C-Band Channel Characteristics: What does the science say? What does experience say?

Michael Rice
Brigham Young University

Frequency Bands

Lower L-Band	1435 - 1525 MHz	Telemetry is the primary service (part of mobile service) in USA.
Lower L-Band	1525 - 1535 MHz	Mobile satellite service (MSS) is the primary service, telemetry is the secondary service in USA.
Upper L-Band	1710 - 1850 MHz	
Lower S-Band	2200 - 2290 MHz	Telemetry is the co-primary service in USA
Upper S-Band	2310 - 2360 MHz	Wireless Communication Service (WCS) and broadcast satellite (sound) service (BSS) are the primary services, telemetry is the secondary service in USA.
Upper S-Band	2360 - 2390 MHz	Telemetry Service is primary in USA
C-Band	4400 - 4900 MHz 5091 - 5150 MHz 5925 - 6700 MHz	(WRC 2007) (we will never use this one in USA)

Frequency Bands (IEEE)

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Band	Frequency Range	Origin of name*
HF band	3 to 30 MHz	**H**igh **F**requency
VHF band	30 to 300 MHz	**V**ery **H**igh **F**requency
UHF band	300 to 1000 MHz	**U**ltra **H**igh **F**requency
L band	1 to 2 GHz	**L**ong wave
S band	2 to 4 GHz	**S**hort wave
C band	4 to 8 GHz	**C**ompromise between S and X
X band	8 to 12 GHz	Used in WW II for fire control, X for cross (as in crosshair)
Ku band	12 to 18 GHz	**K**urz-**u**nder
K band	18 to 27 GHz	German **K**urz (short)
Ka band	27 to 40 GHz	**K**urz-**a**bove
V band	40 to 75 GHz	
W band	75 to 110 GHz	W follows V in the alphabet
mm band	110 to 300 GHz	

*IEEE Std 521-2002 *Standard Letter Designations for Radar-Frequency Bands*. Reaffirmed standard of 1984; originally dates back to World War 2.

What does the science teach us?

- Line-of-sight propagation
  - frequency dependent components in link budget
- Multipath propagation
  - earth bounces as a function of frequency
  - impact of antenna gain pattern
  - scattering as a function of frequency
- Tracking

Line-of-Sight Propagation – Link Budget

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$$\left[\frac{C}{N_0}\right]_{\mathrm{dB}} = \left[P_T G_T(\theta,\phi)\right]_{\mathrm{dB}} + \left[\left(\frac{\lambda}{4\pi R}\right)^2\right]_{\mathrm{dB}} + \left[\frac{G_R(\theta',\phi')}{T_{\mathrm{eq}}}\right]_{\mathrm{dB}} - [k]_{\mathrm{dB}} + [L]_{\mathrm{dB}}\,.$$

Effective Isotropic Radiated Power (EIRP)

Transmit Antenna Gain in direction (θ, ϕ): e.g., -6 dB

Transmit Power: e.g., 10 W

Line-of-Sight Propagation – Link Budget

$$\left[\frac{C}{N_0}\right]_{\text{dB}} = \left[P_T G_T(\theta,\phi)\right]_{\text{dB}} + \left[\left(\frac{\lambda}{4\pi R}\right)^2\right]_{\text{dB}} + \left[\frac{G_R(\theta',\phi')}{T_{\text{eq}}}\right]_{\text{dB}} - [k]_{\text{dB}} + [L]_{\text{dB}}\,.$$

↓

"spreading loss"

L-Band, R = 100 nmi $$\left[\left(\frac{\lambda}{4\pi R}\right)^2\right]_{\text{dB}} = -141.2\ \text{dB}$$

S-Band, R = 100 nmi $$\left[\left(\frac{\lambda}{4\pi R}\right)^2\right]_{\text{dB}} = -144.8\ \text{dB}$$

C-Band, R = 100 nmi $$\left[\left(\frac{\lambda}{4\pi R}\right)^2\right]_{\text{dB}} = -151.8\ \text{dB}$$

Line-of-Sight Propagation – Link Budget

BYU

$$\left[\frac{C}{N_0}\right]_{\mathrm{dB}} = \left[P_T G_T(\theta,\phi)\right]_{\mathrm{dB}} + \left[\left(\frac{\lambda}{4\pi R}\right)^2\right]_{\mathrm{dB}} + \left[\frac{G_R(\theta',\phi')}{T_{\mathrm{eq}}}\right]_{\mathrm{dB}} - [k]_{\mathrm{dB}} + [L]_{\mathrm{dB}}\,.$$

↓

Ground Station G/T

$G_R(\theta',\phi')$ is the receive antenna gain in direction θ', ϕ'.

Receive Antenna Gain

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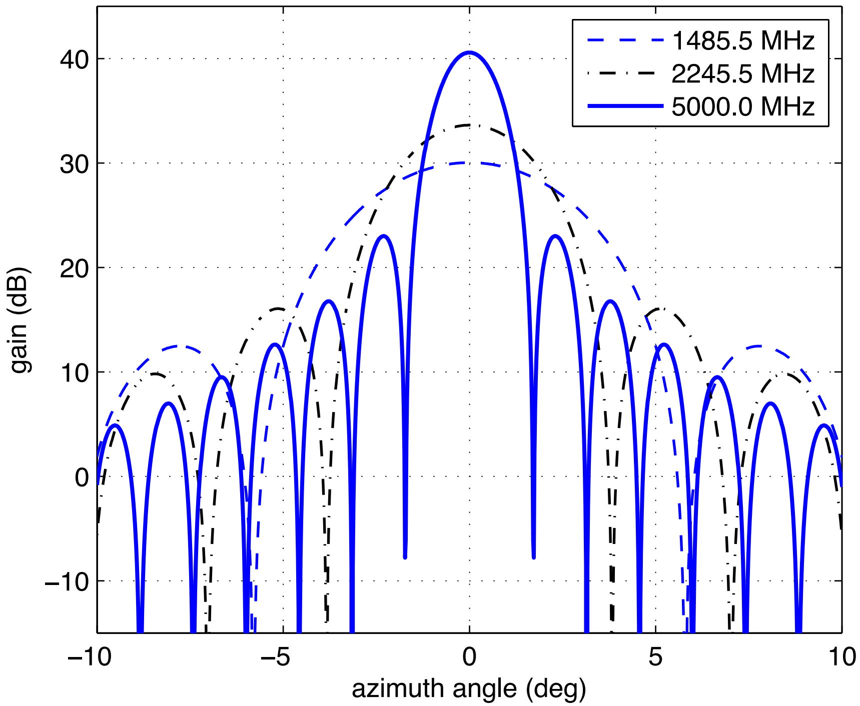
Receive Antenna Gain Pattern

$$G(\phi) = G_0 \times 2 \frac{J_1\left(\frac{\pi D}{\lambda}\sin(\phi)\right)}{\frac{\pi D}{\lambda}\sin(\phi)}$$



Boresight Gain

$$G_0 = \left(\frac{\pi D}{\lambda}\right)^2 \eta$$

Beamwidth (null-to-null)

$$\phi_{\text{null-to-null}} \approx 2\sin^{-1}\left(1.22\frac{\lambda}{D}\right)$$

Beamwidth (half-power)

$$\phi_{\text{3-dB}} \approx 1.02\frac{\lambda}{D}\ (\text{rad}) = 60\frac{\lambda}{D}\ (\text{deg})$$

D = 8 feet, η = 70%
uniform illumination

Line-of-Sight Propagation – Link Budget

$$\left[\frac{C}{N_0}\right]_{\mathrm{dB}} = \left[P_T G_T(\theta,\phi)\right]_{\mathrm{dB}} + \left[\left(\frac{\lambda}{4\pi R}\right)^2\right]_{\mathrm{dB}} + \left[\frac{G_R(\theta',\phi')}{T_{\mathrm{eq}}}\right]_{\mathrm{dB}} - [k]_{\mathrm{dB}} + [L]_{\mathrm{dB}}\,.$$

↓ Ground Station G/T

$G_R(\theta',\phi')$ is the receive antenna gain in direction θ', ϕ'.

The boresight gain is $G_0 = \left(\frac{\pi D}{\lambda}\right)^2 \eta$

L-band, 8-foot dish, 70% illumination efficiency: G_0 = 30.0 dB

S-band, 8-foot dish, 70% illumination efficiency: G_0 = 33.6 dB

C-band, 8-foot dish, 70% illumination efficiency: G_0 = 40.6 dB

Line-of-Site Propagation – Equivalent Temp.

The sky temperature is weakly dependent on frequency

$$T_{\text{sys}} = T_{\text{sky}} + T_{\text{loss}} + T_{\text{receiver}}$$

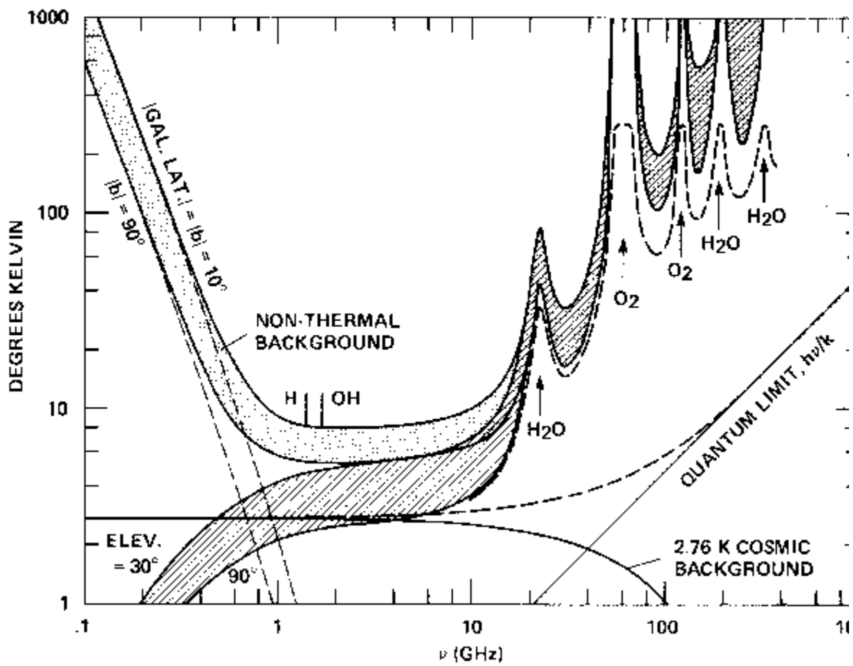
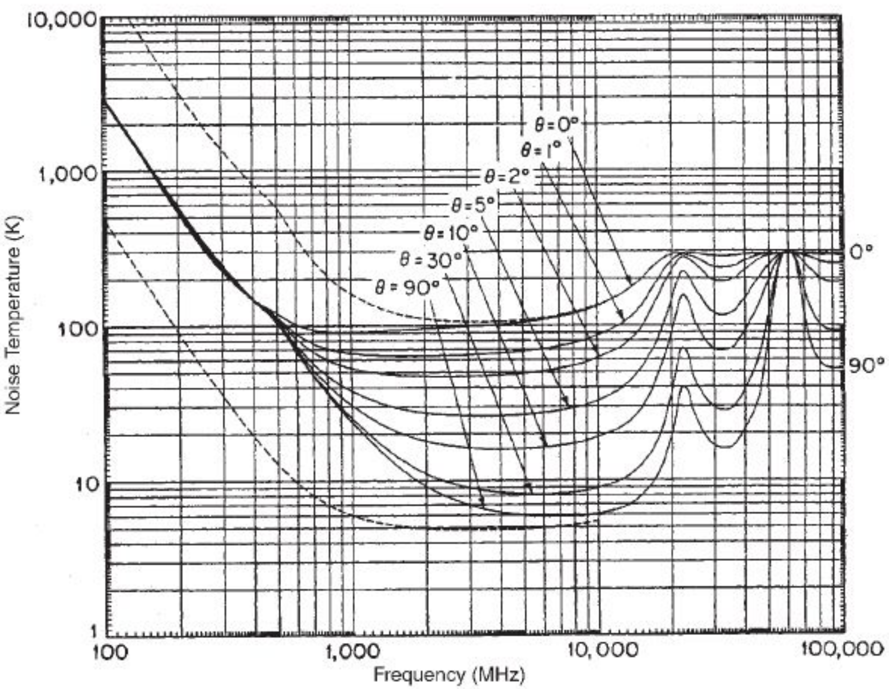


Figure 2. Terrestrial microwave window.

from http://www.ka9q.net/



From L. V. Blake, A guide to basic pulse-radar maximum-range calculation, Naval Research Laboratory Report 5868, December 1962.

Notes on Right-Hand Figure

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Antenna sky temperature. Noise temperature of an idealized antenna (lossless, no Earth-directed sidelobes) located at the Earth's surface, as a function of frequency, for a number of beam elevation angles. Solid curves are for geometric-mean galactic temperature, sun noise 10 times quiet level, sun in unity-gain sidelobe, cool temperate-zone troposphere, 2.7K cosmic blackbody radiation, zero ground noise. The upper dashed curve is for maximum galactic noise (center of galaxy, narrow-beam antenna). Sun noise 100 times quiet level, zero elevation, other factors the same as solid curves. The lower dashed curve is for minimum galactic noise, zero sun noise, 90â—¦ elevation angle. (The bump in the curves at about 500MHz is due to the sun-noise characteristic. The curves for low elevation angles lie below those for high angles at frequencies below 400MHz because of reduction of galactic noise by atmospheric absorption. The maxima at 22.2 and 60 GHz are due to the water-vapor and oxygen absorption resonance.)

Line-of-Sight Propagation – Link Budget

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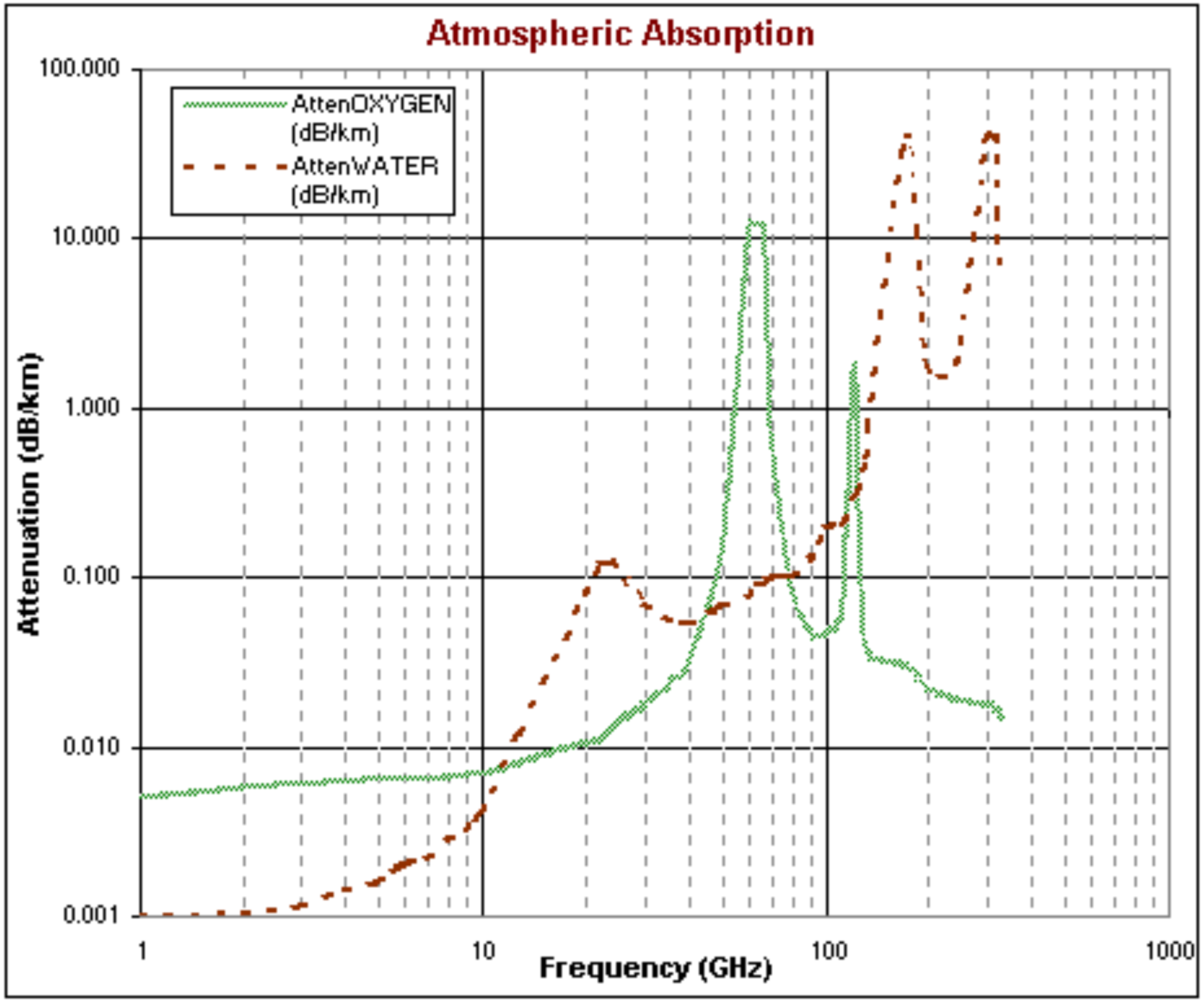
$$\left[\frac{C}{N_0}\right]_{\text{dB}} = \left[P_T G_T(\theta,\phi)\right]_{\text{dB}} + \left[\left(\frac{\lambda}{4\pi R}\right)^2\right]_{\text{dB}} + \left[\frac{G_R(\theta',\phi')}{T_{\text{eq}}}\right]_{\text{dB}} - [k]_{\text{dB}} + [L]_{\text{dB}}\,.$$

↓ all the other losses

Typical items

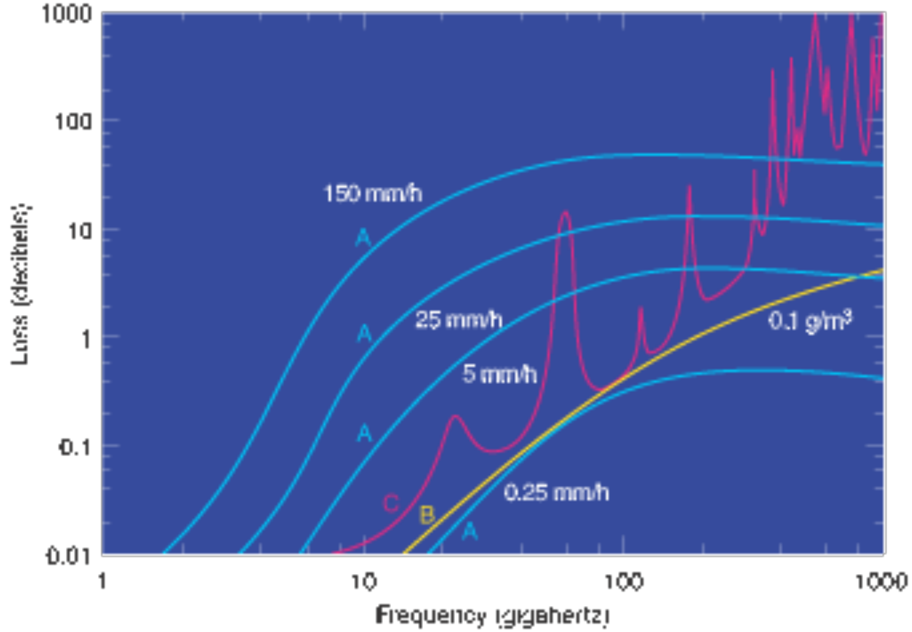
- cable loss from transmitter to transmit antenna
- polarization loss
- tracking loss
- atmospheric loss
- rain loss
- flame (plume) attenuation

Atmospheric Attenuation



from http://www.rfcafe.com

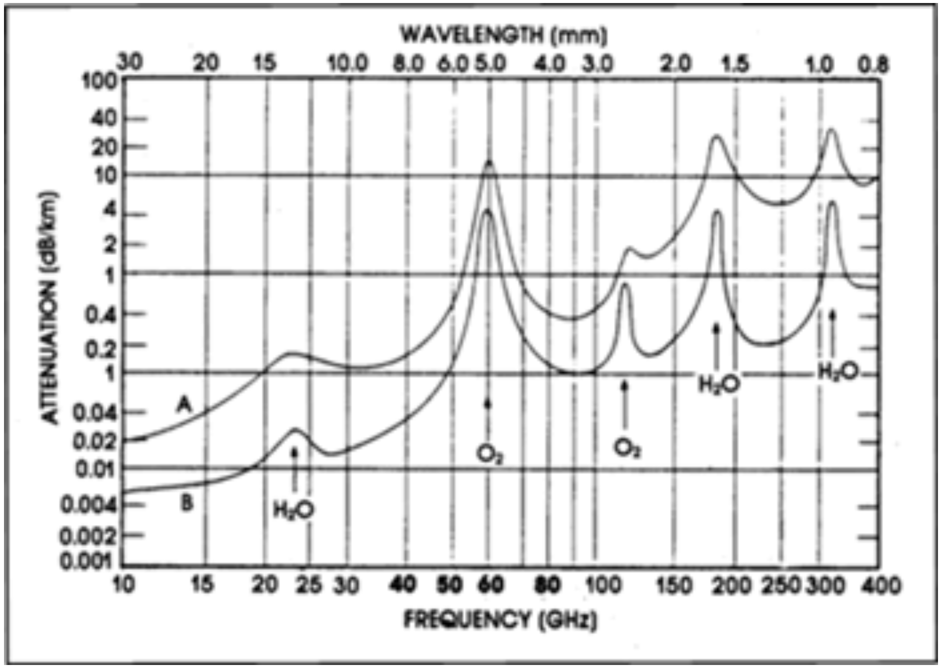
Atmospheric Attenuation



from http://www.aero.org/publications/crosslink/winter2002/02_sidebar1.html

Atmospheric Attenuation

BYU



Line-of-Site Propagation – Link Budget

BYU

$$\left[\frac{C}{N_0}\right]_{\mathrm{dB}} = \left[P_T G_T(\theta,\phi)\right]_{\mathrm{dB}} + \left[\left(\frac{\lambda}{4\pi R}\right)^2\right]_{\mathrm{dB}} + \left[\frac{G_R(\theta',\phi')}{T_{\mathrm{eq}}}\right]_{\mathrm{dB}} - [k]_{\mathrm{dB}} + [L]_{\mathrm{dB}}\,.$$

the dependence on frequency cancels*

$$G_0 = \left(\frac{\pi D}{\lambda}\right)^2 \eta$$

G_T increases (or stays the same) with increasing frequency

These losses generally increase with frequency.

*This is true for constant system equivalent temperature. This assumption is not always true.

