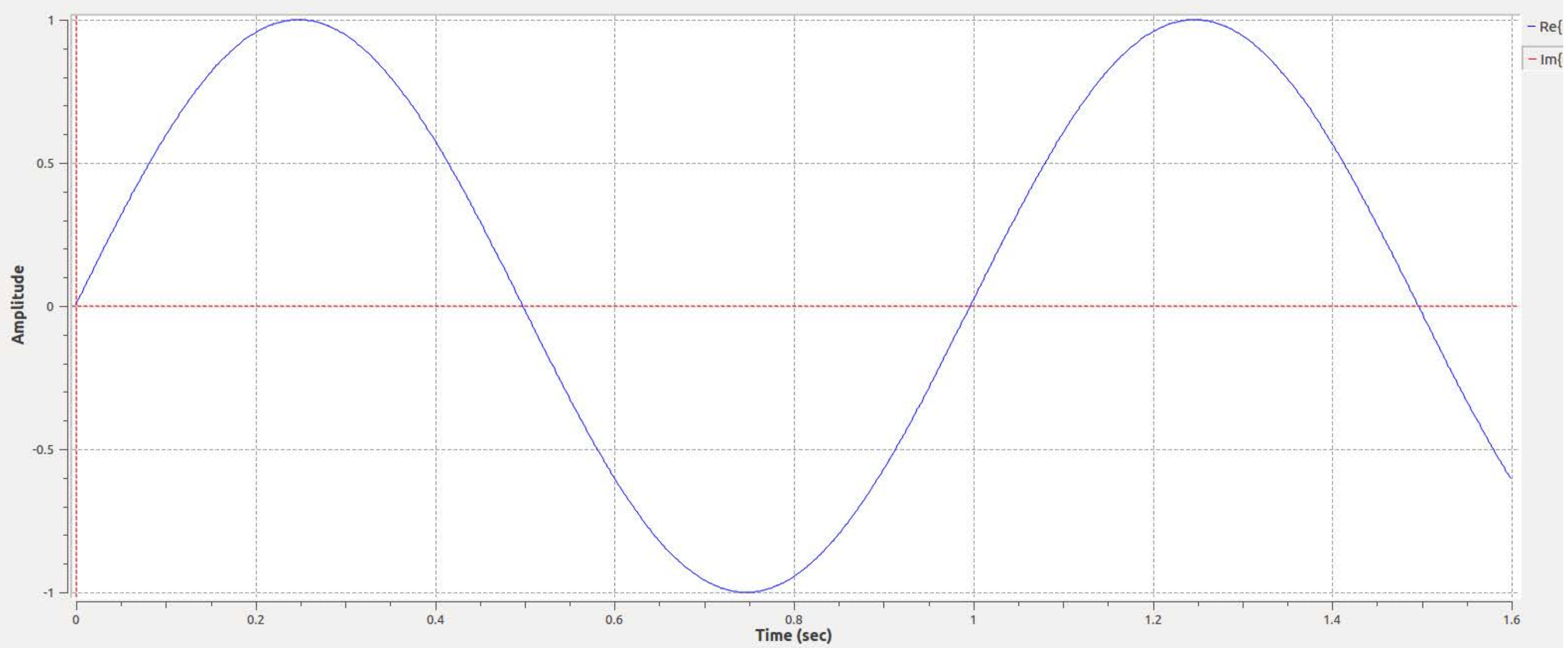
B(t) = baseband signal
R(t) = Received signal
ωt = perfect receive local NCO oscillator
φ(t) = phase noise of the local NCO

- Reference clock phase noise is reduced by division to the NCO local oscillator frequency.
  - 20 dB reduction per decade of frequency division.
- Phase noise of the NCO local conversion oscillator is imprinted onto the baseband signal. This causes baseband jitter.
- Simple model: 1/f noise to 1 kHz, flat to 10 kHz, 1/f beyond. ADC clock jitter: separate impact.
- Track out noise below 1 Hz (somehow).

