Propagation Terminal Design and Measurements

James Nessel

NASA Glenn Research Center
Advanced High Frequency Branch

November 16, 2015

Keeping the universe connected.

Goals of this Presentation

- To provide the motivation behind conducting propagation measurements.
- To understand the system design for beacon receivers (i.e., propagation terminals) and the types of measurements performed.
- To provide examples as to how propagation data can be/has been used for defining requirements for a satellite communications system.

Relevance/Impact

Why do we need Propagation Data?

It is well understood that the largest uncertainty in Earth-space communications system design lies in the impact of the stochastic atmospheric channel on propagating electromagnetic waves.

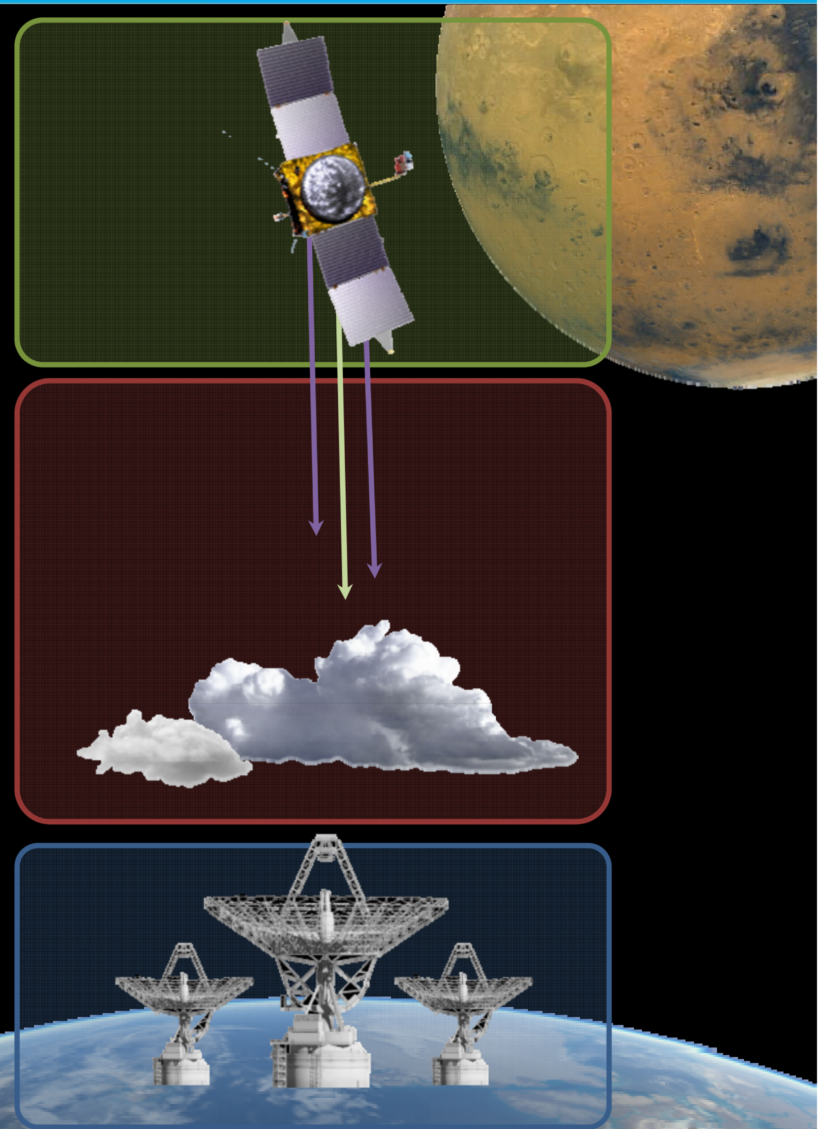
Proper characterization of the atmosphere is necessary to mitigate risk and reduce lifetime costs through the optimal design of the space and ground segment.

As NASA continues to move towards Ka-band operations (currently) and millimeter wave/optical frequencies (future), the need for this data is becoming more and more evident and requested by system designers.