Sample Link Budgets

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TA to GS (L/S/C-Band)
SOQPSK-TG @ 5Mbps

Element	Symbol	Value			Units	Formula/Remarks
		L-Band	S-Band	C-Band		
Vehicle Information						
Transmitter power	Pvt	10.0	10.0	10.0	Watts	Transmitter Power Output
Losses to antenna	Lvt	1.5	2.0	3.1	dB	Transmitter to Antenna Losses
Vehicle antenna gain	Gv	-6.0	-6.0	-6.0	dBi	Transmit Antenna Gain
Vehicle EIRP =	EIRP	2.5	2.0	0.9	dBW	Effective Isotropic Radiated Power
Transmission Loss						
Link frequency	f	1450.0	2250.0	4700.0	MHz	Operating Frequency
Range	Range	100.0	100.0	100.0	nmi	Slant Range in Nautical Miles
Space loss	Lpath	141.0	144.8	151.2	dB	Space Loss (Freq in MHz and Range in NM)
Polarization loss	Lpol	0.5	0.5	0.5	dB	Linear to Circular, Diversity Combining
Tracking Loss	Ltrack	0.0	0.0	0.0	dB	Off-Boresight Tracking Error
Atmospheric loss	Lat	1.0	1.0	1.0	dB	Atmospheric Losses
Flame attenuation	Lflam	0.0	0.0	0.0	dB	Flame Attenuation
Other Losses	Lother	0.0	0.0	0.0	dB	All Other Miscellaneous Losses
Transmission loss =	Lt	142.5	146.3	152.7	dB	Lpath + Lpol + Ltrack + Lat+ Lflam+Lother
Boltzmann's Constant	k	-228.6	-228.6	-228.6	dB	10*LOG10(1.380622E-23)
Figure Of Merit	G/T	4.1	10.6	14.9	dB/K	Antenna System FOM (measured)
Bit Rate	Br	5000000.0	5000000.0	5000000.0	bps	Baseband Data Rate (bps)
		67.0	67.0	67.0	dB(bps)	
Resulting Eb/No	Eb/No(res)	25.7	27.9	24.7	dB	EIRP-Lt-k+G/T-Br
Link Margin						
Required Eb/No	Eb/No(req)	12.5	12.5	12.5	dB	Required Eb/No (SOQPSK-TG) For BER of 1x10-6
Link Margin	Mgn	13.2	15.4	12.2	dB	Estimated Link Margin

Multipath Reflections – Ground Bounce

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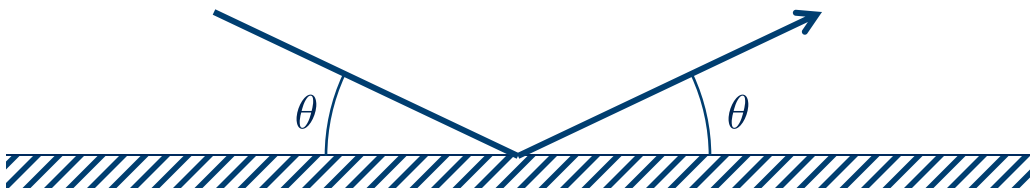


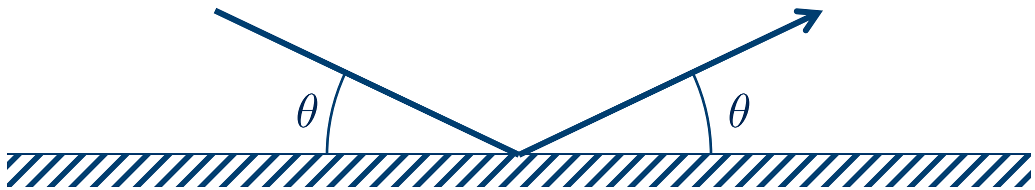
$$\epsilon_r = \frac{\epsilon}{\epsilon_0}, \text{ relative dielectric constant} \qquad \sigma, \text{ conductivity (siemens)}$$

$$\rho_h = \frac{\sin(\theta) - \sqrt{\left(\epsilon_r - j\frac{\sigma}{\omega_0\epsilon_0}\right) - \cos^2(\theta)}}{\sin(\theta) + \sqrt{\left(\epsilon_r - j\frac{\sigma}{\omega_0\epsilon_0}\right) - \cos^2(\theta)}}$$

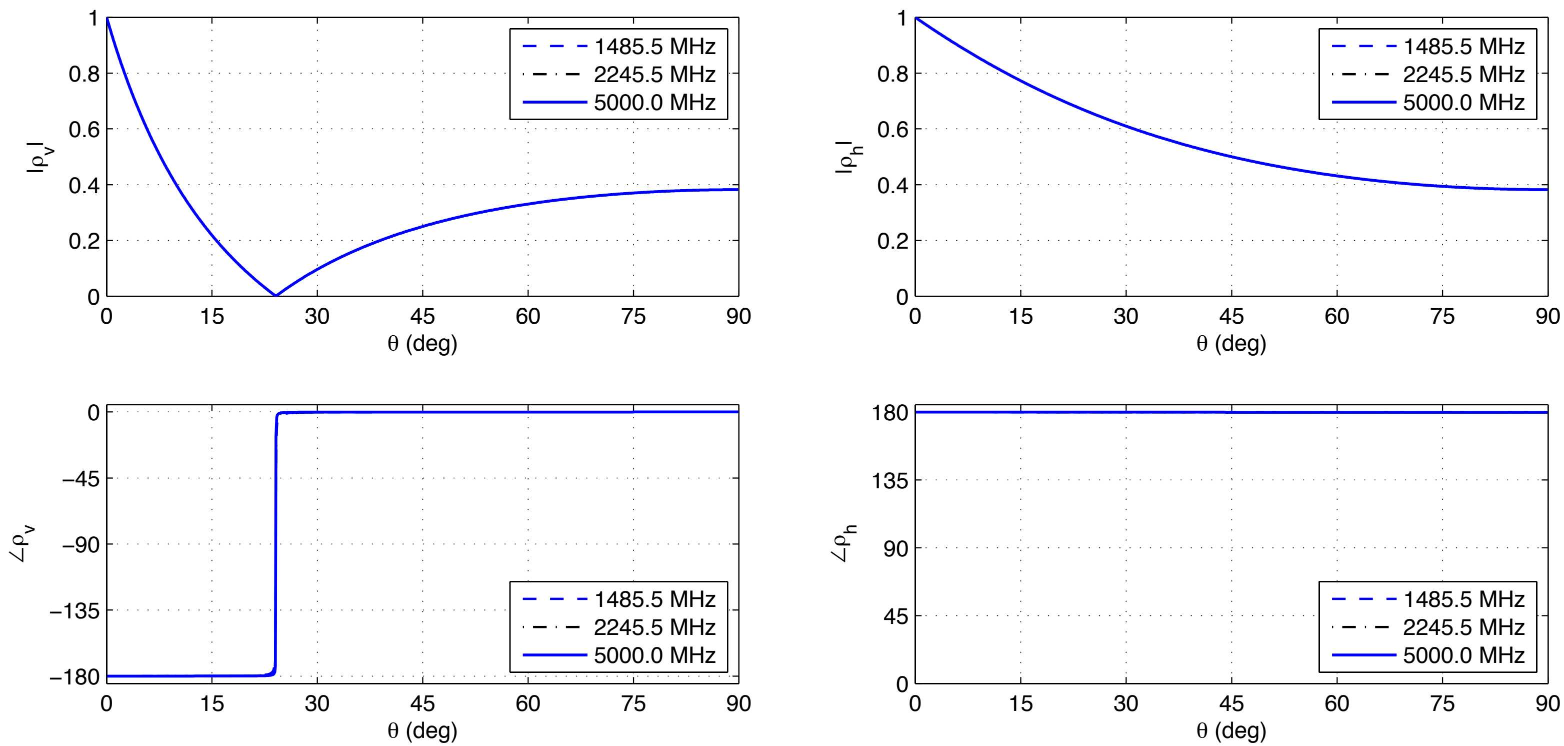
$$\rho_v = \frac{\left(\epsilon_r - j\frac{\sigma}{\omega_0\epsilon_0}\right)\sin(\theta) - \sqrt{\left(\epsilon_r - j\frac{\sigma}{\omega_0\epsilon_0}\right) - \cos^2(\theta)}}{\left(\epsilon_r - j\frac{\sigma}{\omega_0\epsilon_0}\right)\sin(\theta) + \sqrt{\left(\epsilon_r - j\frac{\sigma}{\omega_0\epsilon_0}\right) - \cos^2(\theta)}}$$

Multipath Reflections – Ground Bounce

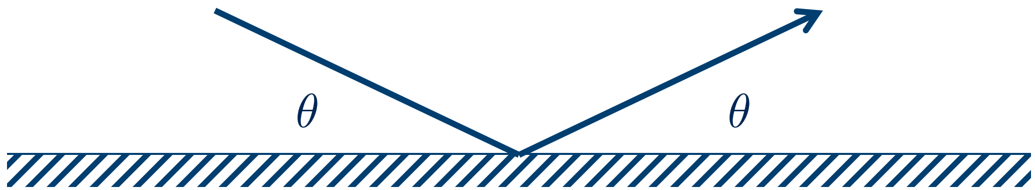
BYU



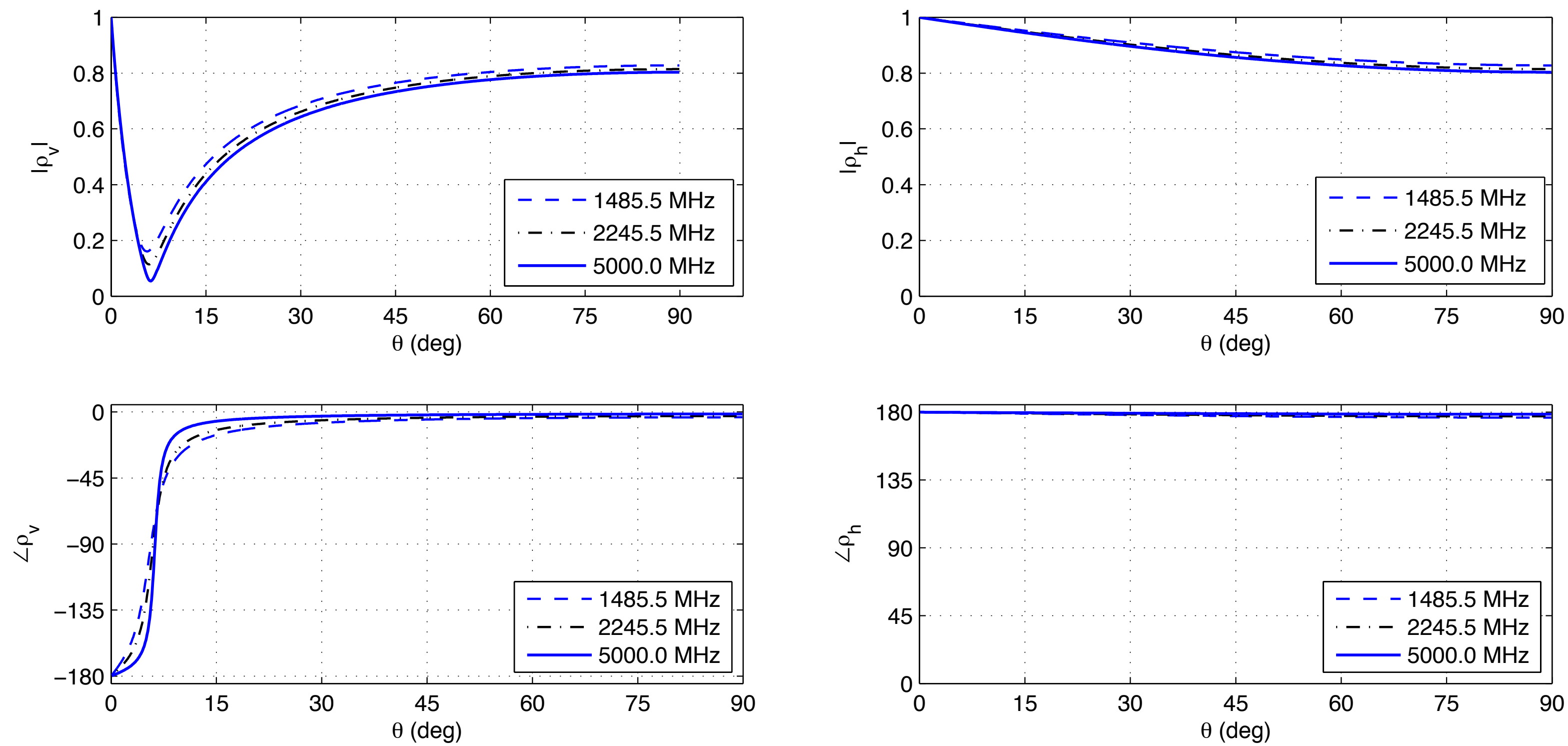
$\epsilon_r = 5, \sigma = 0.001$ siemens, poor (dry) ground



Multipath Reflections – Ground Bounce



$\epsilon_r = 81, \sigma = 5$ siemens, sea water



Multipath Reflections – Antenna Gain Pattern

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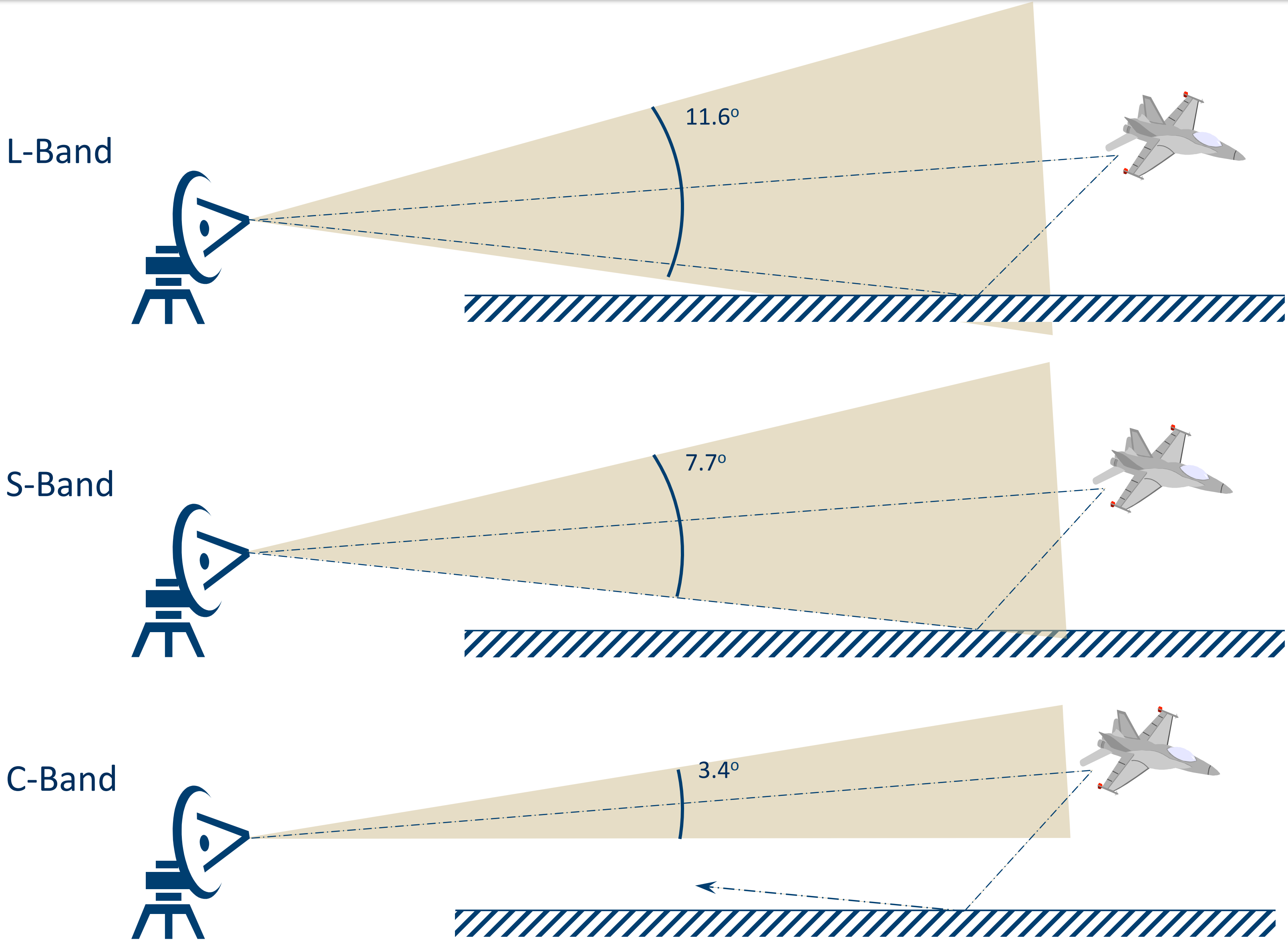
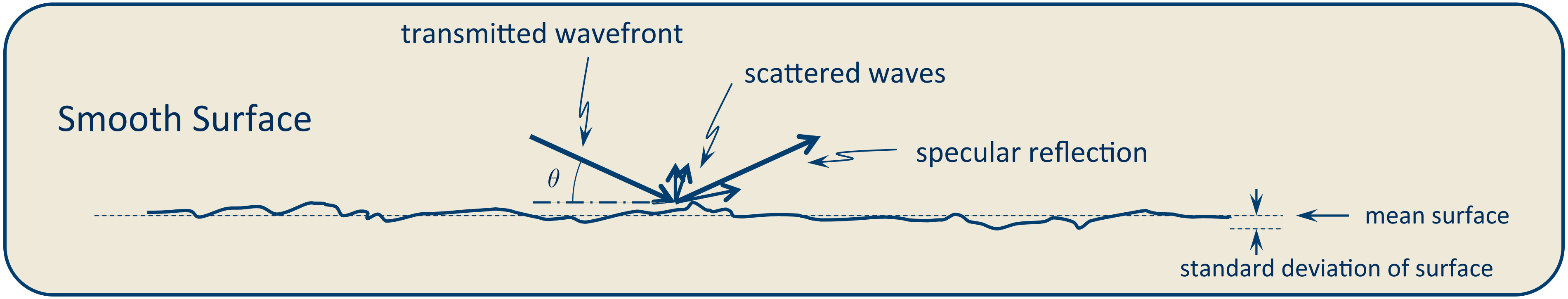
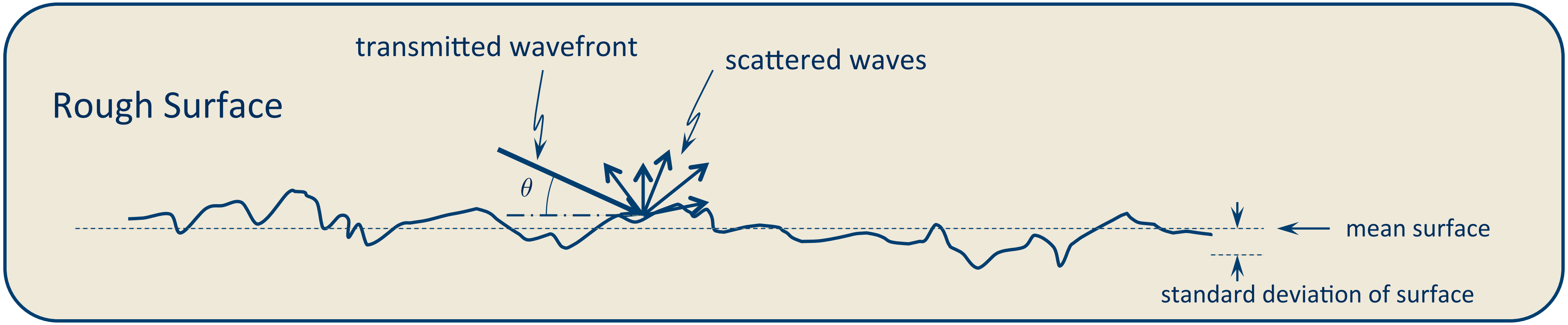


Multipath Reflections – Roughness





Rayleigh Criteria: $C = \frac{4\pi\sigma\theta}{\lambda}$

$C < 0.1$, smooth surface → specular reflection

$C > 10$, highly diffuse reflections → no specular reflection

Multipath Reflections – Roughness

BYU

Rayleigh Criteria: $C = \dfrac{4\pi\sigma\theta}{\lambda}$

C < 0.1, smooth surface → specular reflection

C > 10, highly diffuse reflections → no specular reflection

Relative Roughness

$$\frac{C \text{ at } 5000 \text{ MHz}}{C \text{ at } 1485.5 \text{ MHz}} = \frac{5000}{1485.5} = 3.4$$

$$\frac{C \text{ at } 5000 \text{ MHz}}{C \text{ at } 2245.5 \text{ MHz}} = \frac{5000}{2245.5} = 2.2$$

Surfaces appear more rough at C-band → more scattering
→ weaker specular multipath

Tracking

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The dominant issue is the main beamwidth of the receive antenna

Tracking – Beamwidth

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Receive Antenna Gain Pattern

$$G(\phi) = G_0 \times 2 \frac{J_1\left(\frac{\pi D}{\lambda}\sin(\phi)\right)}{\frac{\pi D}{\lambda}\sin(\phi)}$$

Boresight Gain

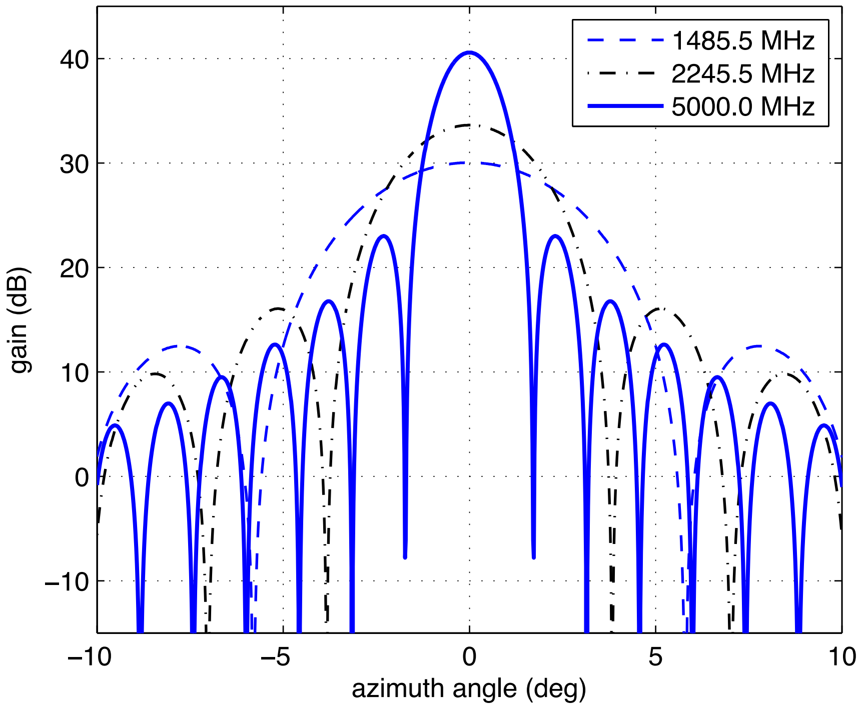
$$G_0 = \left(\frac{\pi D}{\lambda}\right)^2 \eta$$

Beamwidth (null-to-null)

$$\phi_{\text{null-to-null}} \approx 2\sin^{-1}\left(1.22\frac{\lambda}{D}\right)$$

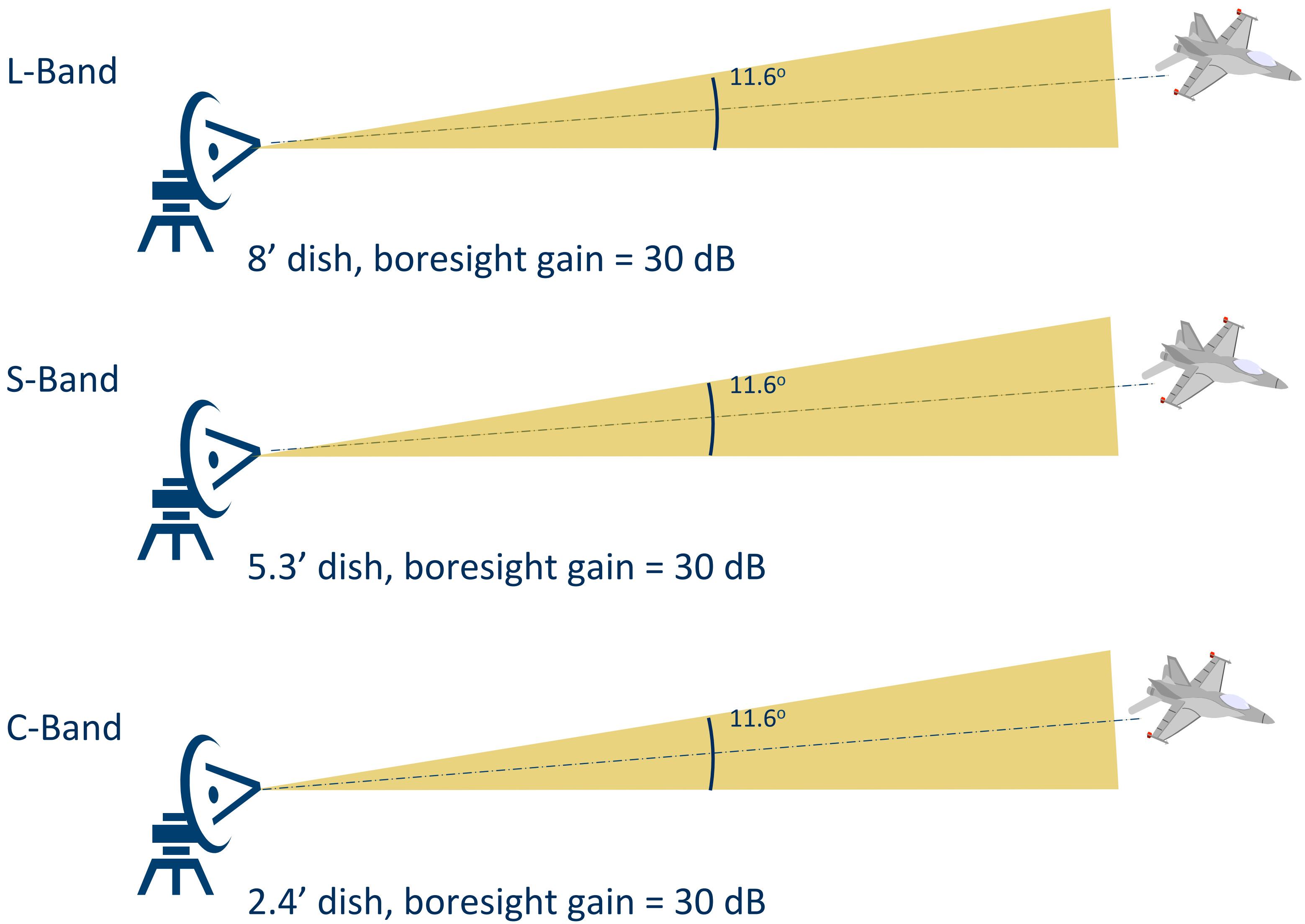
Beamwidth (half-power)

$$\phi_{\text{3-dB}} \approx 1.02\frac{\lambda}{D}\ (\text{rad}) = 60\frac{\lambda}{D}\ (\text{deg})$$



D = 8 feet, η = 70%
uniform illumination

Tracking & Beamwidth: a thought experiment



What does the science teach us?

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- Line-of-sight propagation
  - frequency dependent components in link budget
- Multipath propagation
  - earth bounces as a function of frequency
  - impact of antenna gain pattern
  - scattering as a function of frequency
- Tracking
- Line-of-sight propagation: rain, atmospheric attenuation, and other (e.g., cable, connector, etc.) are higher at C-band, the rest is "a wash" for same dish size and receiver noise figure.
- Multipath propagation is a little less severe at C-band, but changes more rapidly for the same transmitter velocity.
- Tracking: initial acquisition is harder, steady-state tracking performance depends on control loop parameters.
- Steady-state tracking performance *can* be better in multipath-prone areas.

What does experience teach us?

BYU

- S- versus C-band experiment at EAFB
  - K. Temple, "Performance Comparison of Aeronautical Telemetry in S-Band and C-Band," in *Proceedings of the International Telemetering Conference*, San Diego, CA, October 2010.
- L- versus C-band experiment at TPS
  - K. Temple and R. Selbrede, "Performance Comparison of Aeronautical Telemetry in S-Band and C-Band," presented at the AFFTC Lunch Time Series.
- Multipath Channel Sounding Experiments at EAFB
  - M. Rice and M. Jensen, "A Comparison of L-Band and C-Band Multipath Propagation at Edwards AFB," in *Proceedings of the International Telemetering Conference*, Las Vegas, NV, October 2011.
- Project Mercury C-Band Radar Beacon Tracking
  - H. Labitt, "C-Band Radar-Beacon Tracking for Project Mercury," presented at the AIEE Summer General Meeting and Aero-Space Transportation Conference, Denver, CO, 17-22 June, 1962.
- C-band video link at NASA Dryden
  - NASA Dryden Research Center, "Engineering Logistics Plan for the Transition and Turnover of AFT-1 TRIPLEX –Meter Antenna Upgrade System," 30 November 2007.
  - Darryl Burkes, private communication, September – October 2011.