| NCO L(f) at 1 Hertz | NCO L(f) at 1 KHz | Jitter, degrees rms | Jitter, seconds rms, to 1 Hz signal | Jitter, seconds rms, to 1 kHz signal |
|---|---|---|---|---|
| -50 dBC | -110 dBC | 0.19 degrees | 526 µsec | 526 nsec |
| -60 dBC | -120 dBC | 0.06 degrees | 166 µsec | 166 nsec |
| -70 dBC | -130 dBC | 0.019 degrees | 52.6 µsec | 52.6 nsec |
| -80 dBC | -140 dBC | 0.006 degrees | 16.6 µsec | 16.6 nsec |

# Phase Noise Simulation

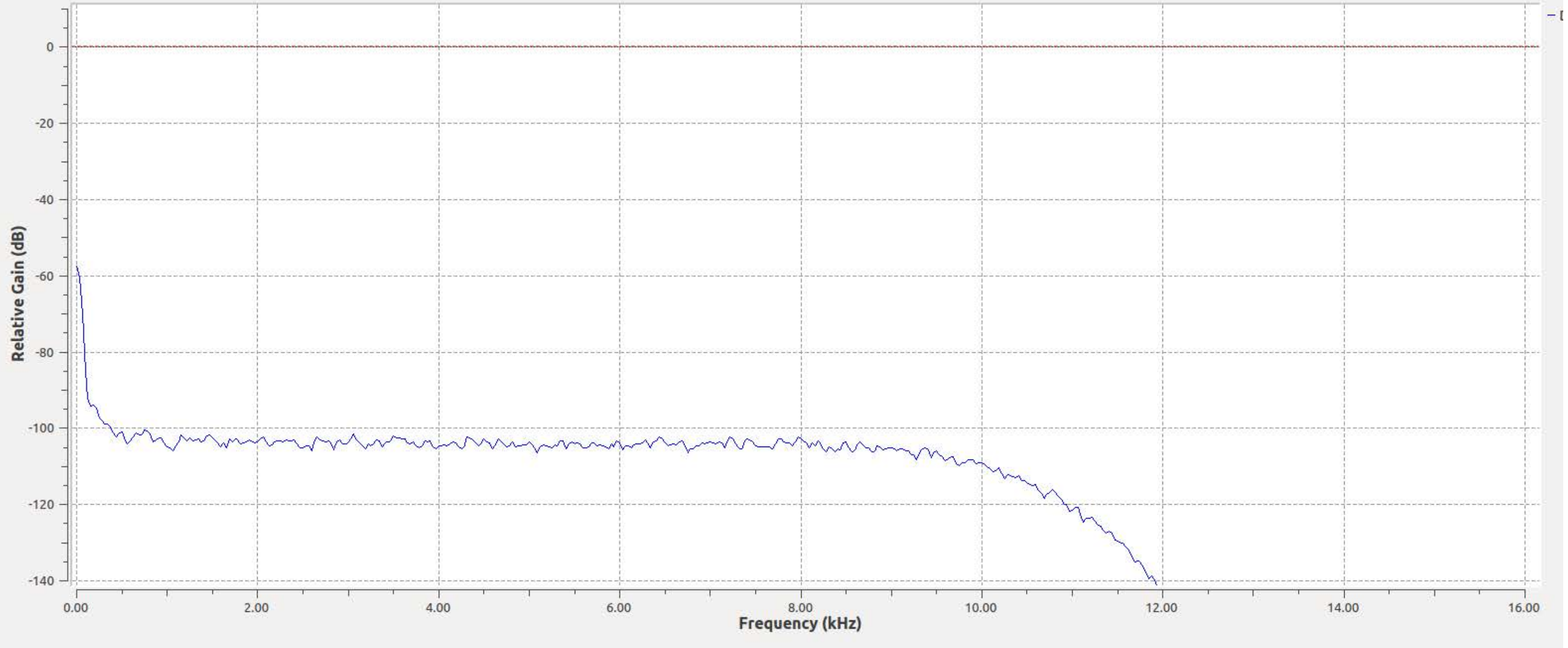
1 Hertz signal phase-modulated by phase noise.
Zero-crossing jitter is readily visible during run-time simulation.
Longer observation intervals → more jitter.
Visually matches calculations (as best that my eyeballs can tell).