What does experience teach us?

BYU

- FAA/NASA Aeronautical Mobile Airport Communication System (AeroMAX)
  - J. Budinger, W. Hall, J. Budinger, J. Wilson, R. Dimond, R. Apaza, B. Phillips, "FAA/NASA Aeronautical Mobile Airport Communications System (AeroMACS) Development Status," International Civil Aviation Working Organization Working Paper ACP-WGM17-WP-xx. Presented at the Aeronautical Communications Panel (ACP) 16th Meeting of Working Group M (Maintenance), Paris France, 17-19 May 2010.
- Range Instrumentation Radars
  - J. Nessmith, "Range Instrumentation Radars," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 12, no. 6, pp. 756 – 466, November 1976.
  - W. Grant, J. Carroll, and C. Chilton, "Spectrum Resource Assessment in the 5650-5925 MHz Band," NTIA Report-83-115, January 1983. (retrieved from http://transition.fcc.gov/ib/files/1_08_02/ntia_sec3.pdf)
  - "Radar" brochure, Atlantic Test Ranges, Patuxent River, MD, December 2010.
  - Radar Museum (on-line), http://www.radomes.org/museum/equip.php (accessed 19 October 2011)
  - Mobile Military Radar, http://www.mobileradar.org
- FAA Microwave Landing System (MLS)
  - "Microwave Landing System," Wikipedia, http://en.wikipedia.org/wiki/Microwave_landing_system, accessed 20 October 2011.

What does experience teach us?

BYU

- L- versus C-band study for Galileo
  - M. Irsigler, et al, “Aspects of C-Band Satellite Navigation: Signal Propagation and Satellite Signal Tracking,” Research Report, Institute of Geodesy and Navigation, University of Munich.
- Dual S-/X-band telemetry tracking system
  - B. Bollerman, et al, “High-Performance LANDSAT/SPOT Dual S-/X-Band Telemetry Tracing and Receiving System,” in *Proceedings of the International Telemetering Conference*, San Diego, CA, October 1986.
- C-band drone tracking control
  - J. Miller and P. Tannenholz, “An Improved Drone Tracking Control System Transponder,” in *Proceedings of the International Telemetering Conference*, San Diego, CA, October 1990.
- UAV Links
  - P. van Blyenburgh, “UAVs – Current Situation and Considerations for the Way Forward,” presented at the Research and Technology Organization (RTO) of the North Atlantic Treaty Organization Course on Development and Operation of UAVs for Military and Civil Applications, Rhode-Saint-Genese, Belgium, September 13-17, 1999. (http://ftp.rta.nato.int/public//PubFulltext/RTO/EN/RTO-EN-009///EN-009-01.pdf)
  - Rochus, W., “UAV Data-Links: Tasks, Types, Technologies and Examples”, paper presented at the Research and Technology Organization (RTO) of the North Atlantic Treaty Organization Course on Development and Operation of UAVs for Military and Civil Applications, Rhode-Saint-Genese, Belgium, September 13-17, 1999. (http://www.dtic.mil/dtic/tr/fulltext/u2/p010757.pdf)

What does experience teach us?

- C-Band Block Downconverter
  - "Feeds and RF Technology," Data Sheet, Telemetry and Communications Systems, Inc. September 2009.

S- versus C-band experiment at EAFB (1)

- Fundamental Questions
  - Can C-band (4400 – 5150 MHz) be used to augment existing telemetry bands?
  - Do telemetry operations in C-band perform in a similar manner as telemetry operations in L- and S-bands?

S- versus C-band experiment at EAFB (2)

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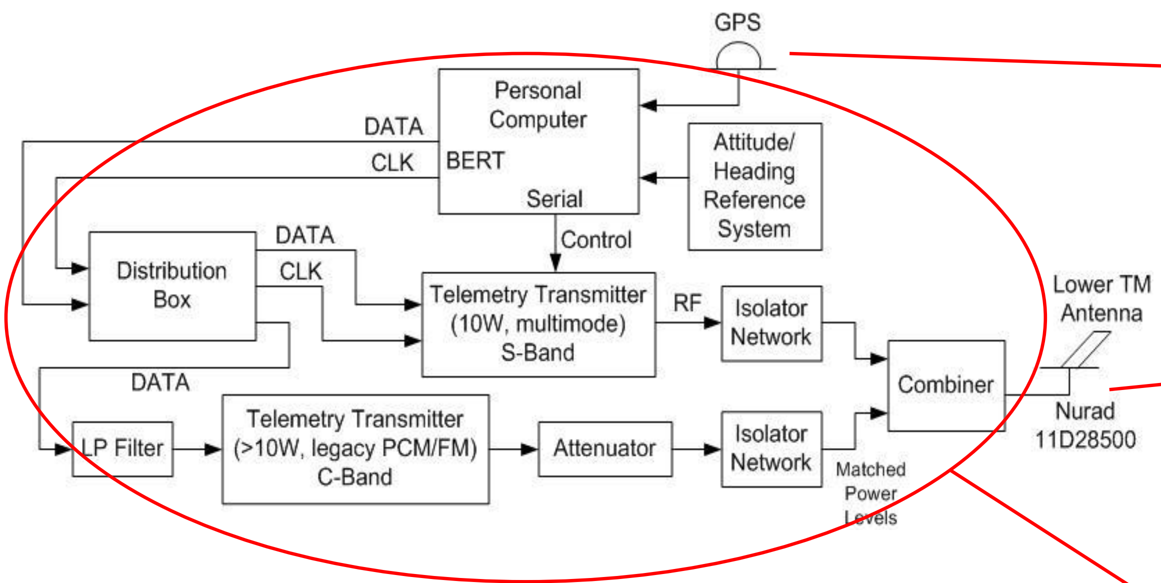

- **Aircraft Platform**
  - **Test Rack in C-12 configured with:**
    - **C-Band telemetry transmitter (analog)**
      - **10W RF power output, PCM/FM, PRBS-11 bit pattern, 5Mbps, f-4515MHz**
    - **S-Band multi-mode transmitter**
      - **10W RF power output, PCM/FM, PRBS-11 bit pattern, 5Mbps, f=2226.5MHz**

S- versus C-band experiment at EAFB (3)

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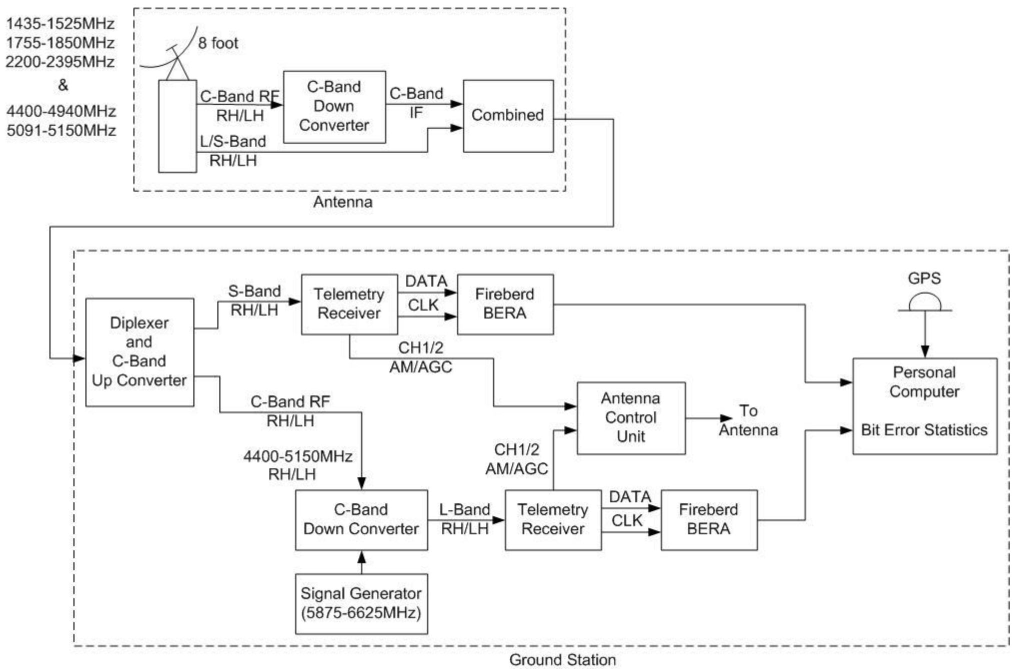
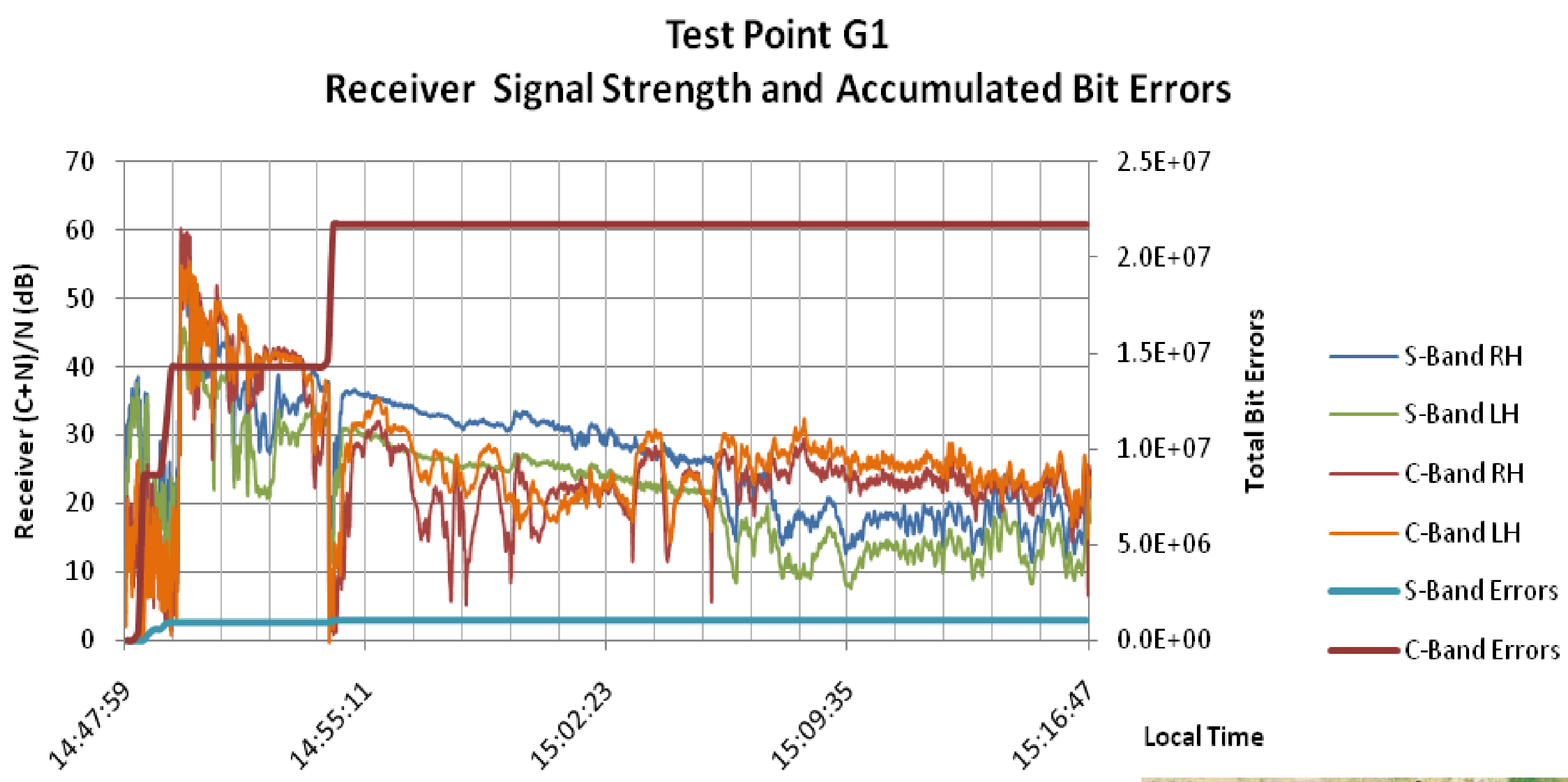
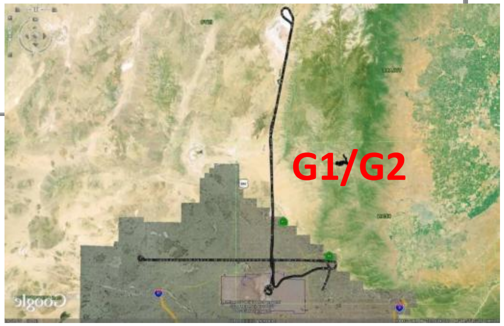


- Portable 8' antenna with multiple band capability (Bldg 4795)
- C-Band conversion
  - Feed down-converts to "C-Band IF" then combines with S-Band
  - Up-converted back to C-Band then to L-Band, S-Band to receiver
  - Extra conversion req'd, no direct method for "C-Band IF" to L-Band
  - L-Band (original C-Band signal) to receiver
- Receivers output Data/Clk to Fireberd 6000A's
- ACU logs receiver AGC levels

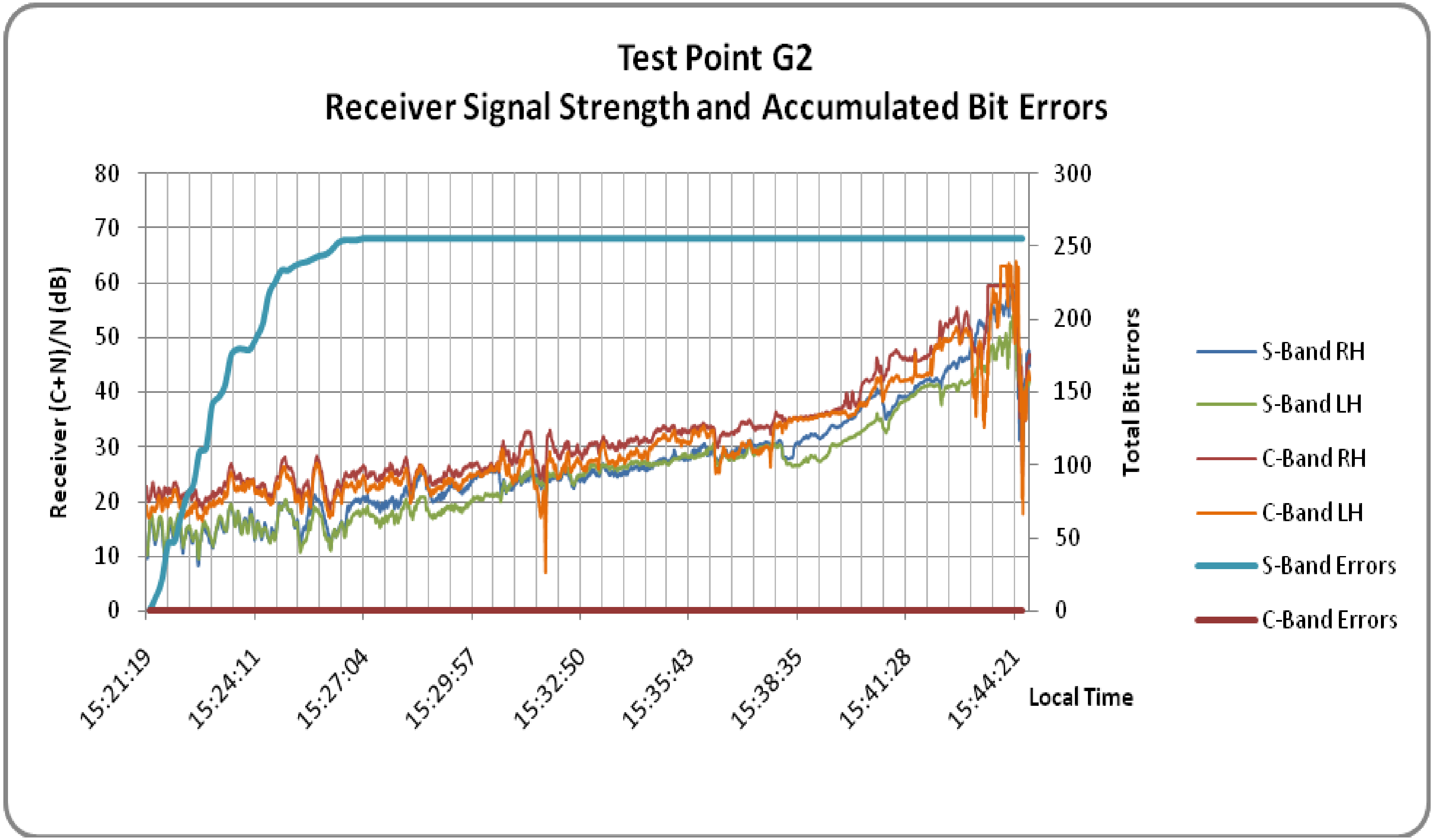
S- versus C-band experiment at EAFB (4)



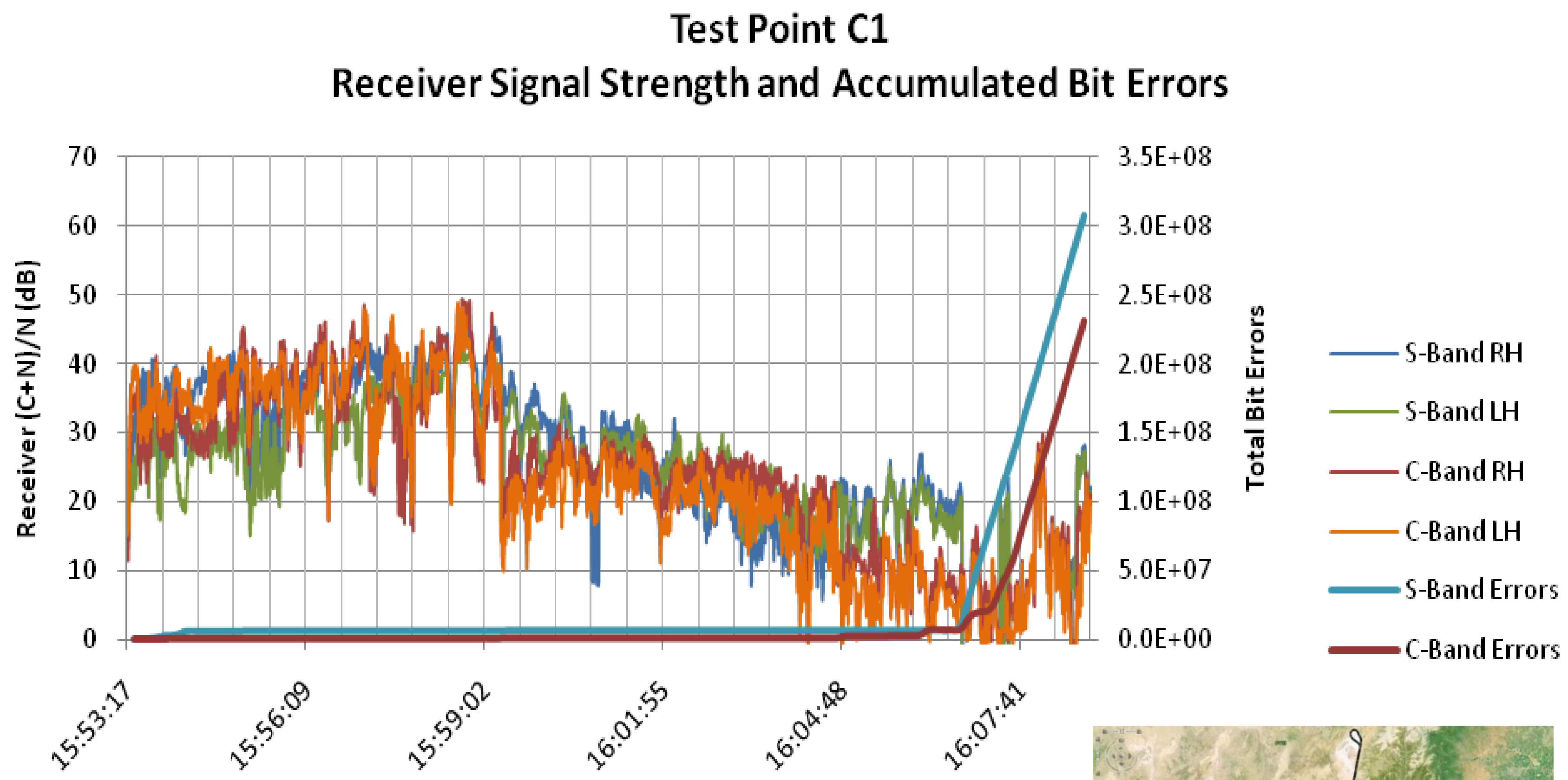


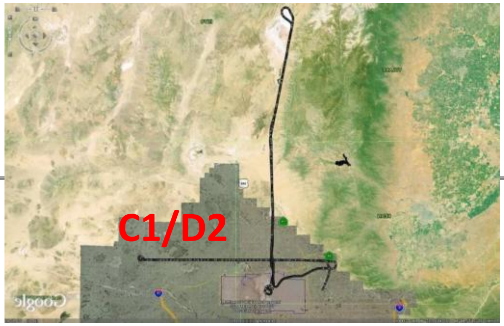
S- versus C-band experiment at EAFB (5)

BYU

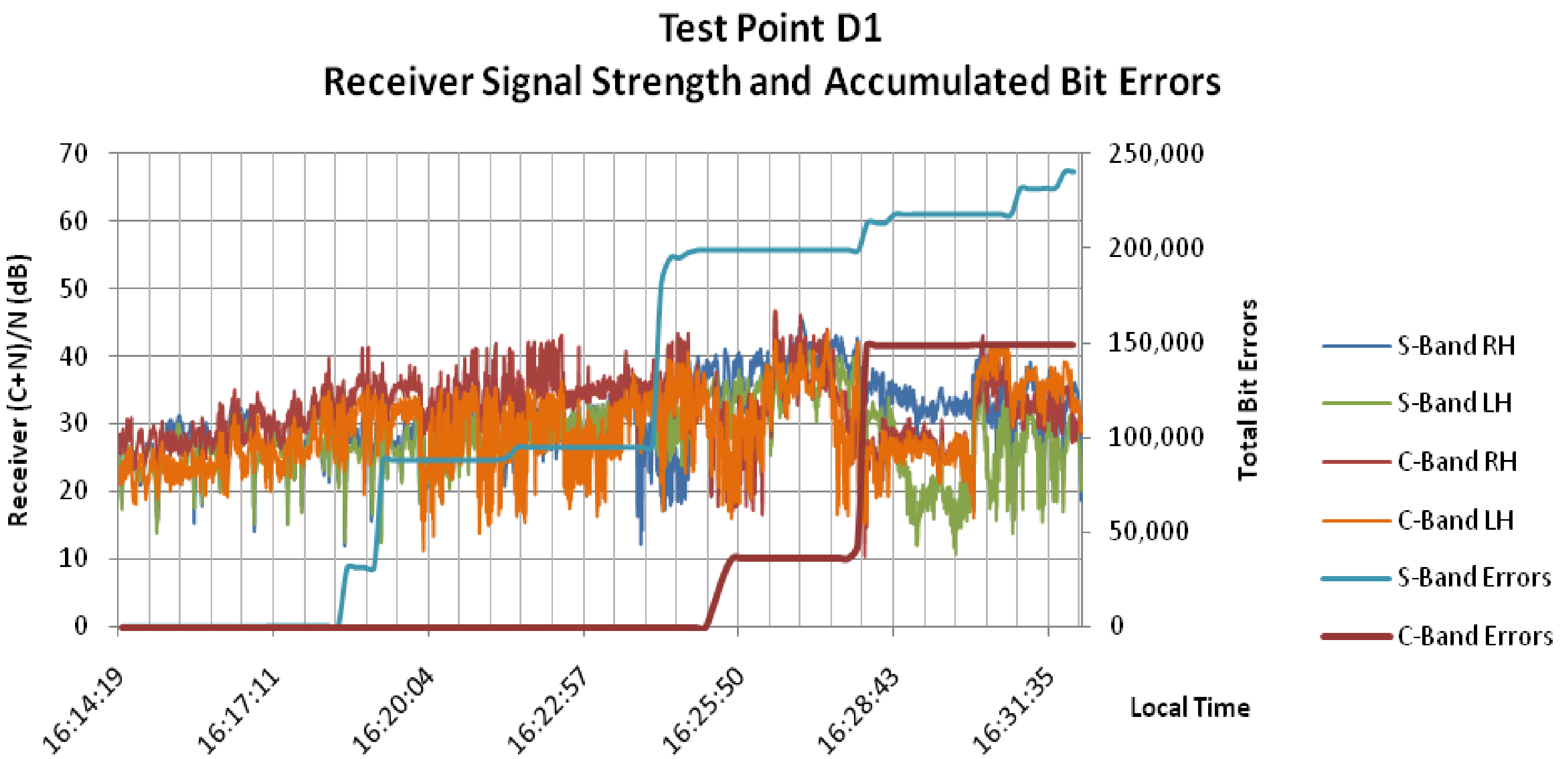


S- versus C-band experiment at EAFB (6)





S- versus C-band experiment at EAFB (7)



S- versus C-band experiment at EAFB (8)

BYU

$$\text{LA} = \frac{\text{Total Run Time} - \text{Severely Errored Time}}{\text{Total Run Time}} \times 100\%$$

Link Availability is a calculated metric that assesses the amount of time the link was "in-service", or providing useable data.

Link Availability Results		
Test Point	S-Band LA (%)	C-Band LA (%)
G1	**98.43%**	**95.87%**
G2	**100.00%**	**100.00%**
C1	**80.11%**	**79.02%**
D1	**97.45%**	**97.74%**
Mission	**93.06%**	**91.91%**

S- versus C-band experiment at EAFB (9)

BYU

- Receiver signal strengths for both S-band and C-band tracked each other throughout the test points leading to the conclusion that the telemetry channel behave tin same fashion at those frequencies. Minor amplitude differences observed can be attributed to the antenna gain pattern differences of the transmit antenna for S- and C-band.
- The telemetry channel for these test points can be characterized as multipath limited, causing large tallies of bit errors during discrete times. The channel is typically not noise limited though test point G1/G2 did stress the link margin.
- Average bit error rate is not a good metric to use to characterize telemetry system performance in this transmission channel. Long error-free intervals were observed interrupted by multipath events causing long outage periods rendering an averaging method painting an incomplete picture. **Link Availability** was used as the link performance metric.
- For this transmission channel, theoretical gains normally associated with optimal ratio combining were not observed mainly due to the lack of polarization diversity in either band.
- Though not empirically tested, antenna tracking was enabled in both bands at separate times during the flight tests with no anomalies noted.

L- versus C-band experiment at TPS (1)

- **Test Pilot School at AFFTC**
  - **Installed C-Band receive capability**
  - **Flights "typically" within R2515**
  - **Migrate TPS fleet to C-Band?**
  - **Antenna tracking selection**

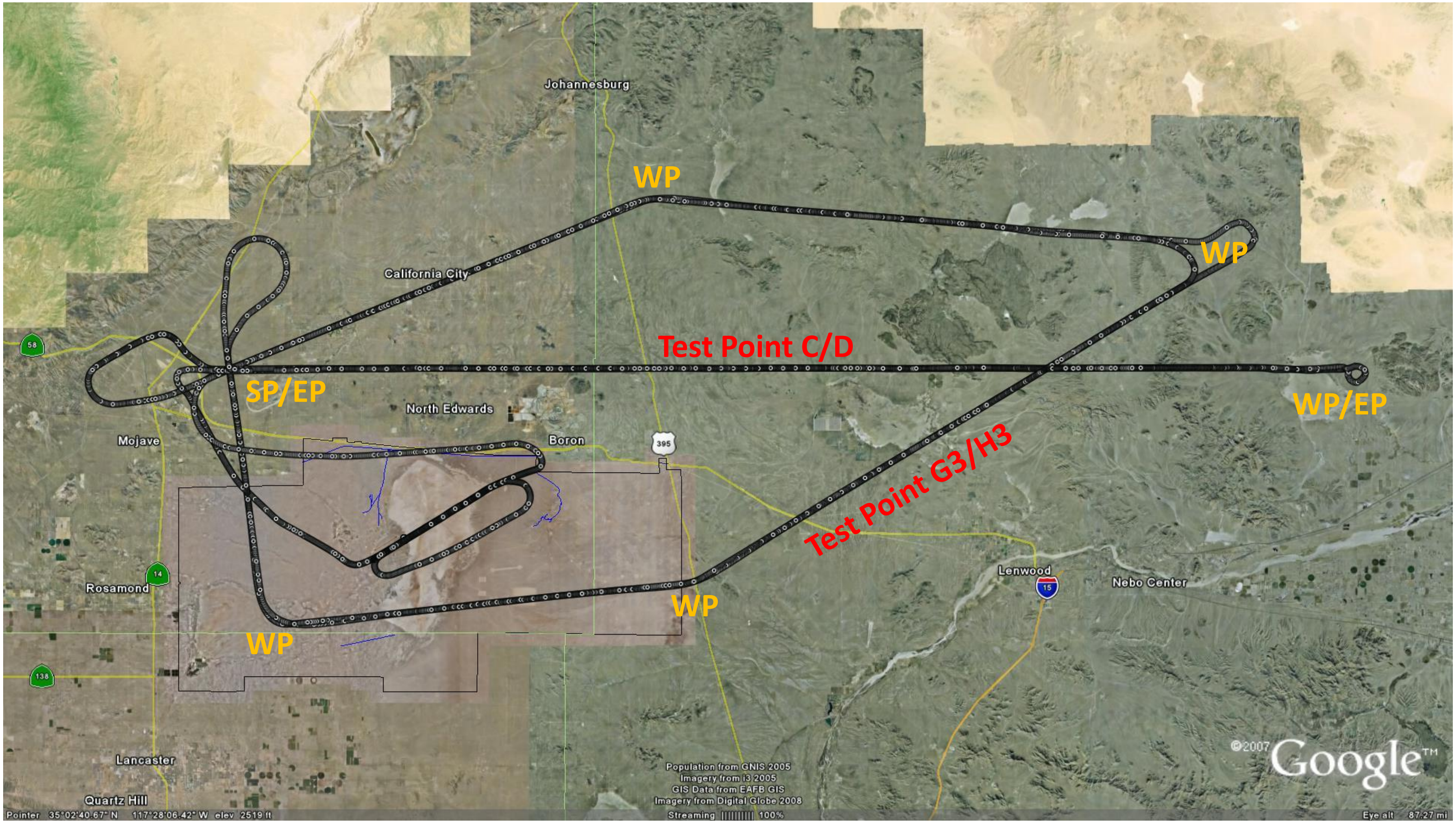
Fundamental Question: Will the school notice any decrease in data quality if they should migrate their fleet away from L-band and into C-band?

Approach to Answering the Question: Performed flight testing on "typical" routes flown during school missions

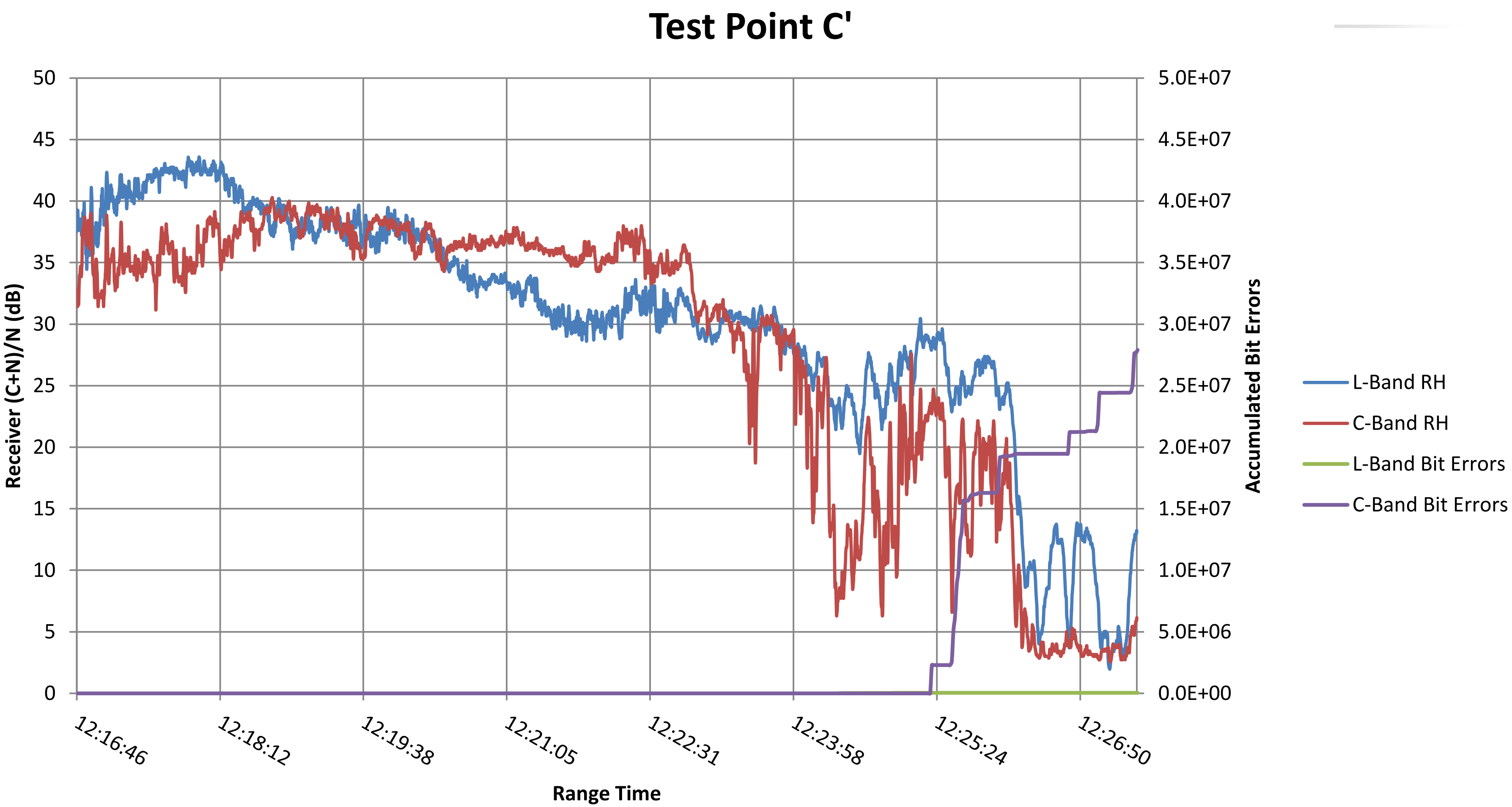
- Flight #1: within R2515, Cords Rd, and R2515 boundary
- Flight #2 Owens Valley

L- versus C-band experiment at TPS (2)

BYU

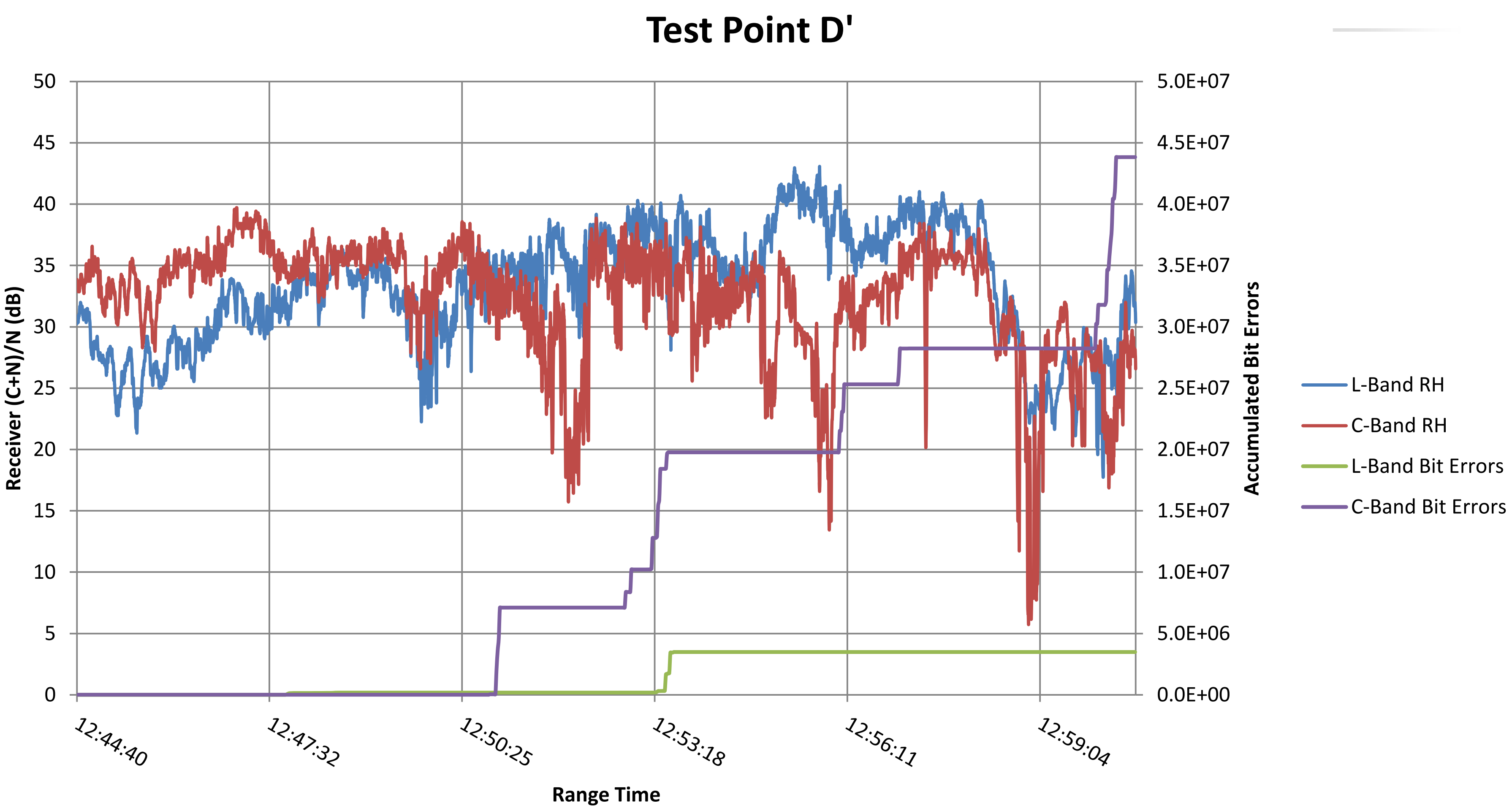


L- versus C-band experiment at TPS (3)

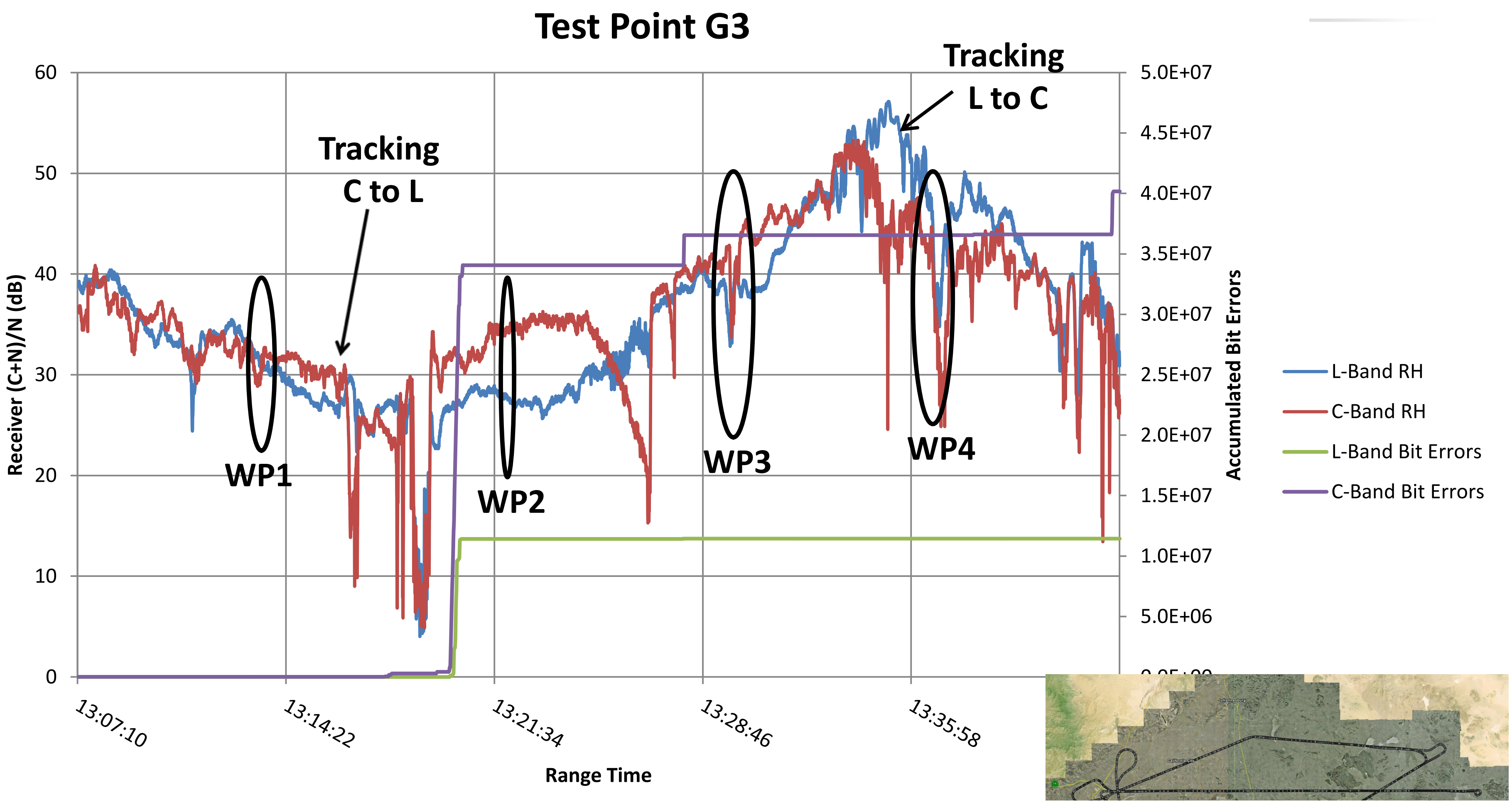


L- versus C-band experiment at TPS (4)

BYU

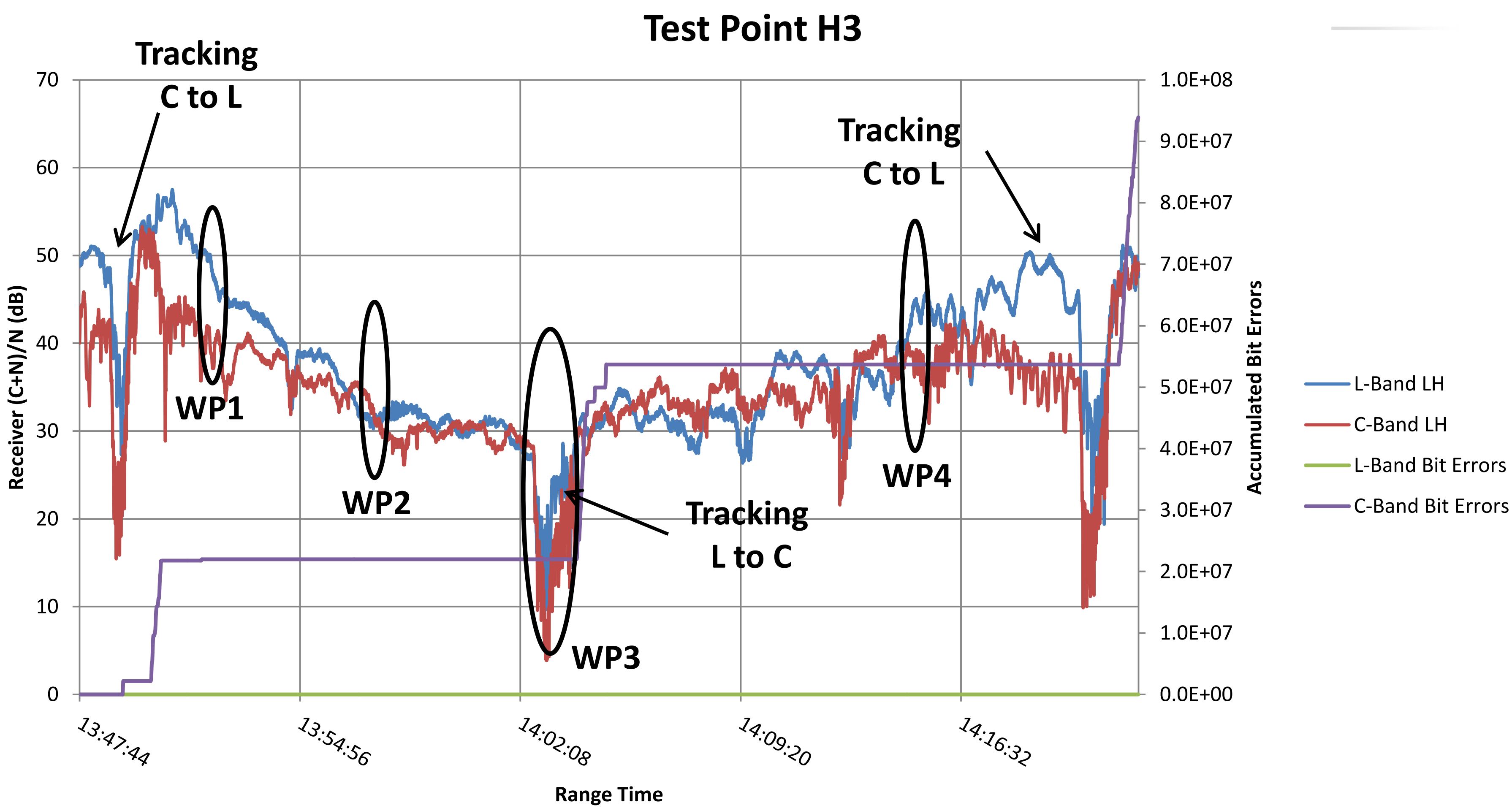


L- versus C-band experiment at TPS (5)

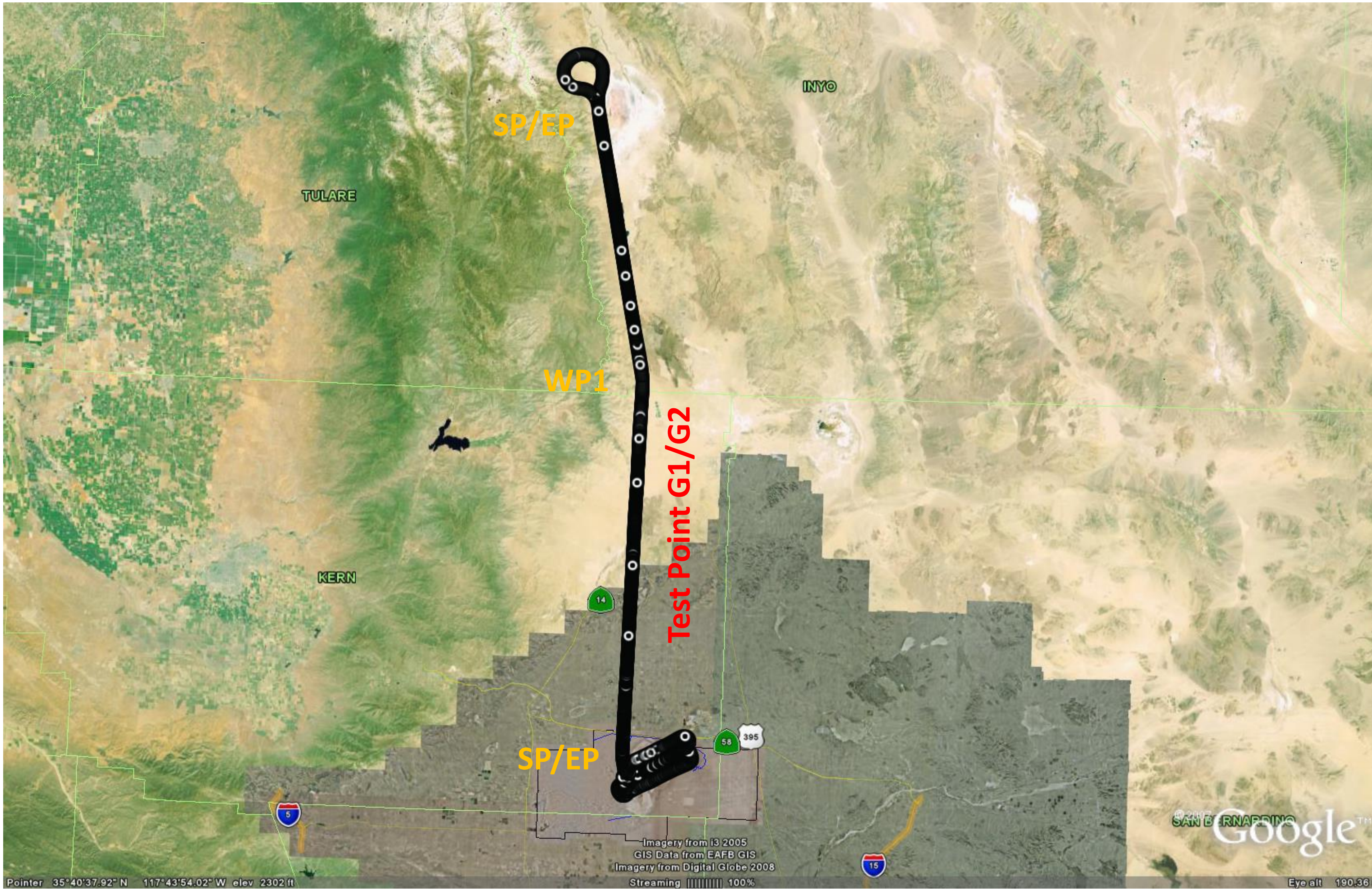


L- versus C-band experiment at TPS (6)