Phase noise approximation:

- 1/f noise from 1 Hz to 1 kHz offset.
- Flat from 1 kHz – 10 kHz.
- 1/f above 10 kHz.

(Gnuradio spectrum doesn't have log(f) plot available)



# Analog to Digital Converter clock jitter

- At 122.88 MHz:
  - 1 psec jitter is 0.04 degrees
  - 10 psec jitter is 0.44 degrees
- Implies model with -60 dbc at 1 Hz declining to -120 dBc at 1 kHz would have
  - .06 / .04 = 1.5 psec jitter.
- → 8 dB SNR degradation at 30 MHz.

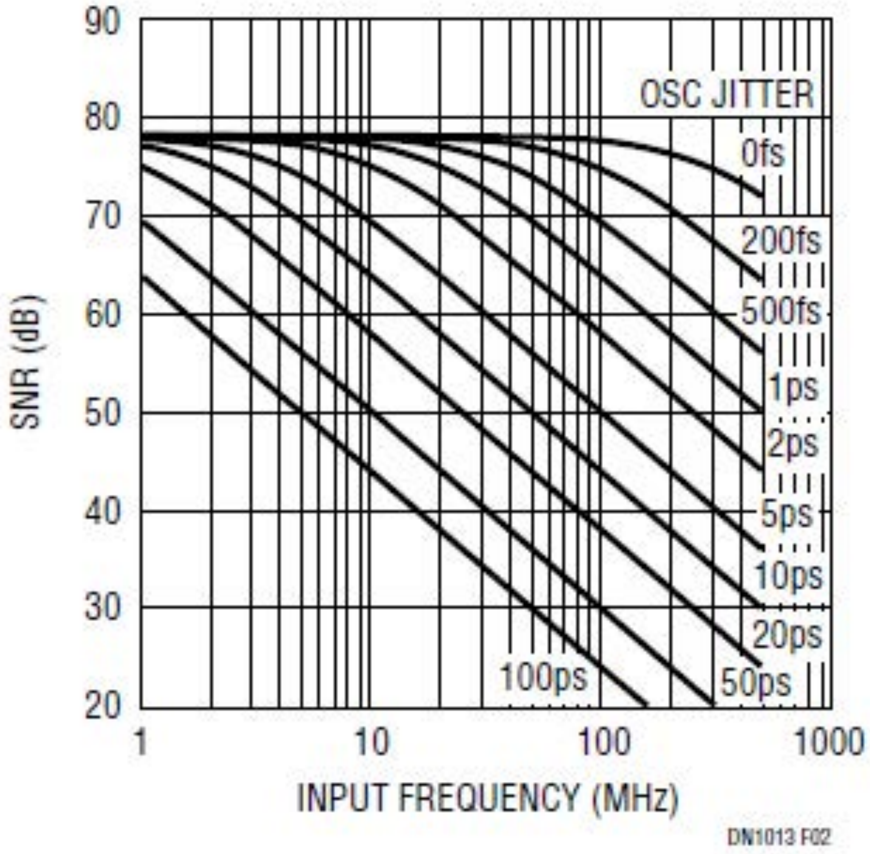


**Figure 2 Jitter Degradation of SNR as a Function of Input Frequency**

# Range Resolution vs. System Requirements

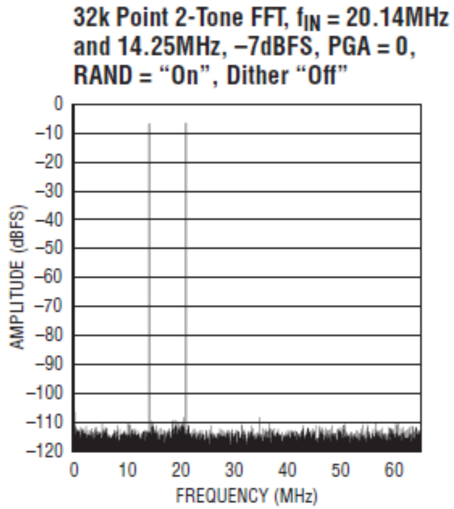
| Range Resolution | System Bandwidth Needed* | Data rate (Nyquist 2x sampling, 16 bit data, 2 channels) | Receiver data interface options | Storage needed for 24 hours | Phase noise @ 1 Hz and 1 kHz** | SATA-3 typical (80-100 MBps) Striped array width. |
|---|---|---|---|---|---|---|
| 1 meter | 100 MHz | 6.4 Gbps / 800 MBps | 1 or 2 x 10GE, or PCIe x4 Gen 2, 3 | 69 TB | -100 dBc / -160 dBc | 8-10 drives in parallel (RAID 0) striped array. High performance SAN network more likely. |