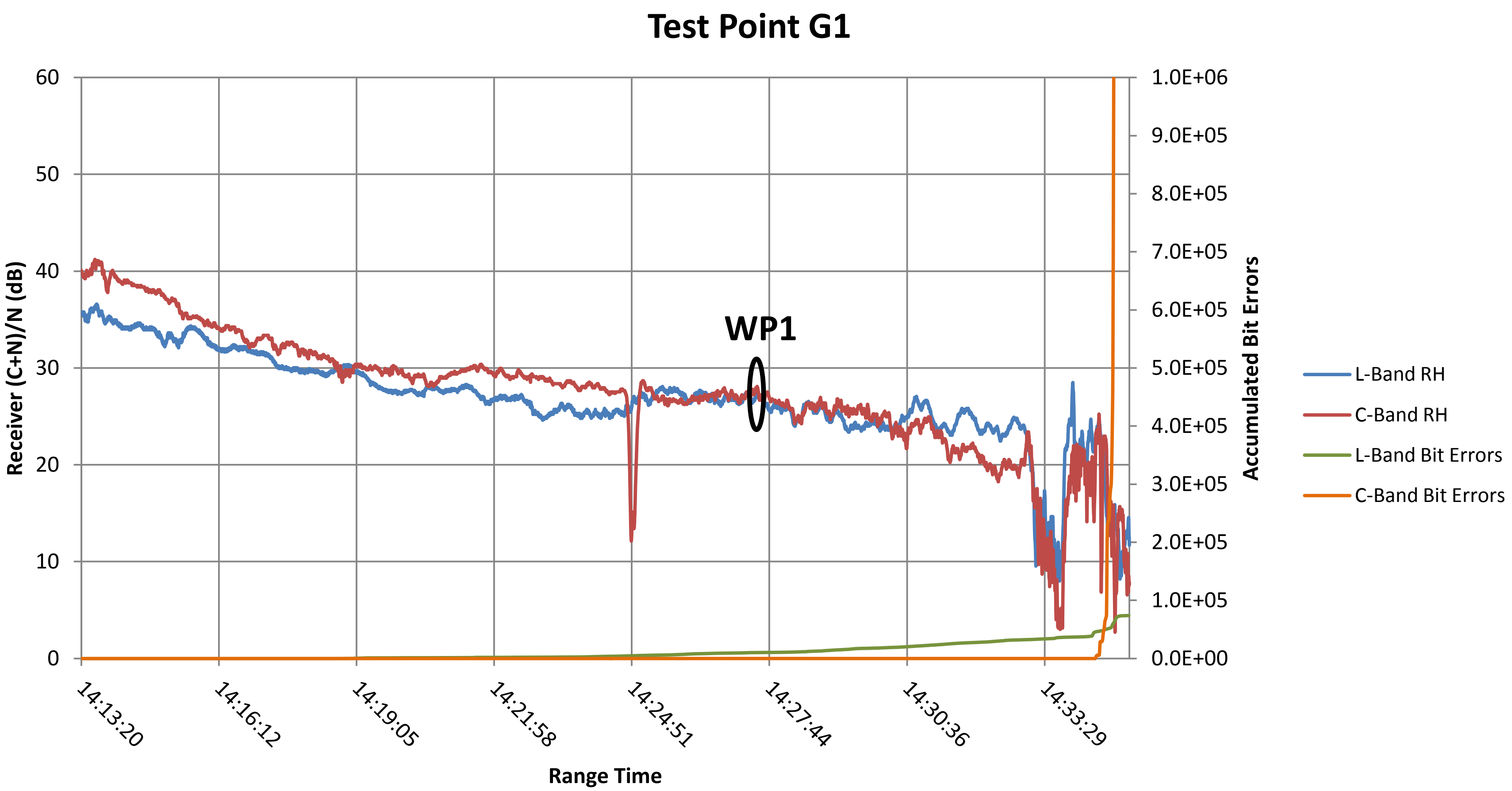
BYU



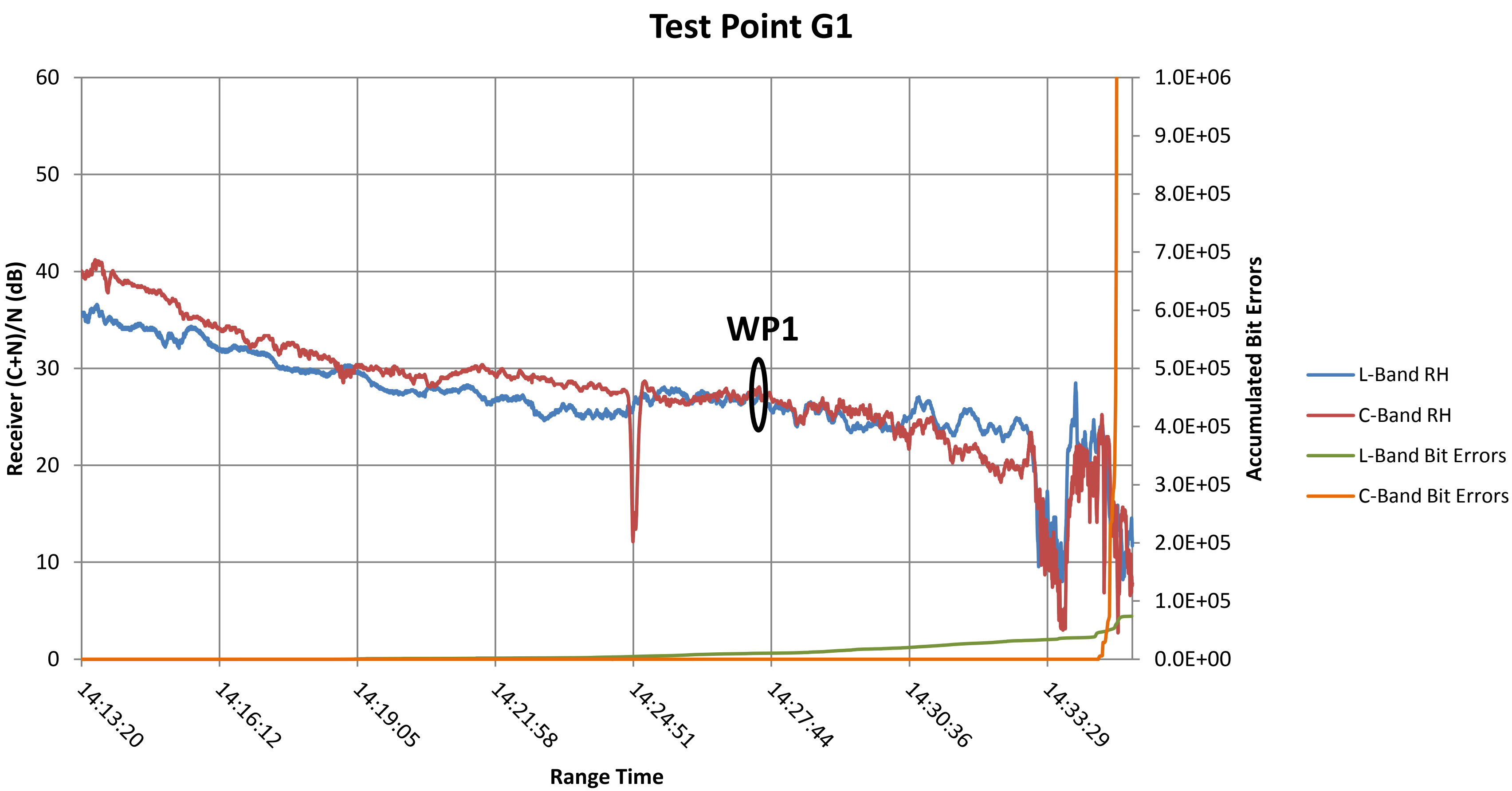
L- versus C-band experiment at TPS (7)



L- versus C-band experiment at TPS (8)

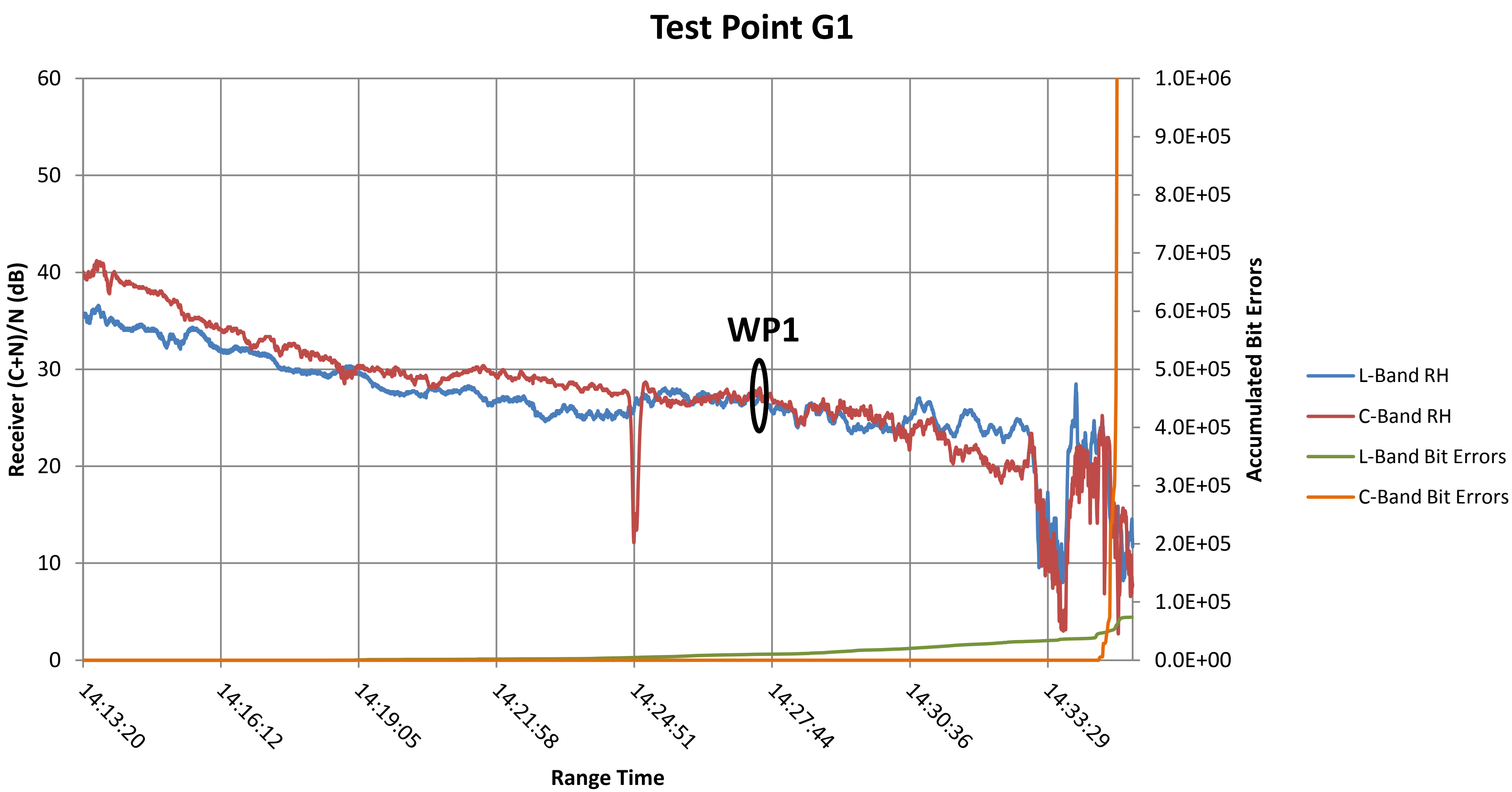


L- versus C-band experiment at TPS (9)



L- versus C-band experiment at TPS (10)

BYU



L- versus C-band experiment at TPS (11)

$$\text{LA} = \frac{\text{Total Run Time} - \text{Severely Errored Time}}{\text{Total Run Time}} \times 100\%$$

Link Availability (TPS Flight #1)

Test Point	L-Band	C-Band
C	99.5%	92.0%
D	98.0%	94.7%
G3	100.0%	100.0%
H3	100.0%	100.0%

Link Availability (TPS Flight #2)

Test Point	L-Band	C-Band
G1	100.00%	98.02%
G2	100.00%	100.00%

L- versus C-band experiment at TPS (11)

BYU

- Main points
  - Comparable *Link Availability* between links (except points C/D which include long intervals of no SNR negatively biasing the results).
  - Similar receiver S/N profiles, i.e., transmission channel behaved similarly for both links (all points)
  - Similar maximum link range (points G1/G2)
  - Antenna tracking was consistent between L- and C-band selection
- Conclusion
  - "Data indicates similar telemetry link performance between telemeters in L-Band and C-Band when operating in R2515 over the flight paths flown."

Combined Summary

BYU

Comparison of G1/G2 test points for S-band tests (initial testing) and L-band tests (TPS testing)

Link Availability Results (S-Band Flight)		
Test Point	S-Band LA (%)	C-Band LA (%)
G1	**98.43%**	**95.87%**
G2	**100.00%**	**100.00%**

Link Availability (TPS Flight #2)

Test Point	L-Band	C-Band
G1	100.00%	98.02%
G2	100.00%	100.00%

Test Point	C-Band (Trailer)	C-Band (TPS)	S-Band	L-Band
G1	95.87%	98.02%	98.43%	100.00%
G2	100.00%	100.00%	100.00%	100.00%

Note: Differing receive station antennas, antenna locations, and aircraft antennas make LA comparisons difficult.

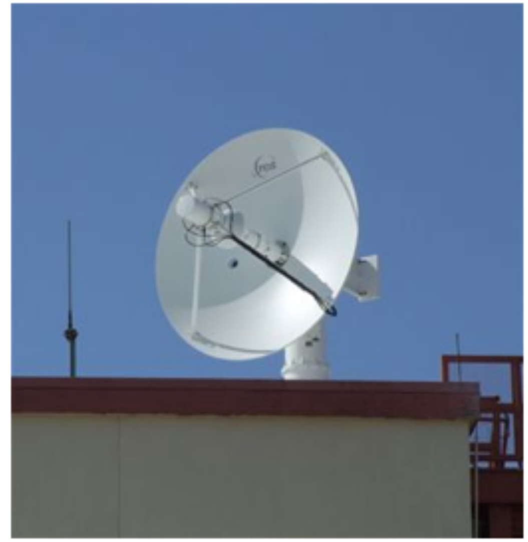
Combined Summary

BYU

- Main Points
  - "Fluctuating SNR values in the test points where multipath is not a contributing factor (G3, H3, G1, G2) are associated with aircraft antenna pattern inconsistencies."
  - "Lower Link Availability numbers in points G1 as opposed to G2 are again associated with antenna pattern anomalies."
  - "It is not known why there are accumulating bit errors in the L-band and S-band links for Test Point G2. These errors were not observed in the B-band link. This will require further investigation."
  - C-Band/S-Band/L-Band
    - "C-band performance is closer to S-band performance than L-band."
    - "Antenna pattern anomalies were more prevalent with the C-band link than with the L-band link."
- The Punch Line
  - "[The] customer will not notice TM link performance degradation if they typically fly in S-band. Minimal degradation 'may' be observed if they typically fly in L-band."

Air Force Print News Today
Air Force news from around the world

TPS adding more bandwidth



A newly installed antenna sits atop the U.S. Air Force Test Pilot School. The antenna is part of a new aeronautical telemetry ground system that will allow airborne data to be transferred to the ground in the C-band frequency range -- an addition to the L- and S-band frequency ranges currently used. The new tri-band system will increase bandwidth and allow more frequencies to be used by both the civilian community and Edwards Air Force Base. (Courtesy photo)

by Kenji Thuloweit
95 Air Base Wing Public Affairs

5/12/2010 - **EDWARDS AIR FORCE BASE, Calif.** -- With advances in satellite television, cell phones and more complex communication systems, the skies are becoming cluttered with frequency users. The need for more bandwidth is not just something people want for faster video or music downloads; it's also needed to expand communications capabilities between aircraft and ground-based people and equipment.

Telemetry is a technology that allows remote measurement and reporting of information. It is how data from an aircraft is transferred to engineers on the ground to assess the aircraft's performance. Here, at Flight Test Nation, the U.S. Air Force Test Pilot School has installed a first-of-its-kind aeronautical telemetry ground system.

"Due to technological advances and the increase in civilian use of various frequencies, some of which happen to be the same frequencies we use, there has been a need to expand our range of frequencies for flight testing," said John Ward, Test Management Group and Telemetry Systems Integration and Support program manager.

The TSIS program, in collaboration with the TPS, has installed the new aeronautical telemetry ground system, which is capable of acquiring airborne telemetry data in the L-, S-, and now, C-band frequency ranges. The system replaces an older ground telemetry system, which was capable of only receiving telemetry in the L and S ranges.

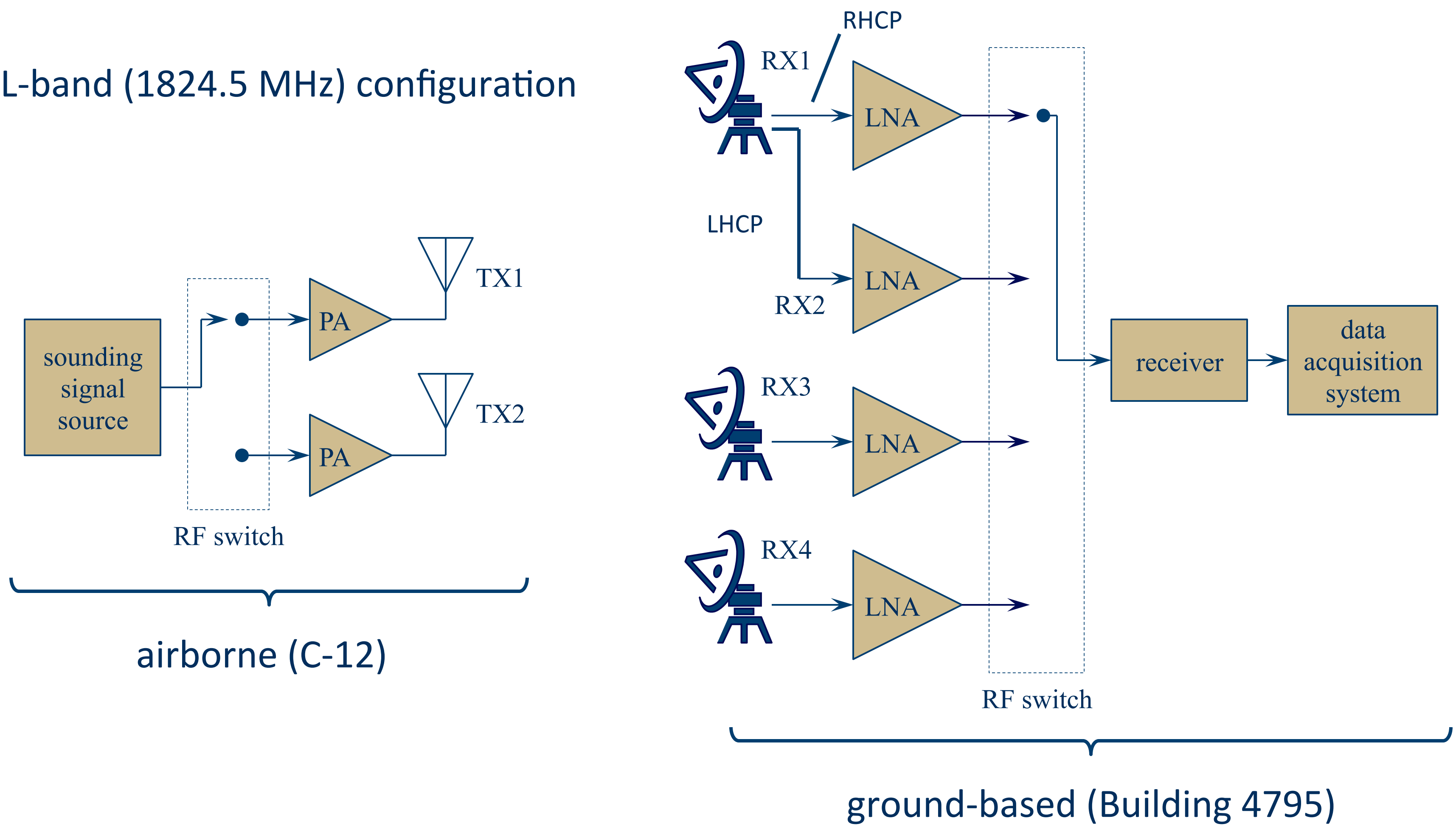
"Air-to-ground telemetry has always been conducted in the 1435-1525 Megahertz (L-Band) and 2200-2395 Megahertz (S-Band) frequency ranges." said Mr. Ward. "However, as we test aircraft with greater technology advancements, more telemetry bandwidth use is inevitable and this new tri-band telemetry capability will expand the range of available telemetry frequencies into the 4 Gigahertz and 5 Gigahertz ranges (C-band)."

The additional frequencies added will benefit both the surrounding community and the different squadrons on base by relaxing the encroachment of frequencies used by civilians and other squadrons.

"You may have emergency response companies and cell phone companies all desiring to use more and more frequencies and that could cause congestion in the frequencies we use here for flight tests," Mr. Ward said.

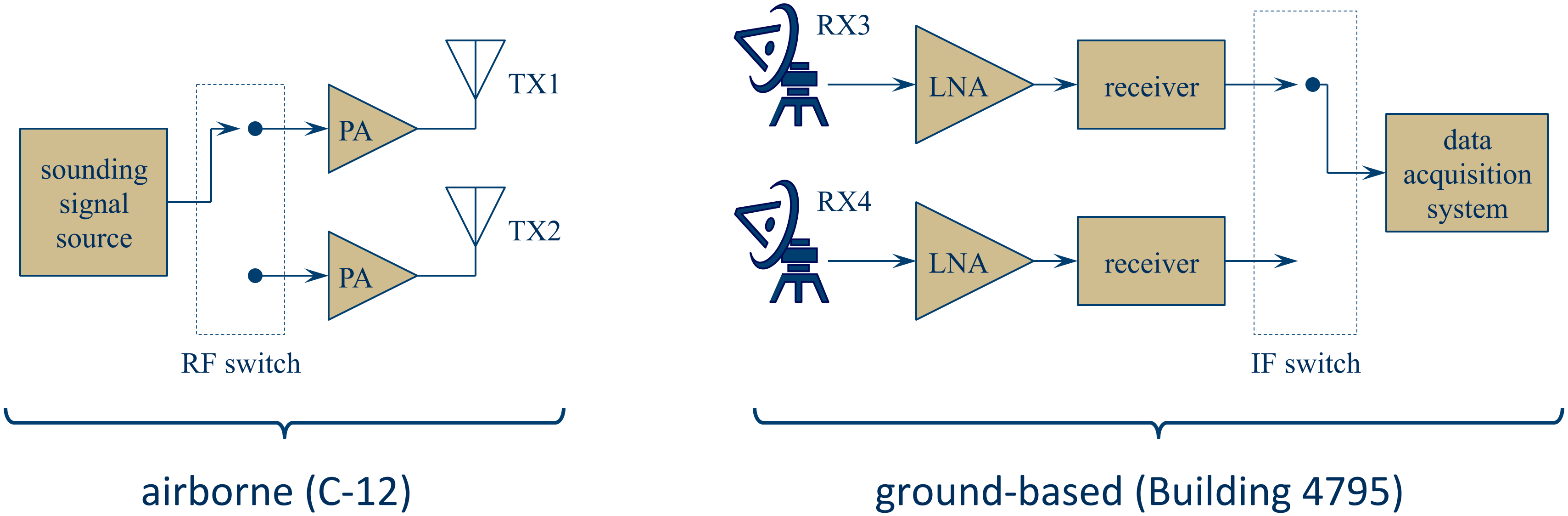
Multipath Channel Sounding Experiments @ EAFB

L-band (1824.5 MHz) configuration



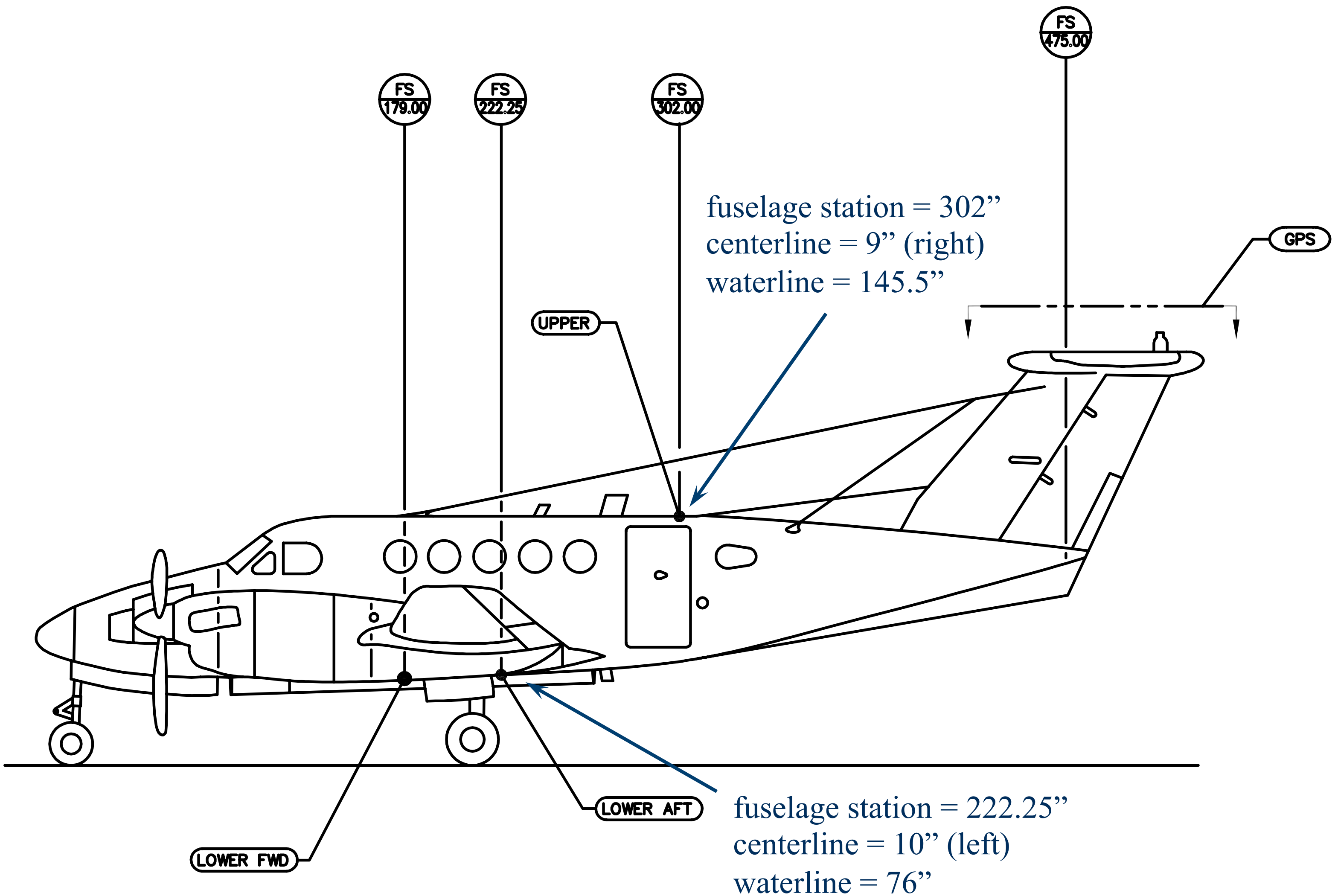
Multipath Channel Sounding Experiments @ EAFB

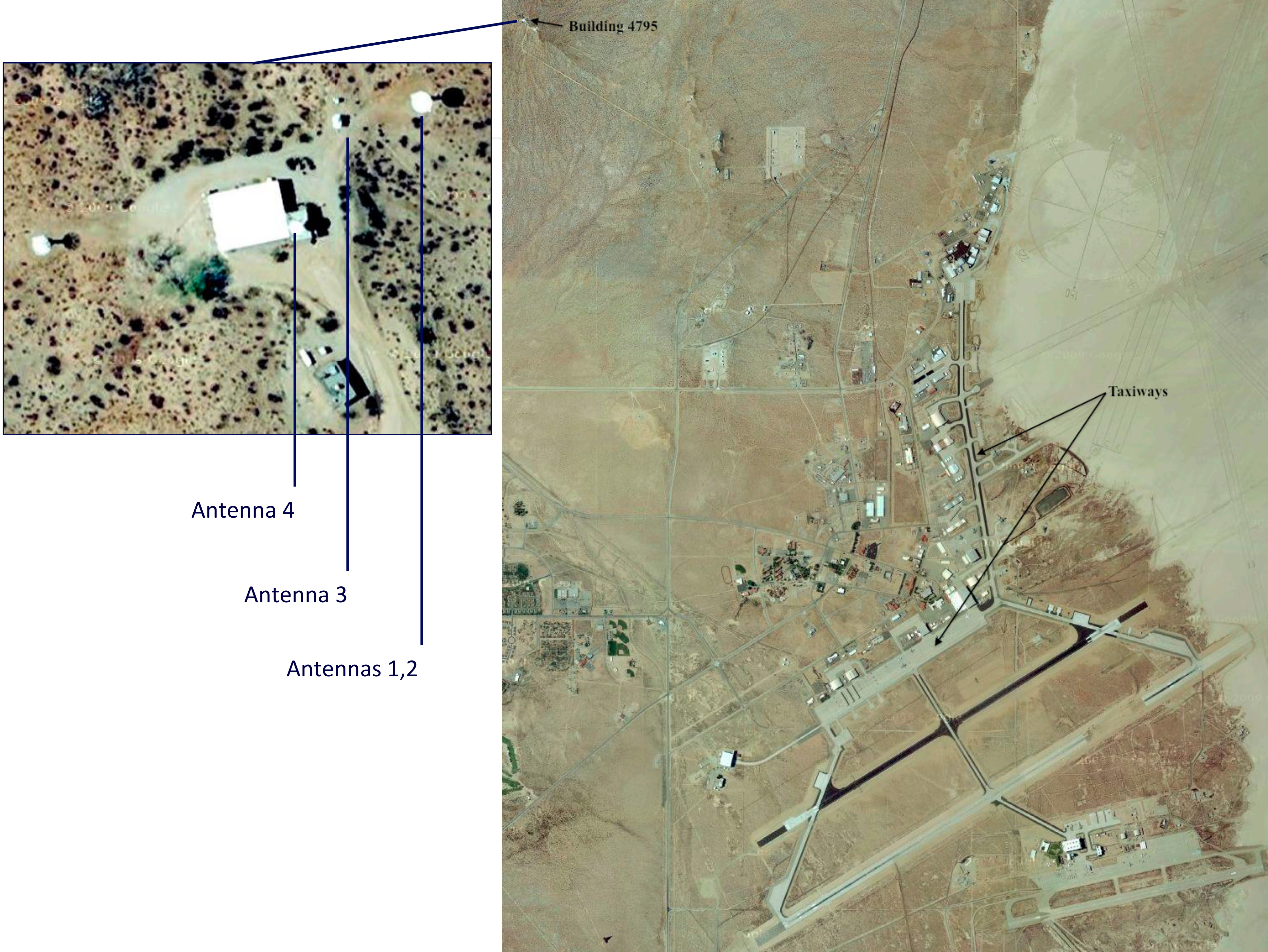
C-band (5124.0 MHz) configuration



Multipath Channel Sounding Experiments @ EAFB

BYU

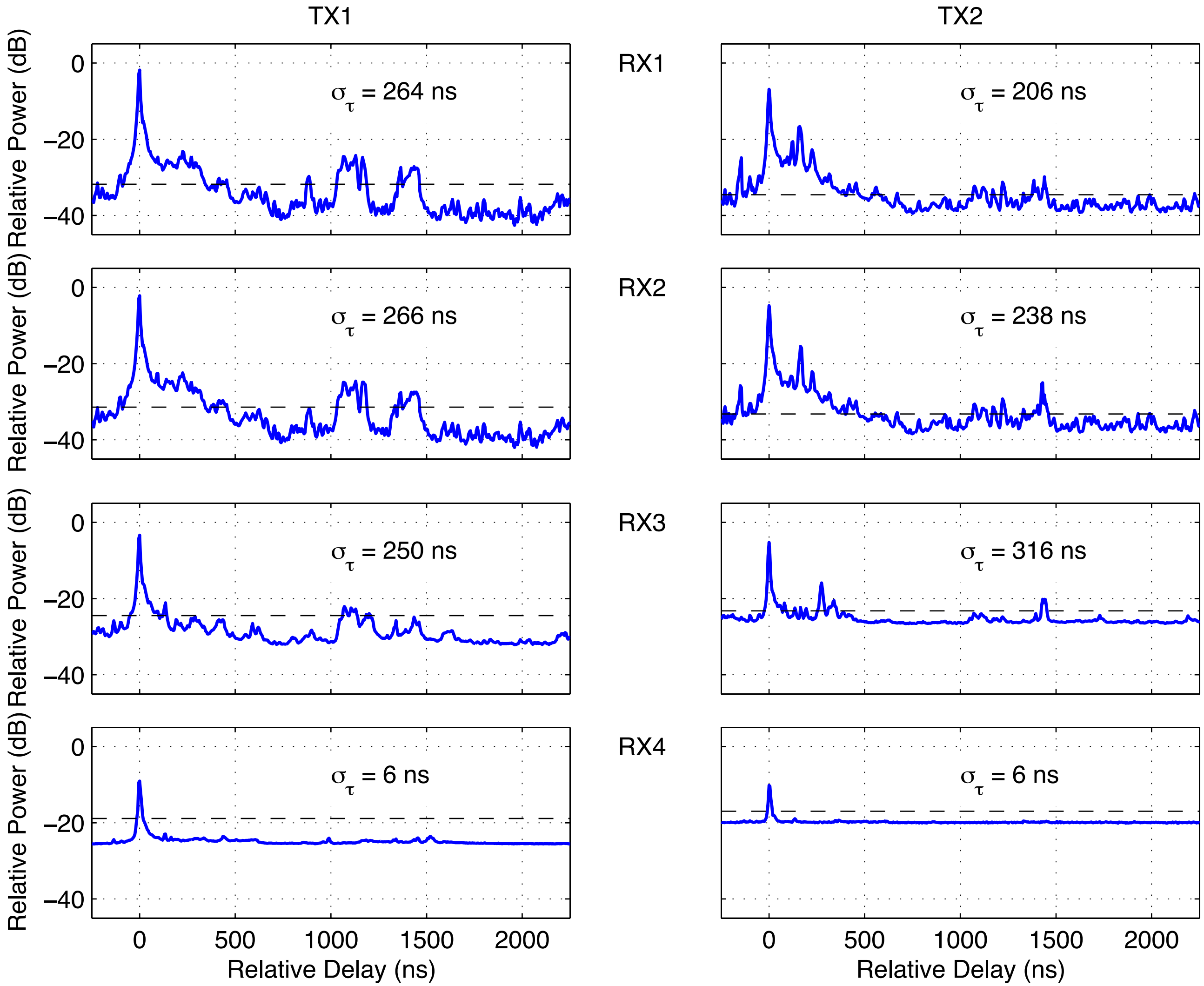




Building 4795
Taxiways
Antenna 4
Antenna 3
Antennas 1,2

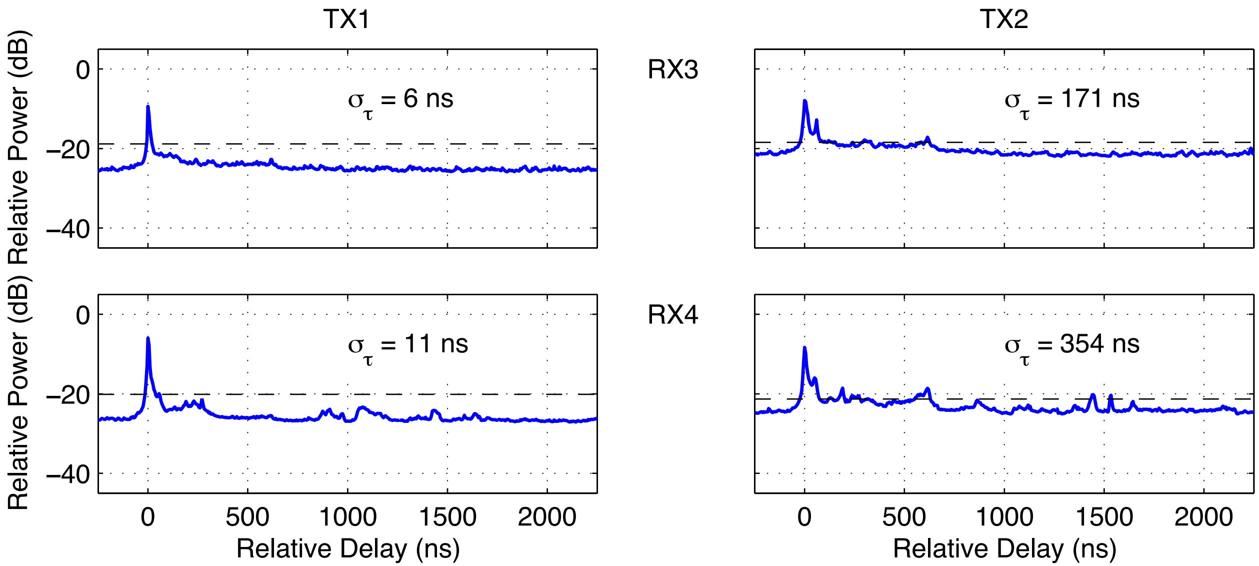
Multipath Channel Sounding Experiments @ EAFB

Taxiway F, southwest → northeast
(L-Band)



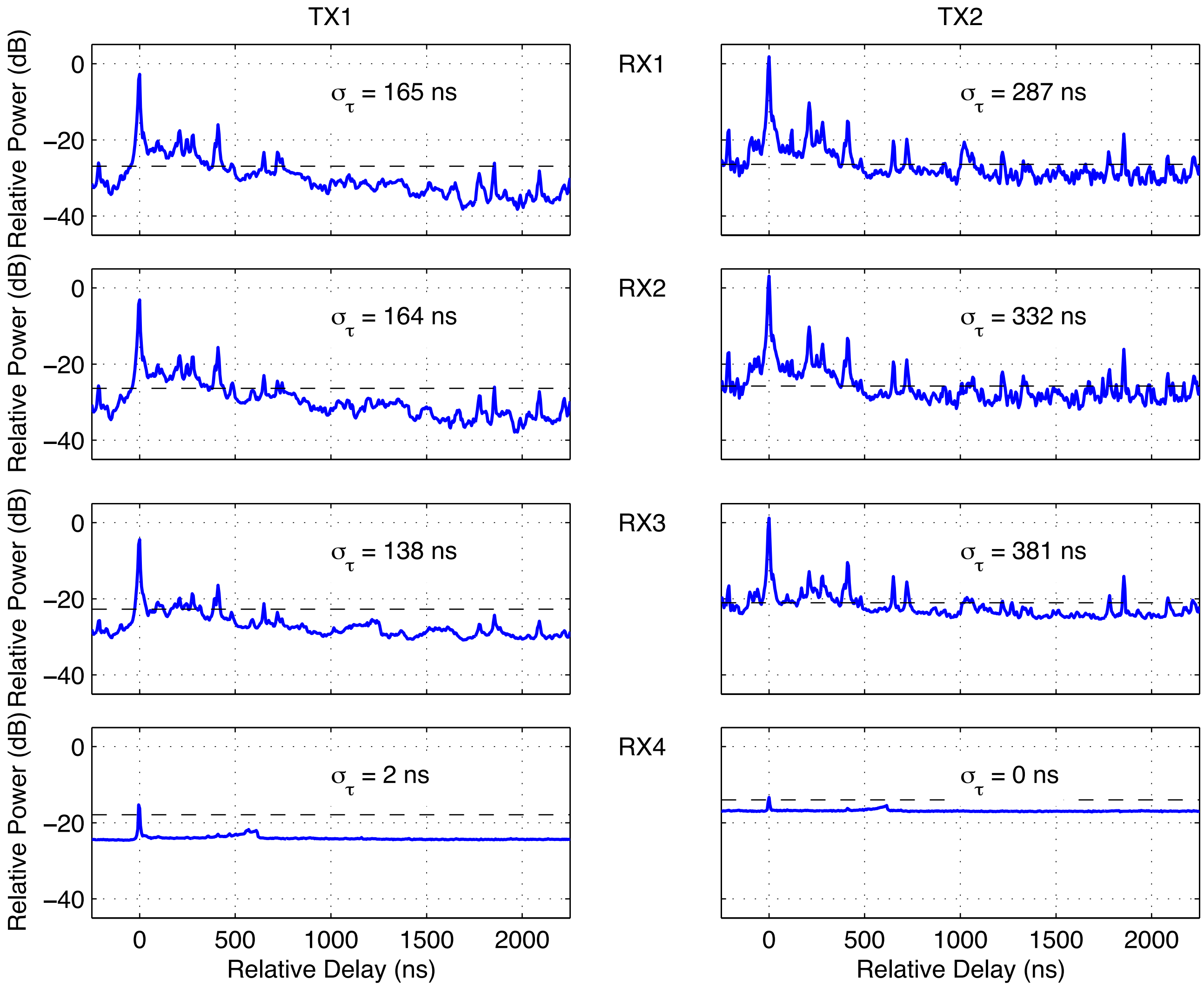
Multipath Channel Sounding Experiments @ EAFB

Taxiway F, southwest → northeast
(C-Band)



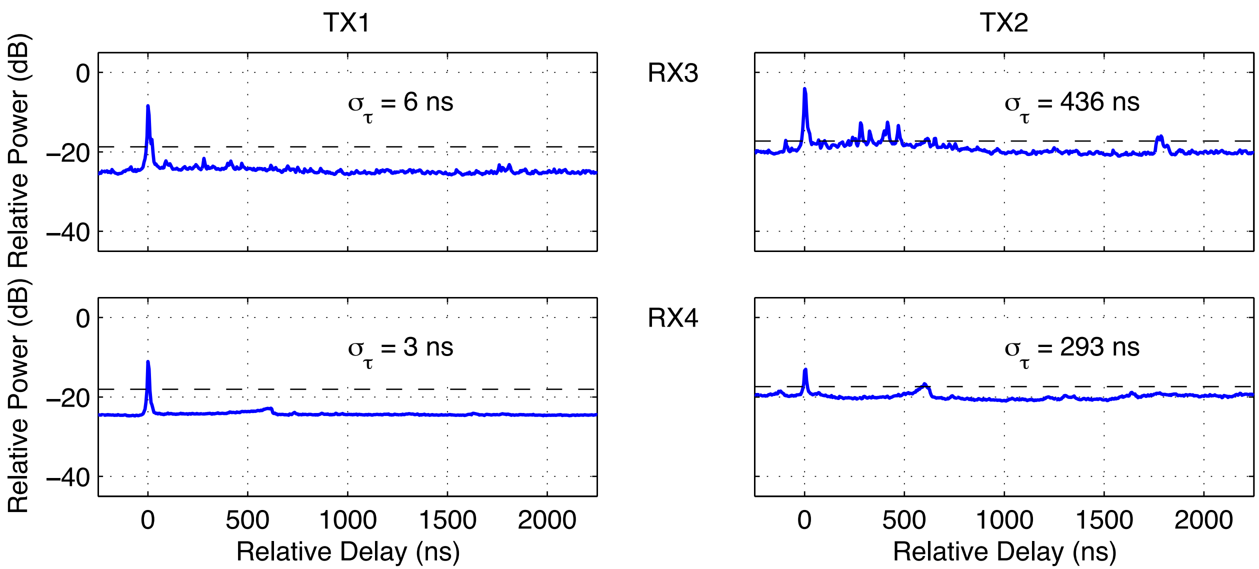
Multipath Channel Sounding Experiments @ EAFB

Taxiway E, south → north
(L-Band)



Multipath Channel Sounding Experiments @ EAFB

Taxiway E, south → north
(C-Band)



Multipath Channel Sounding Experiments @ EAFB

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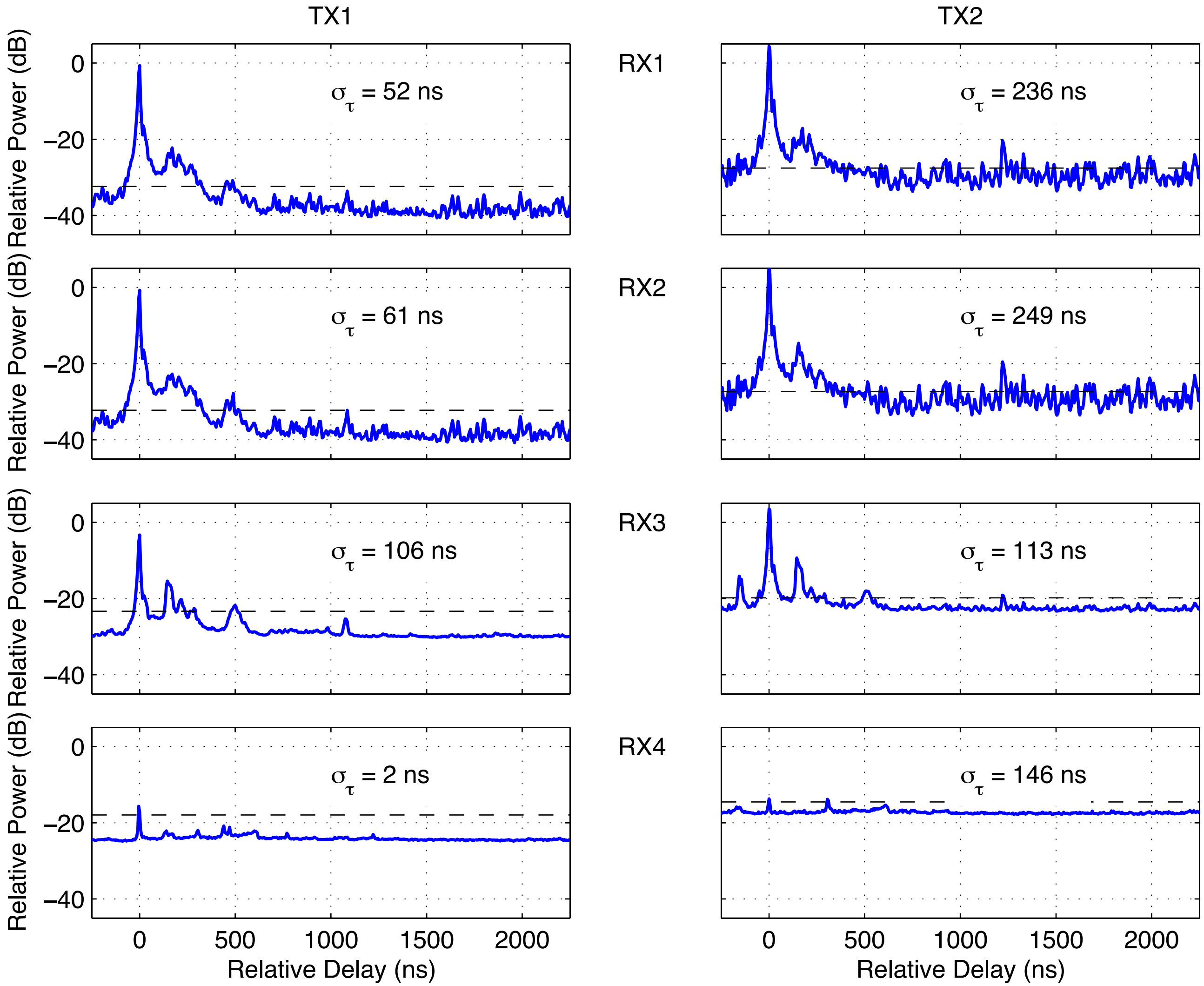
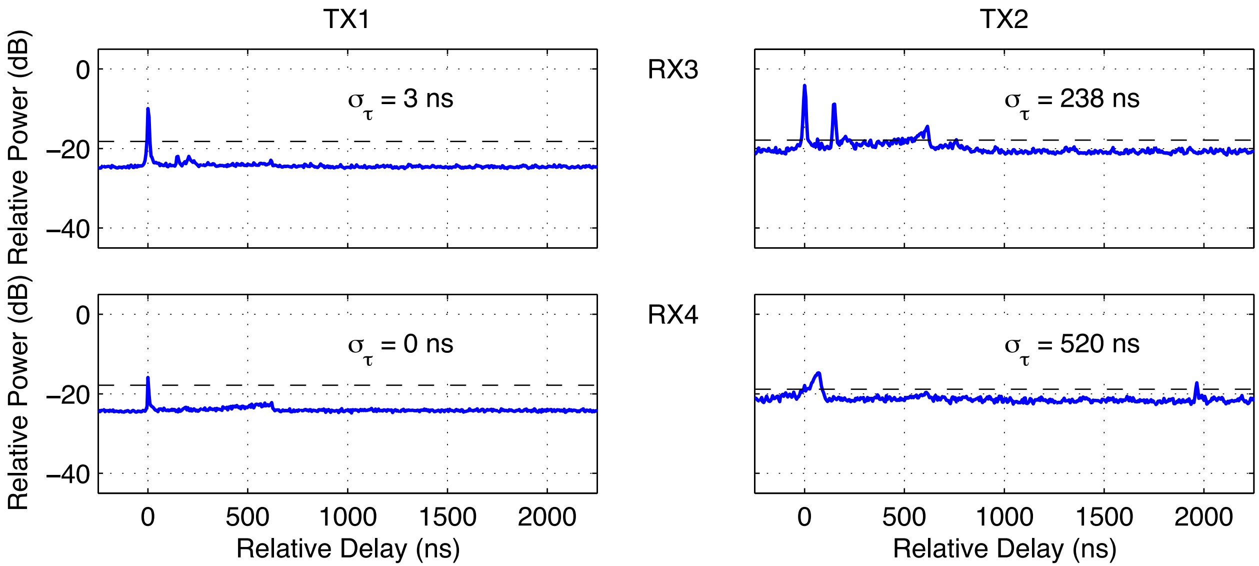
Taxiway E, turnaround
(L-Band)



Multipath Channel Sounding Experiments @ EAFB

Taxiway E, turnaround
(C-Band)



Multipath Channel Sounding Experiments @ EAFB

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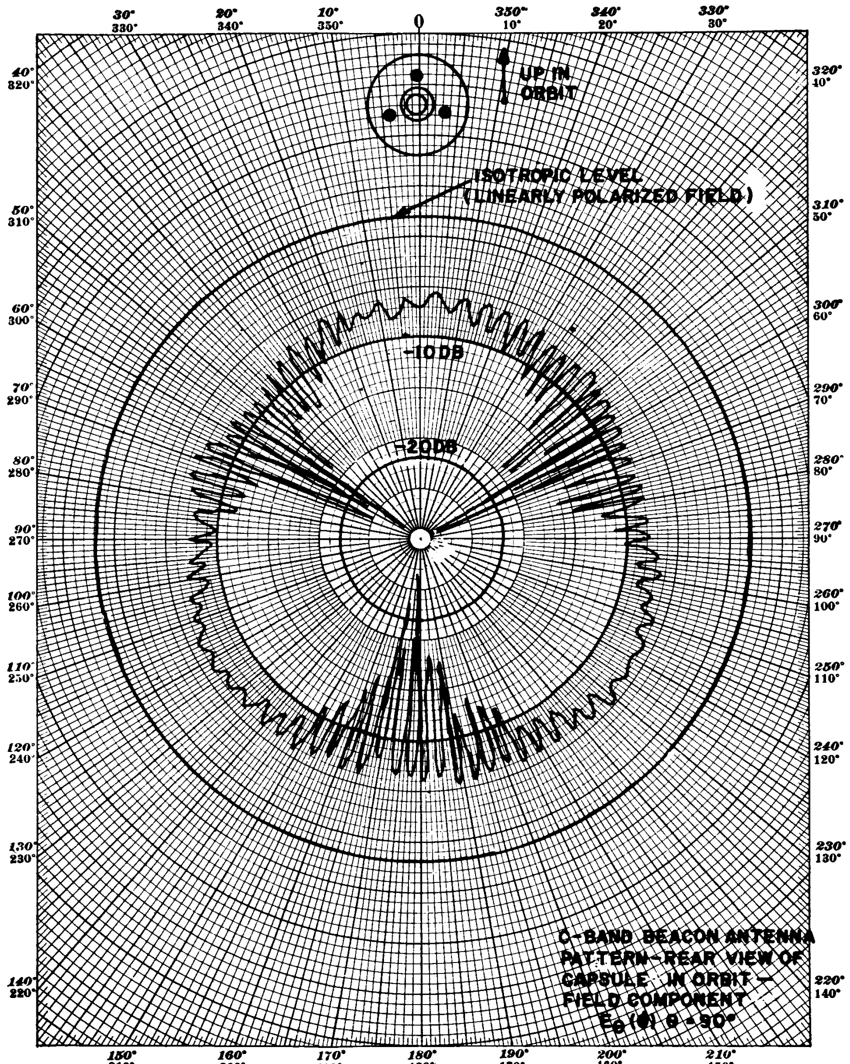
- C-band has smaller delay spread than L-band.
- C-band more susceptible to outages than L-band.
- C-band propagation experiences higher attenuation with reflection → multipath components smaller relative to LOS component.
- For a fixed antenna diameter, antenna beamwidth is smaller at C-band → smaller angular spread captured by antenna.