| 10 meters | 10 MHz | 640 Mbps / 80 MBps | 1 GE, or PCIe x4 | 6.9 TB | -80 dBc / -140 dBc | 1-2 drives in parallel (RAID 0) striped array. SSD might work without RAID 0. |
| 100 meters | 1 MHz | 64 Mbps / 8 MBps | 100 ME | 690 GB | - 60 dBc / -120 dBc | 1 drive sufficient. |
| 1 km | 100 kHz | 6.4 Mbps / 800 kBps | 10 ME | 69 GB | # -60 dBc / -120 dBc | 1 drive sufficient. |
| 10 km | 10 kHz | 640 kbps / 80 kBps | 10 ME | 6.9 GB | # -60 dBc / -120 dBc | 1 drive sufficient. |

*ADC may need > 350 Msps for 1 meter Range Resolution depending on detailed science requirements.
** Assuming > 1 kHz edge sharpness of the reflection.
# Phase noise impacts ADC SNR more than resolution

# Approach to reduce data rate.

- Use (well-known) Digital Down Conversion and decimation
  - Reduce sample rate by orders of magnitude.
  - Significant drawback is reduced system bandwidth
- Example: 8 x 192 ksps RF channels. Back of the envelope analysis:
  - 8 channels x 2 antennas x 192 ksps x 4 bytes (single precision FP) x 2 (I+Q) = 24.6 MB/s ( ~ 197 Mbits/sec).
  - Interface: 1 GbE is suitable
  - 24 hours → 2.13 TB storage.
  - SATA3: 80~160 MB/s is suitable.