Project Mercury C-Band Radar-Beacon Tracking

BYU



C42-216

It can be seen that severe interference regions exist every 120°, midway ween helical cavities. Possible deleterious effects of such an antenna angement are twofold:

a) The nulls of the interference regions may be deep enough to cause erratic triggering of the beacon. This situation is especially serious in cases where the angular line-of-sight to the capsule is constant for long periods of time.

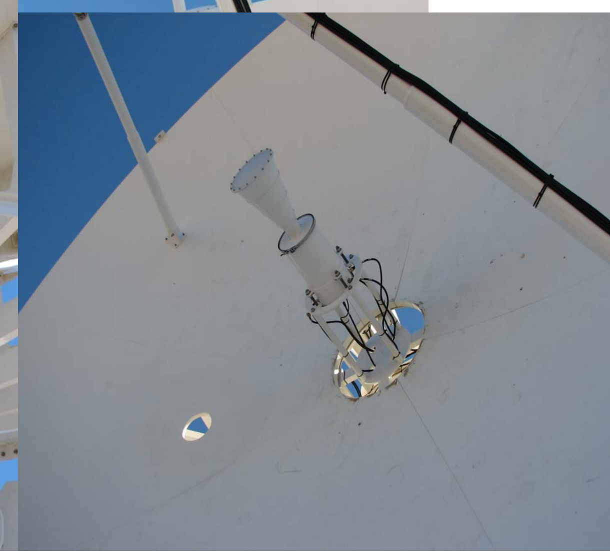
b) If such an antenna system has angular motion with respect to the ground tracking radar, the interference regions may effectively scan the tracking radar. If the tracking radar is a monopulse radar (as is the AN/FPS-16 in the C-band Mercury system), it is possible for a serious "glint" problem to arise. In this instance, the phase reversal present from one side of a null to the other provides an effective tilt in the phase front emanating from the capsule. Thus, it is possible for a monopulse radar to have serious angular perturbations.[3]

The report describes a phase shifting technique to reduce (eliminate) the nulls in the radiation pattern.

H. Labitt, "C-Band Radar-Beacon Tracking for Project Mercury," presented at the AIEE Summer General Meeting and Aero-Space Transportation Conference, Denver, CO, 17-22 June, 1962.

NASA Dryden Video Links

- Airborne Platforms
  - NASA research vehicles (e.g., F-15, F-18)
  - Chase aircraft (F-18)
- 4550 – 4850 MHz
- LNB Output: 830 – 1130 MHz
- Bandwidth = 18 MHz
- Receive Antennas
  - Triplex (7m)
  - MFTS (7m)
  - Rooftop (4m)



C-Band Block
Downconverter

AeroMACS

BYU

FAA/NASA **<u>Aero</u>**nautical **<u>M</u>**obile **<u>A</u>**irport **<u>C</u>**ommunications **<u>S</u>**ystem = C-Band airport surface communication system based on IEEE 802.16e (WiMAX) standard for mobile broadband data communications.

The International Civil Aviation Organization is currently working on this standard.

ACP-WGM16/WP-xx
17 May 2010

International Civil Aviation Organization

WORKING PAPER

AERONAUTICAL COMMUNICATIONS PANEL (ACP)

16th MEETING OF WORKING GROUP M (Maintenance)

Paris, France 17 – 19 May 2010

Agenda Item 1: Status of On-Going Data Communications Programs; (c) Surface Wireless Communications

FAA/NASA Aeronautical Mobile Airport Communications System (AeroMACS) Development Status

(Presented by James M. Budinger, NASA Glenn Research Center)
(Prepared by Ward Hall, ITT Corporation;
James Budinger, Jeffery Wilson, Robert Dimond, NASA;
Rafael Apaza, Brent Phillips, FAA)

BYU

4.2 <u>Spectrum Allocation</u> – The World Radiocommunications Conference held in November 2007 (WRC-07) approved the addition of an Aeronautical Mobile Route Service [AM(R)S] allocation within the 5091-5150 MHz band to the ITU-R International Table of Frequency Allocations. This decision removed prior limitations in the so-called Microwave Landing System (MLS) Extension Band for, "support of navigation/ surveillance functions," only. The new AM(R)S designation provides protected spectrum for safety and regularity of flight applications. This enables the ICAO to develop international standards for an airport mobile surface wireless communications networks.

4.2.1 The WRC-07 allocation limits communications with aircraft to only when wheels are in contact with the airport surface. The FAA interpretation of the WRC-07 allocation allows for the inclusion of fixed airport assets within the mobile wireless communications network to the extent those assets directly impact safety and regularity of flight. Examples of such fixed assets include communications, navigation, and surveillance equipment that produce data used for control of aircraft and other vehicles movement on the surface.

4.2.2 The 5091-5150 MHz band includes co-allocations for non-geostationary satellite feeder links such as the GlobalStar constellation, and for aeronautical telemetry such as control and monitoring performance of developmental aircraft. No interference to or from other occupants in the band is allowed.

4.2.3 This new frequency band is ideal for airport surface wireless networks with short range (~10 km or less sector coverage) and high aggregate data throughput (up to 10s of Mb/s). Glenn holds multiple licenses to operate prototype equipment in this band to experiment with the performance of the proposed AeroMACS. An additional AM(R)S allocation in the 5000-5030 MHz band has been proposed for WRC-2011. Accordingly, the design of the AeroMACS takes this potential, additional allocation into consideration, and does not preclude the direct translation of equipment designed for 5091-5150 MHz from operating in this lower 30 MHz of spectrum when and if it becomes available.

4.3 <u>Spectrum Interference</u> – For the 5091-5150 MHz band, the issue of immediate interest is interference from AeroMACS into the Mobile-Satellite Service (MSS) feeder uplinks. Practical limits on AeroMACS trans-missions from airports are being established so that the threshold of interference into MSS is not exceeded. This threshold as established from Annex 1 to Resolution 418 of WRC-07 is 2 percent of the satellite receiver thermal noise equivalent.

Ground-Based Radar

BYU

The ground based radar systems operating in the 5650 – 5925 MHz frequency band are a sophisticated mixture of tracking and/or instrumentation radars. The majority of these systems are located at the various missile test ranges within CONUS. The common features of all these radars are

(a) high peak pulse power of 150 kW to 5000 kW

(b) short pulse widths ranging from 0.1 to 10 microseconds

(c) variable pulse repetition rates

(d) P0 and/or P9 modulation designators

(e) pencil beam antennas of the order of 1 and gains on the order of 35 to 45 dBi

(f) antenna pointing capabilities which usually cover the complete upper hemisphere above the radar location.

A brief list of ground based radar systems with their use and peak power outputs is shown in Table 8.

W. Grant, J. Carroll, and C. Chilton, "Spectrum Resource Assessment in the 5650-5925 MHz Band," NTIA Report-83-115, January 1983. (retrieved from http://transition.fcc.gov/ib/files/1_08_02/ntia_sec3.pdf)

Ground-Based Radar

Table 8. Typical Ground Based Radar Systems, Uses, and Powers

Radar	Use	Peak Power (kW)	Necessary Bandwidth MHz
AN/FPO-4	Instrumentation	3000	25.4
AN/FPO-6	"	2800	25.4
AN/FPQ-10	"	1000	25.4
AN/FPQ-13	"	5000	4.2
AN/FPQ-14	"	2800	25.4
AN/FPQ-15	"	5000	6.4
AN/FPS-16	"	≤5000	25.4
AN/FPS-105	"	1000	25.4
AN/MPQ-32	Artillery Locator	5000	12.7
AN/MPS-19	Tracking	250	8.0
AN/MPS-25	Instrumentation	1000	25.4
AN/MPS-26	Tracking	250	25.4
AN/MPS-36	Instrumentation	1000	25.4
SCR-584	"	250	8.0
AN/TPQ-18	"	2800	25.4
AN/TPQ-39	"	250	4.2
AN/TPS-68	Weather	150	3.2
VEGA 6104	Control of Remotely Piloted Vehicles	3.5	25.4
VEGA 657	" " "	1.5	31.8
VEGA 811C	" " "	1.2	21.2

Government parts – MIL-STD-196E decoder ring

BYU

Army Navy **AN/XYZ-99** model number of specific type

Installation

A = piloted aircraft
B = underwater mobile, submarine
C = cyptographic
D = pilotless carrier
F = fixed ground
G = general ground use
K = amphibious
M = mobile (ground)
P = portable
S = water
T = transportable (ground)
U = general utility
V = vehicular (ground)
W = water surface and underwater combined
Z = piloted-pilotless airborne vehicles combined

Type of Equipment

A = invisible light, heat radiation
B = comsec
C = carrier – electronic wave/signal
D = radiac
E= laser
F= fiber optics
G = telegraph or teletype
I = interphone and public address
J = electromechanical
K = telemetering
L = countermeasures
M = meteorological
N = sound in air
P = radar
Q = sonar and underwater sound
R = radio
S = special or combination
T = telephone (wire)
V = visual and visible light
W = armament
X = facsimile or television
Y = data processing or computer
Z = communications

Purpose

A = auxiliary assembly
B = bombing
C = communications
D = direction finder, recon., surveillance.
E = ejection and/or release
G = fire control or searchlight directing
H = recording/reproducing
K = computing
M = maintenance/test assemblies
N = navigational aids
Q = special or combination
R = receiving/possible detecting
S = detecting/range and bearing. search
T = transmitting
W = automatic flight or remote control
X = identification and recognition
Y = surveillance (search, detect and multiple target tracking) and control (both fire control and air control)
Z = secure

Radar Systems (1)

BYU

System	Type	Band	Mfg	SAGE	Notes
AN/CPS-1	S	S/X	MIT Rad Lab	N	MEW, or "microwave early warning radar"; 3000 MHz, range up to 200 miles
AN/CPS-4	H	S	MIT Rad Lab	N	Often paired w/ AN/FPS-3 during early '50s at permanent sites
AN/CPS-5	S	L	Bell Labs, GE	N	Lashup w/TPS-10 HF
AN/CPS-6,6A,6B	S/H	S	MIT Rad Lab	N	Combined search & height-finder radar
AN/FPQ-16 PARCS	T		Raytheon	N	Phased-Array Radar, originally part of the Safeguard ABM system
AN/FPS-10	S	S	MIT Rad Lab	N	Stripped version of AN/CPS-6B. 13 in the permanent network
AN/FPS-100	S	L	Bendix	Y	Modified AN/FPS-20
AN/FPS-107,-107V1,-107V2	S	L	Westinghouse	Y	Modification to AN/FPS-7
AN/FPS-108	T	L	Raytheon	N	Cobra Dane; located on Shemya Island
AN/FPS-115	S	UHF	Raytheon	N	PAVE PAWS Missile-Warning Radar, first model, two radar faces; originally installed at Cape Cod AFS, MA, and Beale AFB, CA, and later at Robins AFB, GA, and Eldorado AFS, TX. Upgrades include AN/FPS-120, AN/FPS-123, and AN/FPS-126 models.
AN/FPS-116	H	S	GE (now LMCO)	Y	Modernized AN/FPS-6 & AN/FPS-90 for JSS
AN/FPS-117	3D	L	GE (now LMCO)	N	3D radar used at Alaskan sites and on the North Warning System (NWS)
AN/FPS-118	S	LF	GE (now LMCO)	N	Over-the-Horizon Backscatter (OTH-B)
AN/FPS-120	S	UHF	Raytheon	N	PAVE PAWS Missile-Warning Radar, upgraded from AN/FPS-115 model, two (2) radar faces; presently installed at Thule AB, Greenland (BMEWS Site 1).

Adapted from http://www.radomes.org/museum/equip.php (accessed 19 October 2011)

Radar Systems (2)

BYU

AN/FPS-123	S	UHF	Raytheon	N	PAVE PAWS Missile-Warning Radar, upgraded from AN/FPS-115 model, two (2) radar faces; presently installed at Cape Cod AFS, MA; Beale AFB, CA; and Clear AFS, AK (BMEWS Site 2).
AN/FPS-124	S	S	Unisys	N	Short-Range Radar used in the modern North Warning System (NWS); cylindrical array, electronic scanning
AN/FPS-126	S	UHF	Raytheon	N	PAVE PAWS Missile-Warning Radar, upgraded from AN/FPS-115 model, three (3) radar faces; presently installed at RAF Fylingdales Moor, England (BMEWS Site 3).
AN/FPS-129	D	X	Raytheon	N	HAVE STARE; deployed in northern Norway to detect missile launches
AN/FPS-14	G	S	Bendix	Y	Gap-filler radar with magnetron; 65 nmi.
AN/FPS-16	T	C	NRL and RCA		Space launches, Project Mercury, NASA MFSN
AN/FPS-17	T	VHF	GE	N	Missile-tracking radar
AN/FPS-18	G	S	Bendix	Y	Gap-filler radar with klystron; 65 nmi.
AN/FPS-19	S	L	Raytheon	Y	The Primary Search Radar for DEW-Line sites in Canada and Alaska
AN/FPS-20,20A,20B	S	L	Bendix	Y	AN/FPS-3 with AN/GPA-27; variants include the AN/FPS-64,65,66,67,68,72,87,91,93,100
AN/FPS-23	S	UHF	Motorola	N	AN/FPS-23 radars were continuous-wave (CW) systems that were comprised of geographically-separated AN/FPT-4 Fluttar Transmitters and AN/FPR-2 Fluttar Receivers.
AN/FPS-24	S	VHF	GE	Y	Frequency-diverse search radar designed for SAGE. 85-ton antenna.
AN/FPS-26,26A	H	C	AVCO	Y	Frequency-diverse height-finder radar designed for SAGE. Seven -26s later modified by AVCO to AN/FSS-7 SLBM D&W.

Radar Systems (3)

BYU

AN/FPS-27,27A,27B	S	S	Westinghouse	Y	Frequency-diverse search radar designed for SAGE. Search alt. 150K, 220-nmi range
AN/FPS-28	S	VHF	Raytheon	Y	Frequency-diverse search radar designed for SAGE. Field tested at Houma AFS, LA
AN/FPS-3,3A	S	L	Bendix	Y	Predecessor to the AN/FPS-20
AN/FPS-30	S	L	Bendix	Y	DEW-Line radar used in Greenland
AN/FPS-31	S	VHF	MIT Lincoln Labs	Y	Frequency-diverse search radar designed for SAGE. Antenna 120'x16'; field tested at West Bath, ME.
AN/FPS-35	S	VHF	Sperry Gyroscope	Y	Frequency-diverse search radar designed for SAGE. 70-ton antenna.
AN/FPS-3B	S	L	Bendix	Y	Incorporated AN/GPA-27 increased search alt to 65K
AN/FPS-4	H	X	RCA	N	Updated TPS-10
AN/FPS-49	T	UHF	RCA	N	BMEWS Tracker, 105 tons on azimuth bearing
AN/FPS-5	S		Hazeltine	N	Limited deployment in 1950s
AN/FPS-50	S	UHF	GE	N	BMEWS Detection Radar, scanned stationary antennae
AN/FPS-6,6A,6B	H	S/C	GE	Y	High-power variants include AN/FPS-89 and AN/FPS-90; mobile version is AN/MPS-14
AN/FPS-63	G	S	Budd	Y	Frequency-diverse gap-filler radar, similar to AN/FPS-74; neither was ever fielded.
AN/FPS-64,65,66,67,68,72	S	L	Bendix	Y	Modified versions of AN/FPS-20
AN/FPS-7,7A,7B,7C,7D	S	L	GE	Y	Search alt 100K, 270 miles
AN/FPS-74	G	S	Budd	Y	Frequency-diverse gap-filler radar, similar to AN/FPS-63; neither was ever fielded.

Radar Systems (4)

BYU

AN/FPS-8	S	L	GE	Y	Variants: AN/GPS-3, AN/MPS-11, AN/FPS-88.
AN/FPS-85	T	UHF	Bendix	N	Spacetrack radar at Eglin AFB, FL
AN/FPS-87A	S	L	Bendix	Y	Based on AN/FPS-20
AN/FPS-88	S	L	GE	Y	Updated version of AN/FPS-8
AN/FPS-89	H	S	GE	Y	Improved version of AN/FPS-6
AN/FPS-90	H	S	GE	Y	Hi-powered version of AN/FPS-6
AN/FPS-91	S	L	Bendix	Y	Version of AN/FPS-20
AN/FPS-92	T	UHF	RCA	N	Upgraded AN/FPS-49 BMEWS tracker
AN/FPS-93	S	L	Raytheon	Y	Modified AN/FPS-20
AN/FRT-80 OTH-F TX	D			N	Over-the-Horixon Forwardscatter (OTH-F), 440L System, transmitter; used to detect missile launches
AN/FSA-10	DP			Y	Television convertor-display unit for the SAGE gap-fillers. This unit used a television camera to superimpose the gap-filler data on the LRR scope. It could display up to six GFAs' radar data.
AN/FSQ-32	DP		IBM	Y	Super SAGE Computer (not fielded)
AN/FSQ-7	DP		IBM	Y	SAGE Direction-Center Computer
AN/FSQ-76 OTH-F RX	D			N	Over-the-Horixon Forwardscatter (OTH-F), 440L System, receiver; used to detect missile launches
AN/FSQ-8	DP		IBM	Y	SAGE Control-Center Computer
AN/FSS-7	S	C	AVCO	Y	FPS-26 modified by AVCO to perform SLBM Detection & Warning duties
AN/FST-1	DP			Y	Radar Data Processing System used at SAGE gap-filler radar sites. Analog to digital convertor; slowed-down video unit.

Radar Systems (5)

BYU

AN/FST-2	DP			Y	Radar Data Processing System used at SAGE long-range radar sites
AN/FSW-1	DP			Y	Remote control unit for gap fillers. There was one unit at the prime LRR, and another at the GFA.
AN/FYQ-156				N	Atmospheric Early Warning System, Battle Control System - Fixed (BCS-F) - more info to follow
AN/FYQ-47,49	DP		Burroughs	Y	Replacement for AN/FST-2; FYQ-49 was a FYQ-47 without height racks (used at FAA data-tie radar sites)
AN/FYQ-93	DP		Hughes	N	H5118ME-based computer system, replacement for SAGE; used at JSS ROCC's/SOCC's (now SAOC's)
AN/GKA-5	TDDL		RCA	Y	Time-Division Data Link. Used at the GATR sites for SAGE radar sites and certain Direction Centers (sometimes followed with the AN/FRT-49 Amplifier / Transmitter), and also used at BOMARC "B" model missile launch sites.
AN/GPA-98				N	ECM Simulator
AN/GPS-3	S	L	GE	Y	Variant of the AN/FPS-8
AN/GPS-T2	Simu		RCA	N	Used a 70 mm film to simulate radar data
AN/GPS-T4	Simu			N	Simulated 12 individually controllable (speed, altitude, bank, climb and turn rates plus IFF) radar targets
AN/GRR-24	GATR			Y	Ground-air radio equipment (GATR)
AN/GRT-22	GATR			Y	Ground-air radio equipment (GATR)
AN/GSQ-235				N	ROCC-AWACS Digital Information Link (RADIL)
AN/MPS-11	S	L	GE	N	Mobile version of the AN/FPS-8
AN/MPS-14	H	S	GE	Y	Mobile version of the AN/FPS-6

Radar Systems (6)

BYU

AN/MPS-16,-16A,-16B	H	C	Avco	N	The AN/MPS-16, -16A and -16B are high-power, long-range, mobile height finders. The radar sets are capable of accepting azimuth control from, and furnishing height data to, search radar sets equipped with either Indicator Group OA-175/FPS-3 or AN/UPA-35. These are normally transported on four M-35 trucks.
AN/MPS-7	S	L	Bendix	N	Mobile version of the FPS-3
AN/MPS-8	H	X	RCA	N	Mobile version of the AN/FPS-4
AN/TPQ-39	T	C	GE		Instrumentation tracking radar
AN/TPS-10,10A	H	X	MIT Rad Lab	N	Zenith built -10A post-war; dubbed "Little Abner."
AN/TPS-1B,1C	S	L	Bell Telephone Labs	N	WW-II 120-nmi, 10,000 ft.
AN/TPS-1D	S	L	Bell Telephone Labs	N	Mobile search radar; "Tippsy 1 Dog"
AN/TPS-37	H	C	AVCO		
AN/TPS-40	H	C	AVCO		Related tn AN/MPS-16
AN/TPS-43	S			N	Tactical/Mobile search radar
AN/TPS-44	S			N	Tactical/Mobile search radar
AN/TPS-75	TAC			N	Tactical 3D air battle management radar
AN/UPA-35				N	Manual Ops PPI scope
AN/UPX-14,21	SIF			Y	Selective Identification Feature (SIF) / Identification Friend or Foe (IFF); used in conjunction with search radars

Radar Systems (7)

ARSR-1	S	L	Raytheon	N	FAA search radar, similar to FPS-20
ARSR-2	S	L	Raytheon	N	FAA upgrade to ARSR-1
ARSR-3,3D	S	L	Westinghouse	N	FAA D model had height-finder capability
ARSR-4	S/H		Westinghouse	N	FAA 3D system began deploying in 1990s
ATCBI-5	SIF			Y	FAA version of SIF, for "Air Traffic Control Beacon Interrogator"; also called "secondary radar" by the FAA
SCR-270	S		Westinghouse	N	The Pearl Harbor radar
SCR-271	S		Westinghouse	N	variant of SCR-270
TDX-2000			Sensis	N	Target Data Extractor - used for preparing FAA radar target data for USAF use, among other things.

AN/FPS-6

Type of Radar: Height Finder

	S-Band	C-Band
Frequencies	2700 to 2900 MHz	5400 to 5900 MHz
Peak Power	5 MW	3 MW
Pulse width	2 μs	2 μs
PRF	400 pps	400 pps
Coverage (vertical)	-2° to +32°	
Resolution (az.)	3.2°	
Beamwidth (az.)	3.2°	
Elevation accuracy	1,000 ft.	
Scanning Rate	20 or 30 cpm	
Range	200 nmi	
Altitude	75,000 ft.	

AN/FPS-16

The NASA Manned Space Flight Network (MSFN) land based C-band pulse radar types consist of the AN/FPS-16, AN/MPS-39, AN/FPQ-6 and the AN/TPQ-18.

Radar Ground Station Characteristics

	AN/FPS-16	AN/FPQ-6
Frequency band (MHz) . .	5400-5900	5400-5900
Peak power (MW)	1.3	3.0
Antenna size (meters)	3.9	9.2
Antenna gain (dB)	47	52
Receiver noise figure (dB)	6.5	8
Angle precision (units) . . .	0.15	0.1
Range precision (meters)..	4.5	3.0

AN/FPS-16, Wikipedia, http://en.wikipedia.org. Accessed 19 October 2011.

AN/FPS-16

```
AN/FPS-16 RADAR SET
TYPICAL TECHNICAL SPECIFICATIONS
------------------------

Type of presentation: Dual-trace CRT,
   A/R and R type displays.

Transmitter data -
   Nominal Power: 1 MW peak (fixed-frequency magnetron);
                  250 kW peak (tunable magnetron).
   Frequency
      Fixed: 5480 plus or minus 30 MHz
      Tunable: 5450 to 5825 MHz

Pulse repetition frequency (internal):
   341, 366, 394, 467, 569, 682, 732, 853,
   1024, 1280, 1364 or 1707 pulses per second

Pulse width: 0.25, 0.50, 1.0 µs

Code groups: 5 pulses max, within 0.001 duty cycle limitation of transmitter.
```


AN/FPS-16, Wikipedia, http://en.wikipedia.org. Accessed 19 October 2011.

AN/FPS-16

Radar receiver data –

Noise Figure: 11 dB

Intermediate Frequency: 30 MHz

Bandwidth: 8 MHz

Narrow Bandwidth: 2 MHz

Dynamic Range of Gain Control: 93 dB

Gate width

Tracking: 0.5 μs, 0.75 μs, 1.25 μs

Acquisition: 1.0 μs, 1.25 μs, 1.75 μs

Coverage

Range: 500 nm

Azimuth: 360° continuous

Elevation: minus 10 to plus 190 degrees

Servo bandwidth

Range: 1 to 10 Hz (var)

Angle: 0.25 to 5 Hz (var)

Operating power requirements: 115 V AC, 60 Hz, 50 kV·A, 3 phase

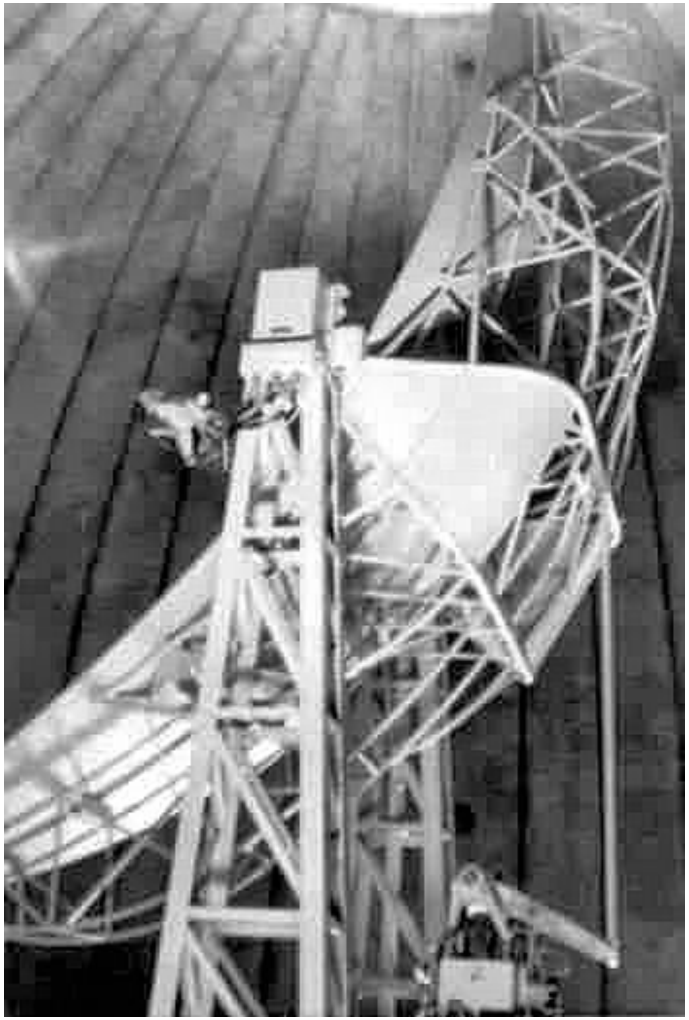
AN/FPS-26

Height-finder radar designed for SAGE deployed in 1960s

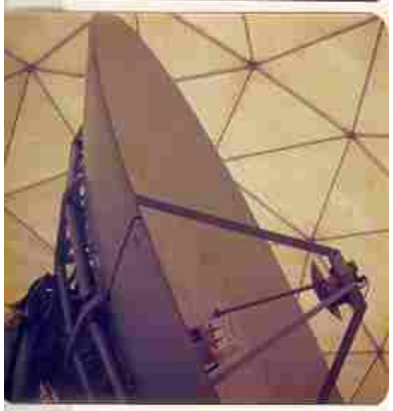
Frequency-diversity radar

Frequency band: 5400 to 5900 MHz

Power: 2 MW (pulsed)



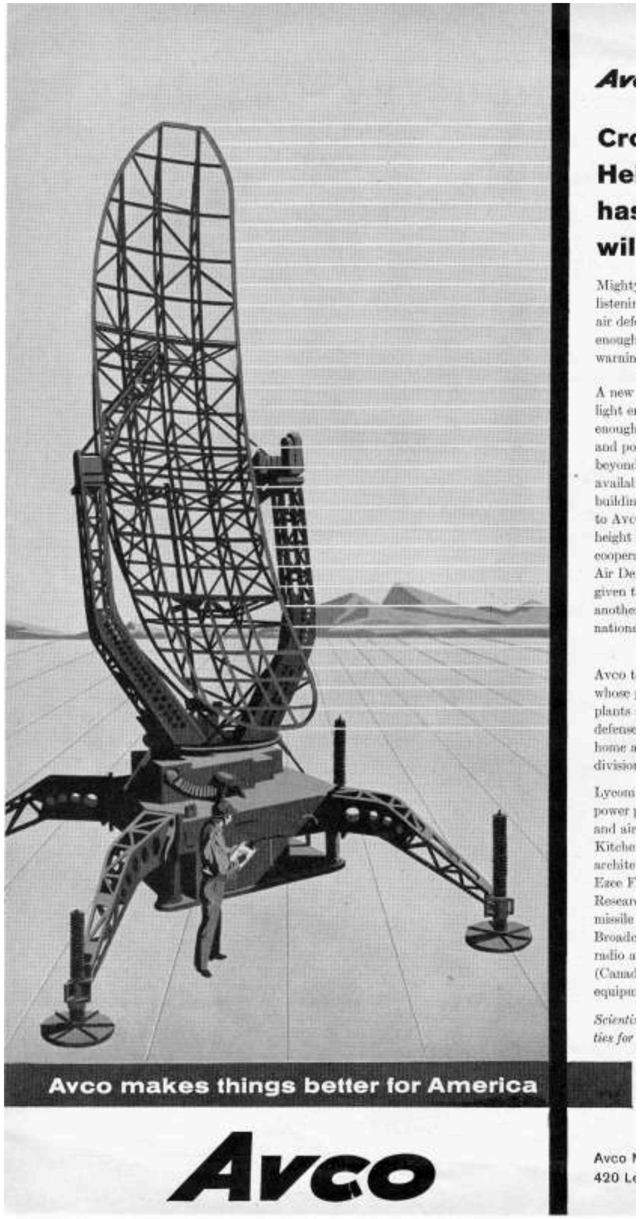
AN/FSS-7



The AN/FSS-7 (modified AN/FPS-26) was a height-finder designed to detect submarine-launched missiles. The system was deployed to 7 sites:

Charleston AFS, ME
Fort Fisher AFS, NC
Laredo AFS, TX
MacDill AFB, FL
Mill Valley AFS, CA
Mount Hebo AFS, OR
Mount Laguna AFS, CA

AN/MPS-16



A high-power, long-range, mobile height finder.

Specifications

frequency	5200 to 5300 MHz
PRF	300 to 364 ppm nominally 360 ppm
pulsewidth:	2.5 µseconds
peak power	1 MW
average power:	900 watts
displayed range	200 nautical miles (370 km)
beamwidth	β:2,4° ε:0,6°
antenna rotation	0 to 8 rpm
noise figure	10 dB
gain	43 dB
antenna	21′ (h) by 5′5′′ (w)

AN/TPQ-39

BYU

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TPQ-39 - Instrumentation Tracking Radar

Frequency:        5450 to 5825 MHz
Power Output:     250 kw
Pulse Width:      1.52 μs, 2 pulses at 0.75 μs
PRR:              640 pps
Range:
Vertical Coverage: 0 to 90
Horizontal Coverage: 360
Antenna:
     Shape:       Parabolic
     Gain:        37 dBi
Manufacturer:     General Electric
```

AN/TPS-40

AN/TPS-40 is a mobile high-powered, long-range height finder radar.

Specifications

Frequency	5280 MHz
Range	200 nmi
Coverage	-2° to 32° (elevation)

RIR-778

RANGE INSTRUMENTATION RADAR

The three RIR-778 (Range Instrumentation Radar) are precision, computer-based, single-object-tracking systems that are designed to obtain continuous and highly accurate position of targets for flight test programs.

- X- and C-band, 8.5-9.6 and 5.4-5.9 GHz
- 250Kw peak power, magnetron based
- 0.25, 0.5 and 1.0 microsecond gated CW transmitted pulse width at 160, 320, 640 and 1024 PPS
- Output data rate (TSPI information), 100 Hz
- Auto acquisition using Raster scan or Circular scan
- Option of angle tracking with optical contrast tracker

RIR-778 C-band

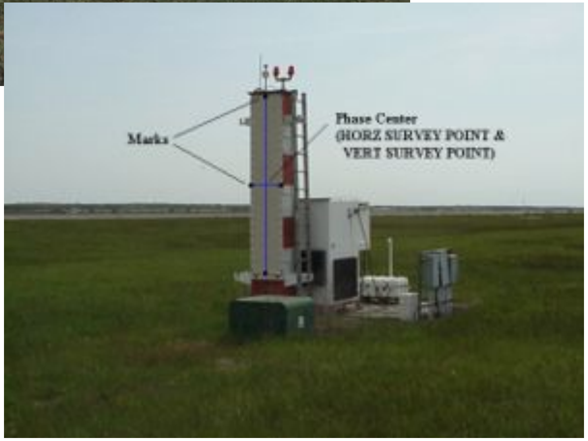
RIR-778 X-band

From the "Radar" brochure, Atlantic Test Ranges, Patuxent River, MD, December 2010.

FAA MLS

Microwave Landing System (MLS)

- precision landing system
- scanning beams sent towards approaching aircraft
- aircraft in scanned volume calculates position by measuring arrival time of the beams
- frequencies: 5031 – 5091 MHz
- A few systems became operational in early 1990s
- Replaced by GPS-based WAAS
- All MLS systems in USA have been turned off.
- A **LOT** of multipath propagation studies conducted in 1980s: more than you ever wanted to know about C-band multipath at JFK, Lambert Field – St. Louis, Miami International, Tulsa International, etc.



Galileo L- versus C-Band Study

M. Irsigler, et al, "Aspects fo C-Band Satellite Navigation: Signal Propagation and Satellite Signal Tracking," Research Report, Institute of Geodesy and Navigation, University of Munich.

Signal Parameters		GPS L1-C/A	GPS L1-P(Y)	Galileo C
Carrier Wave	f [MHz]	1575.42	1575.42	5019.86
	λ [m]	0.19	0.19	0.06
Chipping Rate [Mcps]		1.023	10.23	8.184
Chip Length [m]		293.05	29.31	36.63
Data Rate [bps]		50	50	150
Predet. Int. Time [s]		0.02	0.02	0.0067
Bandwidth [MHz]		2.046	20.46	20
Chip Shape		RECT	RECT	RC

Parameter	C	L	Factor
Free space Loss	-	+	10
Ionospheric Path Delay	+	-	10
Ionospheric Amplitude Scintillation	+	-	5.6
Ionospheric Phase Scintillation	+	-	3.1
Ionospheric Refraction	+	-	10
Ionospheric Doppler Shift	+	-	3
Tropospheric Path Delay	o	o	---
Tropospheric Amplitude Scintillation	-	+	2
Tropospheric Phase Scintillation	-	+	3
Water Vapor and Oxygen (worst case)	-	+	0.2dB
Rainfall Attenuation (worst case)	-	+	4.5dB
Clouds and Fog (worst case)	-	+	0.8dB
Foliage Attenuation	-	+	1dB/m

Parameter	C	L
DLL Tracking Performance	o	o
PLL Tracking Performance	-	+
Code Noise	o	o
Phase Noise	+	-
Code Multipath	o	o
Phase Multipath	+	-
Carrier Smoothing Efficiency	+	-

Link Budget Parameter	Unit	GPS L1	C
Effect. C/N_0 (tracking loop)	dBHz	45	45
Implementation loss	dB	6	6
C/N_0 @ user antenna output	dBHz	51	51
Power level (user ant. output)	dBW	-153	-153
Gain of user antenna	dBic	3	3
Power level (user ant. input)	dBW	-156	-156
Depointing loss (user)	dB	0.25	0.25
Polarization Mismatch Loss	dB	3	3
Tropospheric attenuation[3]	dB	0.4	5.9
Free space loss (E=10°)	dB	185.4	195.4
Depointing loss (satellite)	dB	0.25	0.25
EIRP	dBW	33.3	48.8
Gain of satellite antenna	dBic	14.0	14.0
Required satellite antenna input power	**dBW W**	**19.3 85.1**	**34.8 3020.0**

To provide an effective C/N_0 of 45dB-Hz, the satellite antenna input power at C-Band will have to be approximately 35 times higher than at L-Band. Note, however, that the computed values are the result of a worst case analysis. The actual required satellite antenna input power strongly depends on the receiver quality (implementation loss), the type of user antenna (phased array vs. omni directional) and the actual atmospheric attenuation. Whichever scenario is assumed, the required satellite antenna input power at C-Band will be significantly higher than at L-Band (assuming identical conditions at both bands).

Conclusion

C-Band navigation offers both benefits and drawbacks. Although it might be feasible to overcome the technical issues, it is uncertain that a (future) C-Band navigation system can compete with current sophisticated L-Band equipment. Furthermore, the L-Band performance will be permanently upgraded in the near future (GPS modernization, Galileo L-Band). Therefore, satisfactory acceptance of a C-Band system by the SatNav community is doubtful. However, a future C-Band signal might be an interesting option in combination with L-Band signals. Moreover, technological progress might balance some of the disadvantages and might allow C-Band navigation within a future generation of Galileo.

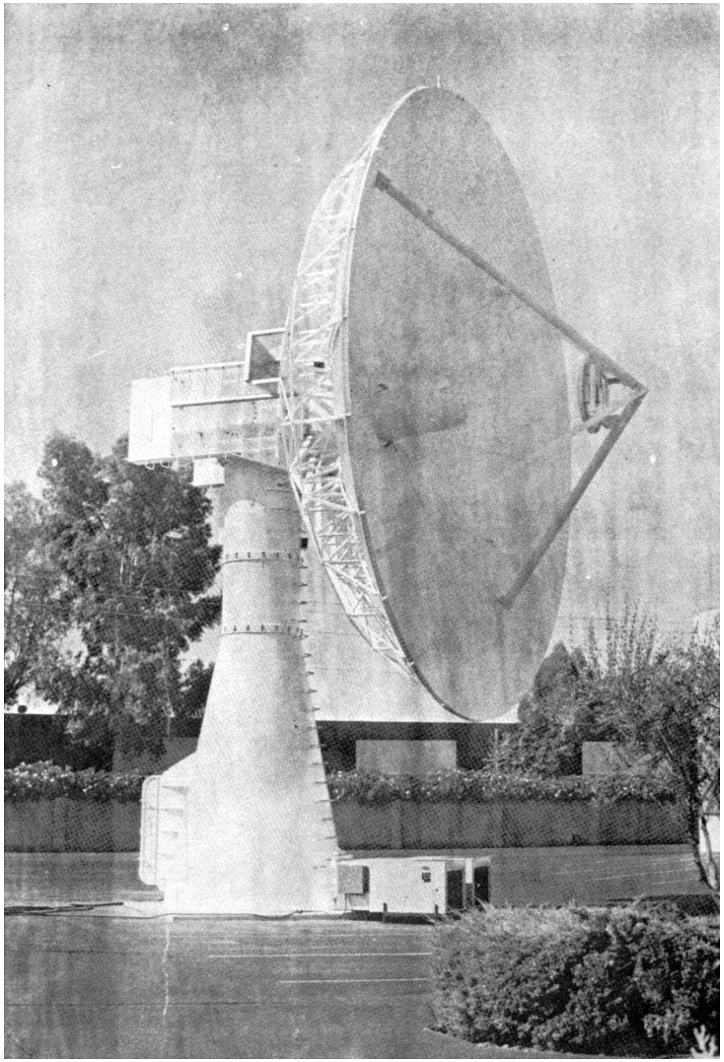
Dual S-/X-Band Telemetry Tracking System

B. Bollerman, et al, "High-Performance LANDSAT/SPOT Dual S-/X-Band Telemetry Tracing and Receiving System," in *Proceedings of the International Telemetering Conference*, San Diego, CA, October 1986.

- Tracking LANDSAT satellites (polar orbit)
- Dual-band: 2265.5 MHz, 2287.5 MHz, 8212.4 MHz
- Cassegrain feed + 10m parabolic reflector
- Tracking
  - 10 deg/sec^2 acceleration.
  - Elevation-over-azimuth tracking pedestal.
  - Wide dynamic range: very slow horizon tracking, very fast near-overhead tracking
  - Meets strict requirements for narrow-beam X-band tracking:

    acceleration error < 0.1 degree

    acceleration error constant ≥ 90/sec^2



C-Band Drone Tracking Control System

BYU

J. Miller and P. Tannenholz, “An Improved Drone Tracking Control System Transponder,” in *Proceedings of the International Telemetering Conference*, San Diego, CA, October 1990.

- Control for unmanned air and/or sufrace vehicles (targets)
- Tunable over 5400 to 5900 MHz with a frequency drift less than ± 1 MHz.
- AGC with 75 dB dynamic range.
- RF rejection from (from RADAR)

UAV Links

BYU

Figure XVII - DATA LINKS - UAV Systems With Operational Range of > 1000 m

DEPLOYING COUNTRY	UAV SYSTEM	STATUS In Serv.	STATUS On Order	UAV SYSTEM MANUFACTURER	DATALINKS C2 Up	DATALINKS Imagery Down	CIVILIAN APPLIC.
Australia	Aerosonde	♦		Aerosonde Robotic Aircraft			♦
Bahrain	Dragon		♦	BAI Aerosystems, USA			
Belgium	Epervier Hunter B	† 	 ♦	MBLE Défense †, Belgium IAI, Israel & Eagle Cons., Belgium	 C-band	 C-band	
Bulgaria	Vigilant 2000	♦		Thomson & Techno-Sud Ind.,France	S-band	S-band	♦
Denmark	Sperwer	♦		Sagem, France	Ku-band	Ku-band	(♦)
Finland	Ranger		♦	Oerlikon-Contraves, Switzerland	UHF	L/S-band	
France	Fox MLCS Heliot CL289 Crecerelle Hunter Vigilant 2000	 ♦ ♦ 	♦ ♦ ♦ ♦	CAC Systèmes, France CAC Systèmes, France Aérospatiale & Dornier Sagem, France IAI, Israel & TRW, USA Thomson & Techno-Sud Ind.	S-band S-band Not appl. 300-600 MHz C-band S-band	S-band S-band Not appl. 300-600 MHz C-band S-band	♦
Germany	CL289 KZO (Brevel) Taifun LUNA	♦ ♦	 ♦ ♦	Dornier & Aérospatiale STN Atlas, Germany STN Atlas, Germany EMT, Germany	Not appl. Ku-band ? 5 GHz	Not appl. Ku-band ? 5 GHz	
India	Searcher Nishant		♦	IAI, Israel ADE-Bangalore, India	C-band L-band	C-band L-band	
International Coop. Dvpmt	Brevel Tucan	♦		Eurodrone (STN Atlas&Matra)	Ku-band C-band	Ku-band C-band	
Israel	Scout Searcher Hermes 450S	♦ ♦ ♦		IAI, Israel IAI, Israel Silver Arrow, Israel	C-band C-band C/L-band	C-band C-band C/L-band	
Italy	Mirach 20 Mirach 26 Mirach 150	♦ ♦ ♦		Meteor, Italy Meteor, Italy Meteor, Italy	420 MHz L & J-band L & J-band	1500 MHz L & J-band L & J-band	

UAV Links

Netherlands	Sperwer LUNA	◆	 ◆	Sagem, France EMT, Germany	Ku-band 5 GHz	Ku-band 5 GHz	
Romania	Shadow 600 Vigilant	◆ ◆		AAI, USA Techno-Sud Ind.	C-band S-band	C-band S-band	 ◆
Singapore	Scout Searcher II Upcoming RFI	◆ ◆		IAI, Israel IAI, Israel Undecided	C-band C-band ?	C-band C-band ?	
South Africa	Seeker Vulture	◆	 ◆	Kentron, South Africa ATE, South Africa	UHF UHF	C-band C-band	(◆)
South Korea	Bijo Searcher II Shadow 400	 ◆	◆ ◆	Daewoo IAI, Israel AAI Corp., USA	C-band C-band C-band	C-band C-band C-band	
Spain	Siva		?	INTA, Spain	UHF	S-band	
Sri Lanka	Scout Ongoing RFP	†		IAI, Israel Undecided	C-band ?	C-band ?	
Sweden	RPG MK III APID Ugglan	† ◆	 ◆	Techment, Sweden Scandicraft Systems, Sweden Sagem, France	L-band L-band C-band	L-band L-band C-band	 (◆)
Switzerland	Ranger	◆	◆	Oerlikon-Contraves,Switzerld.	UHF	L/S-band	
Thailand	Searcher II		◆	IAI, Israel	C-band	C-band	
Turkey	Gnat 750 Upcoming RFP	◆		General Atomics, USA Undecided	C-band ?	C-band ?	
UAE-AbuDhabi	Seeker	◆		Kentron, South Africa	UHF	C-band	
UK	Phoenix	◆		GEC Marconi Avionics, UK	Ku-band	?	
USA	Camcopter	◆		Schiebel, Austria	S-band	S-band	◆

UAV Links

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USA	Darkstar	†		Lockheed & Boeing, USA	UHF/MilSatCom Ku-band/SatCom CDL/LOS X-band CDL/LOS	Ku-band/SatCom X-band/SatCom	
	Exdrone	◆		BAI Aerosystems, USA	UHF	D-band	
	Global Hawk	◆		Teledyne Ryan, USA	UHF UHF/MilSatCom CDL/LOS Ku-band/SatCom	Ku-band/SatCom X-band CDL/LOS	
	Hunter	†		TRW, USA & IAI, Israel	C-band	C-band/LOS	
	Outrider	†		Alliant Techsystems, USA	C-band	C-band/LOS & UHF	
	Pioneer	◆		Pioneer UAV, Inc/AAI Corp.	C-band LOS & UHF	C-band/LOS	
	Sentry	◆		S-Tec Corp.	S- or C-band	S- or C-band	
	Pointer	◆		Aerovironment, USA	?	?	
	Gnat 750	◆		General Atomics, USA	C-band/LOS	C-band	
	Predator	◆	◆	General Atomics, USA	UHF/MilSatCom C-band/LOS Ku-CDL	UHF/MilQSatCom Ku-band SatCom	

From P. van Blyenburgh, "UAVs – Current Situation and Considerations for the Way Forward," presented at the Research and Technology Organization (RTO) of the North Atlantic Treaty Organization Course on Development and Operation of UAVs for Military and Civil Applications, Rhode-Saint-Genese, Belgium, September 13-17, 1999. (http://ftp.rta.nato.int/public//PubFulltext/RTO/EN/RTO-EN-009///EN-009-01.pdf)

Market Place (Conference Proceedings)

BYU

- T. Hamilton, “Upgrade of RCB receivers for C-band reception,” in *Proceedings of the International Telemetering Conference*, Las Vegas, NV, October 2009.
- W. Wang, D. Martz, and K. Hutzel, “L-3 Communications 3rd generation telemetry transmitter, ST-5000 L/S/C band architecture and design efforts,” in *Proceedings of the International Telemetering Conference*, San Diego, CA, October 2010.
- C. Oh, K. Lee, and S. Oh, “Refraction effects for tracking error at C-band and S-band frequencies,” in *Proceedings of the International Telemetering Conference*, San Diego, CA, October 2010.
- G. Blake, D. Shea, Y. Hoory, I. Krepner, J. Pein, and O. Nahshon, “Multi-band (L/S/C) nested concentric cavity coaxial mode RF feed for auto-track telemetry systems,” in *Proceedings of the International Telemetering Conference*, San Diego, CA, October 2010.
- Farr, David, “Airborne Antenna Considerations for C-Band Telemetry Systems”, in *Proceedings of the 2011 European Test & Telemetry Conference*, 2011.

- C-band block downcoverter (and upconverter) by TCS – this is not a conference proceedings, but we used it in our channel sounding experiments.

C-Band Block Downconverter

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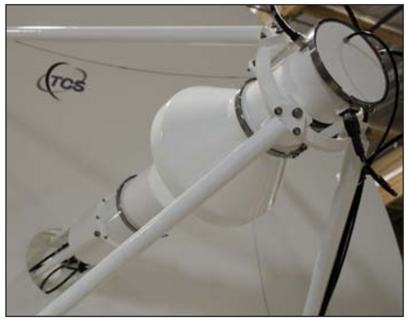
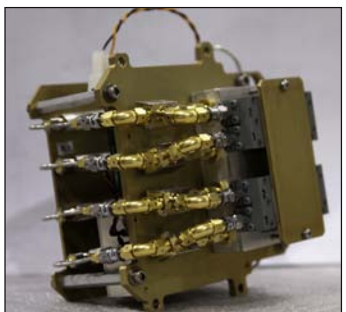
“Feeds and RF Technology,” Data Sheet, Telemetry and Communications Systems, Inc. September 2009.

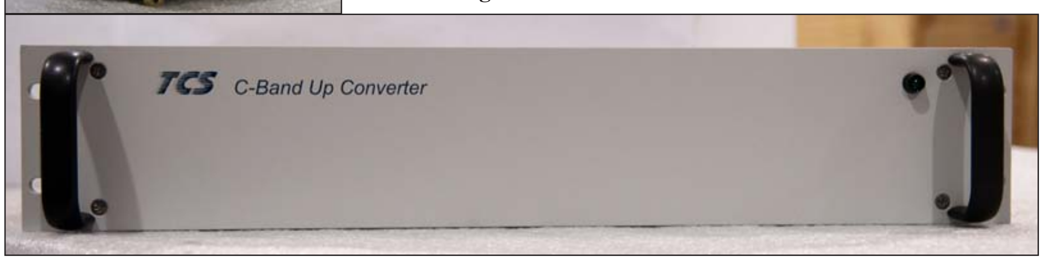
C-Band Conical Scan Feeds (Prime Focus & Cassegrain)



Frequency Range	4400 MHz to 5150 MHz		
G/T *(Typical)*		**8’ Reflector (Cassegrain)**	**10’ Reflector (Cassegrain)**
	4400 MHz	11.2 dB/K	13.2 dB/K
	4940 MHz	12.2 dB/K	14.2 dB/K
	5120 MHz	12.5 dB/K	14.5 dB/K
Scan Speed	20 to 35 Hz, User Selectable		
Polarization	Simultaneous RHCP and LHCP, Vertical and Horizontal, or Switched Linear and Circular		
Options	Downconverter, Upconverter, RF over Fiber, Subreflector for Cassegrain Configuration		



C-Band Downconvert and Upconverter used with our C-Band Autotracking Feeds



Conclusions

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- C-band has long history in Satcom and Radar
- More recent uses for Airport support and UAVs
- Will it work for aeronautical telemetry?
  - Link budget and propagation ➛ need to recover a few dB (increased NF and atmospheric attenuation)
  - C-band tests at EAFB and TPS ➛ YES
  - Multipath Comparison at EAFB ➛ multipath is not worse at C-band
  - Radar ➛ indirect evidence: moving airborne things can be tracked at C-band.
  - Tactical UAVs ➛ indirect evidence: C-band data links are good enough for continued use.
  - Products ➛ satcom and radar products are out there, we are starting to see more C-band products for aeronautical telemetry.