# Setting Levels at HF

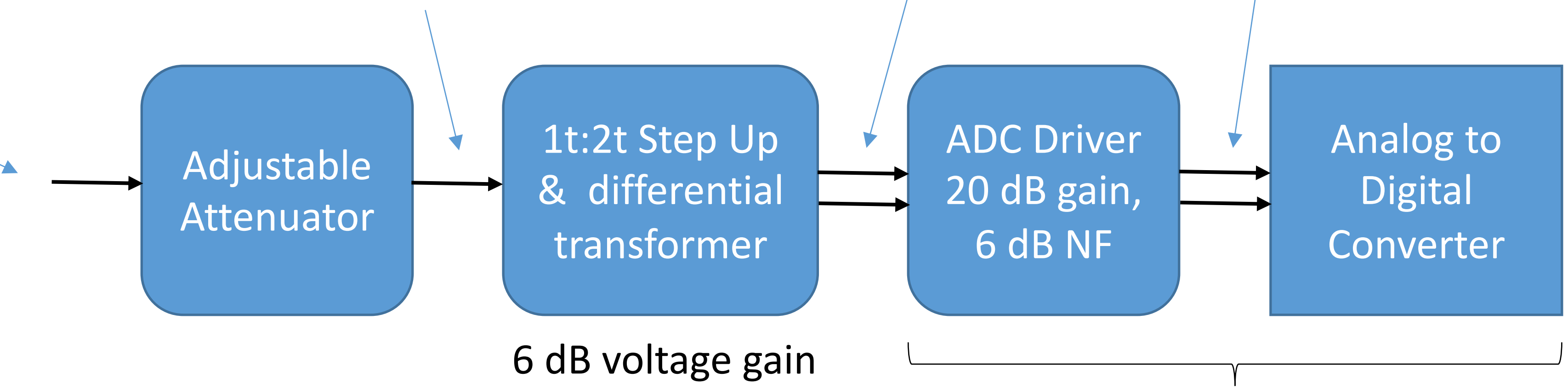

32k Point 2-Tone FFT, $f_{IN}$ = 20.14MHz and 14.25MHz, –7dBFS, PGA = 0, RAND = “On”, Dither “Off”

Overload at -26 dbm
plus attenuation
(~ S9 + 67 dB + atten)

Fs = 0.113 Vpp (354 mV RMS
or -26 dBm)

Fs = 0.225 Vpp

Fs = 2.25 Vpp



Adjustable Attenuator

1t:2t Step Up & differential transformer

ADC Driver 20 dB gain, 6 dB NF

Analog to Digital Converter

6 dB voltage gain

92 dB SFDR typ.

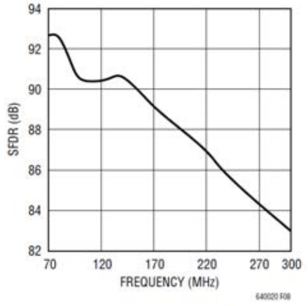
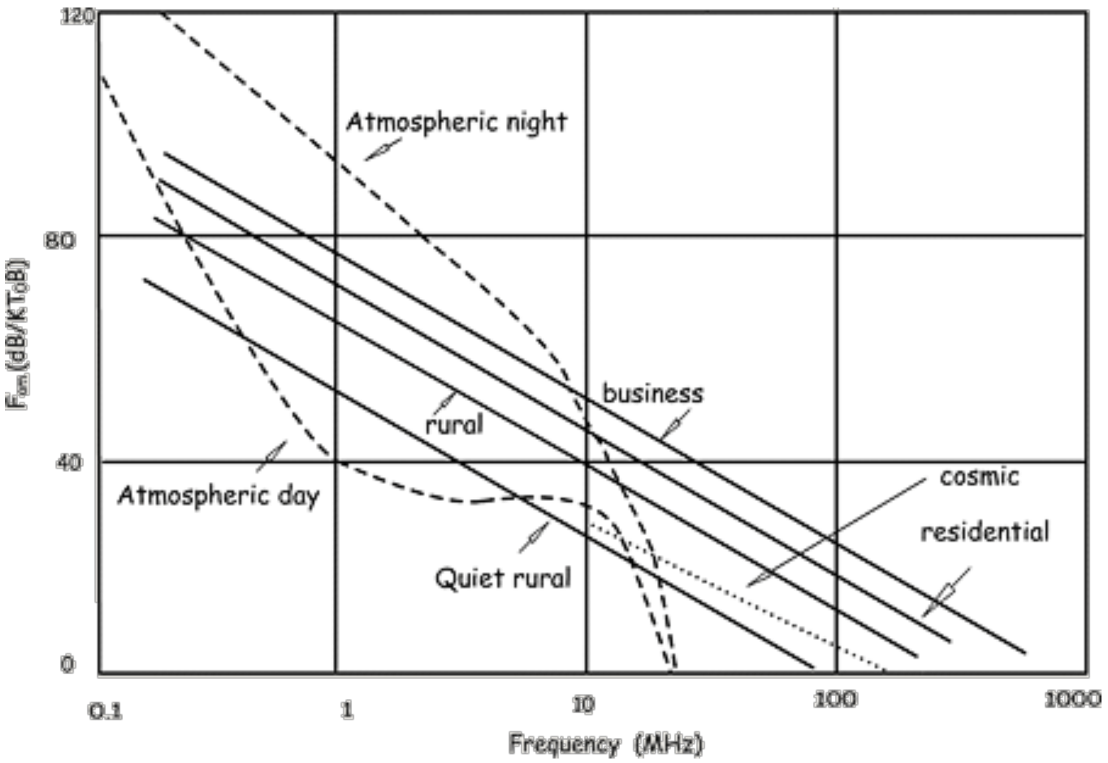


Figure 8. SFDR for the Combination of LTC6400-20 and LTC2208

ADC Noise floor is about -110 dBfs in 4 KHz (datasheet charts).
About -146 dBfs in 1 Hz BW for the ADC.
→ (-6) (-20) (–146) (+6) ~ -166 dBm/Hz chain noise floor
(288K → -174 dBm/Hz)

# Background noise level at HF

- Chart shows ITU expected noise in dB over $KT_oB$
  - 288K thermal noise: roughly 0.9 nanovolt / $\sqrt{\text{Hz}}$ across 50 ohms.
- Receiver with 14- or 16- bit ADC and these levels appears to have sufficient sensitivity < 30 MHz.
  - Manmade noise levels have increased (sometimes significantly) since ITU chart was produced.



# Timing & Frequency Accuracy

- Timing & Frequency accuracy has two aspects:
  - Self receiver comparison accuracy – two cases:
    - Ch1 vs. Ch2 – common conversion clock.
    - Ch1 vs. itself over some time interval.  Longer-term stability criteria.
  - Separate location receiver comparison accuracy.
    - Time-stamping at each receiver.  ±50 nsec accuracy → ±16 meters uncertainty.
- Issues:
  - Ability to identify a specific sample with respect to GPS (or UTC) time.
  - Frequency accuracy of clock – ADC sample clock, NCO clock.
    - ±50 ppb → ±0.5 Hz (at 10 MHz) → 180 degrees / sec phase drift.
  - Phase noise induced jitter onto the receive signal.

# 3 Layers of Overhead*

- Wire protocol
  - From Receiver to local host.
    - Communicates framing, packetization, timing mark, etc.
    - Local host may remove or reformat some of this data.
- Meta Data
  - Information about the observation details
    - Which station, time, date, center frequency, etc.
    - Timing data (date, time, which sample is coincident with GPS mark).
  - Needs to be archived with the associated stored data.
- File Format Metadata
  - Haystack: "Digital RF". (HDF5 is the underlying container format)

*Separate layers suggested by Michelle Thompson, W5NYV

# Potential Wire Protocol & Metadata

- Metadata (and data format) version number (it *will* change over time).
- Receiver
  - Site ID / information, Channel number, Slice number, Slice frequency.
- GPS Time and date.
  - PPS marking should be prepended to each data block.
  - The header could include a monotonically increasing sequence number to help identify missing blocks (time skip).
- Receive source (antenna or noise source).

# HDF5 File Container

- One of several popular data formats used in the research community.
- Open source and free. BSD-style license.
- Designed for long-term data archiving, file contents are self-describing.
- HDF5 files can contain several types of metadata:
  - Library metadata
  - Static user metadata
  - Dynamic user metadata
- Substantial encoding computation requirements.
  - My experience: Single-threaded implementation drops occasional frames with real-time @ 4 x 192 ksps IQ floating point on Core I7-3770 processor to SATA HD.
  - Parallel HDF5 version available. I've not tested.
- Needs thought about where the encoding should be done.

# Summary

- Range Resolution drives the cost of the hardware.
- Range resolution drives the cost and complexity of storing the intermediate results.
- Range Resolution drives most of the time, frequency, and stability requirements.
- Data Overhead must be carefully thought out.
  - Substantial impact to computational capability.
  - Ability to recreate original data from long-term archive.