Spacecraft
Antenna Size
Transmit Power
Gimbal Requirements

Propagation Channel
Rain Attenuation
Gaseous Absorption
Depolarization
Free Space Loss

Ground Station
Antenna Size
System Temperature

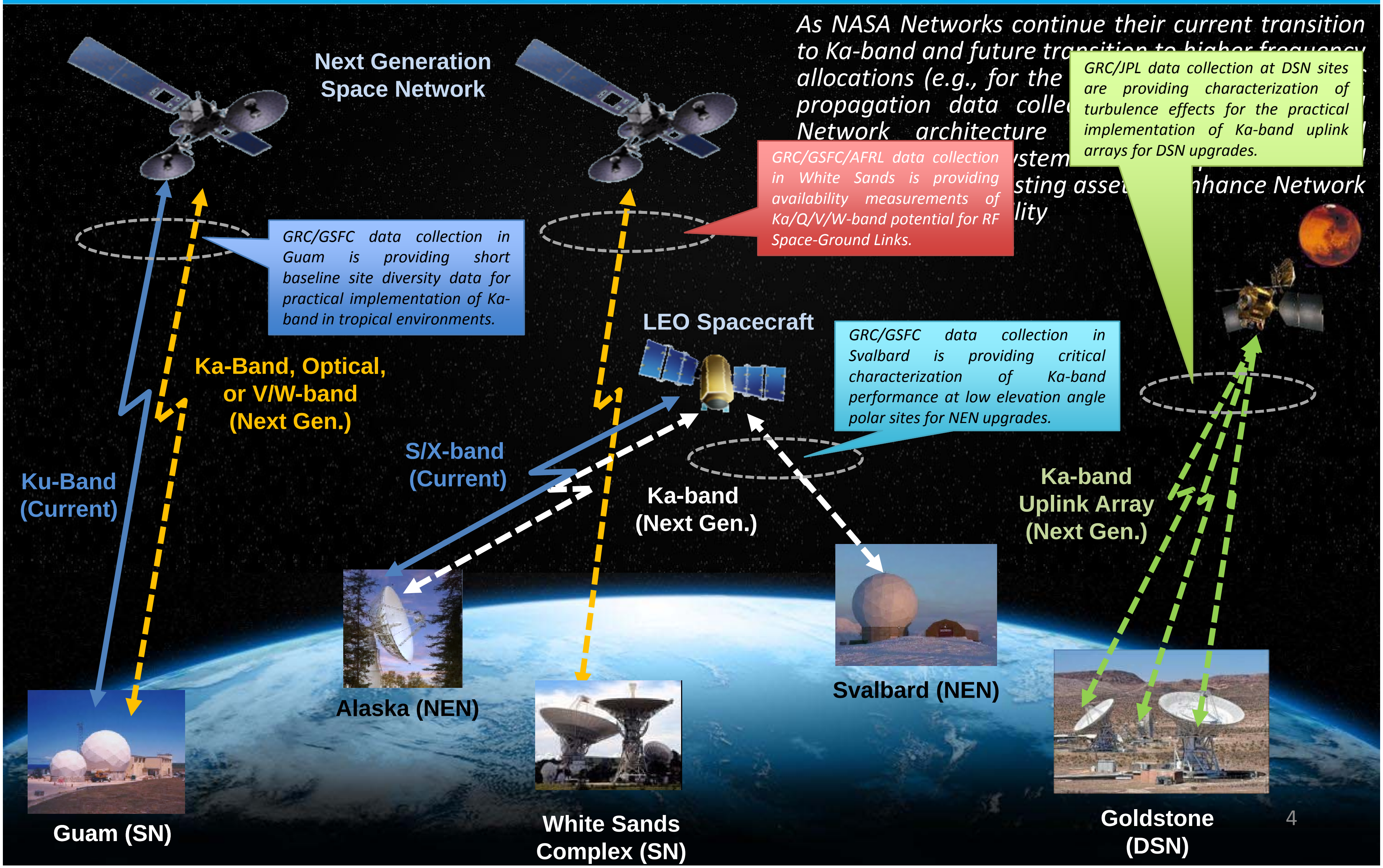


Primary Objectives of Propagation Data Collection:

- **To reduce mission risk and mission costs by ensuring optimal design of SATCOM systems**
- **To improve predictions of global propagation models**

Relevance/Impact

What Propagation Data Helps Support



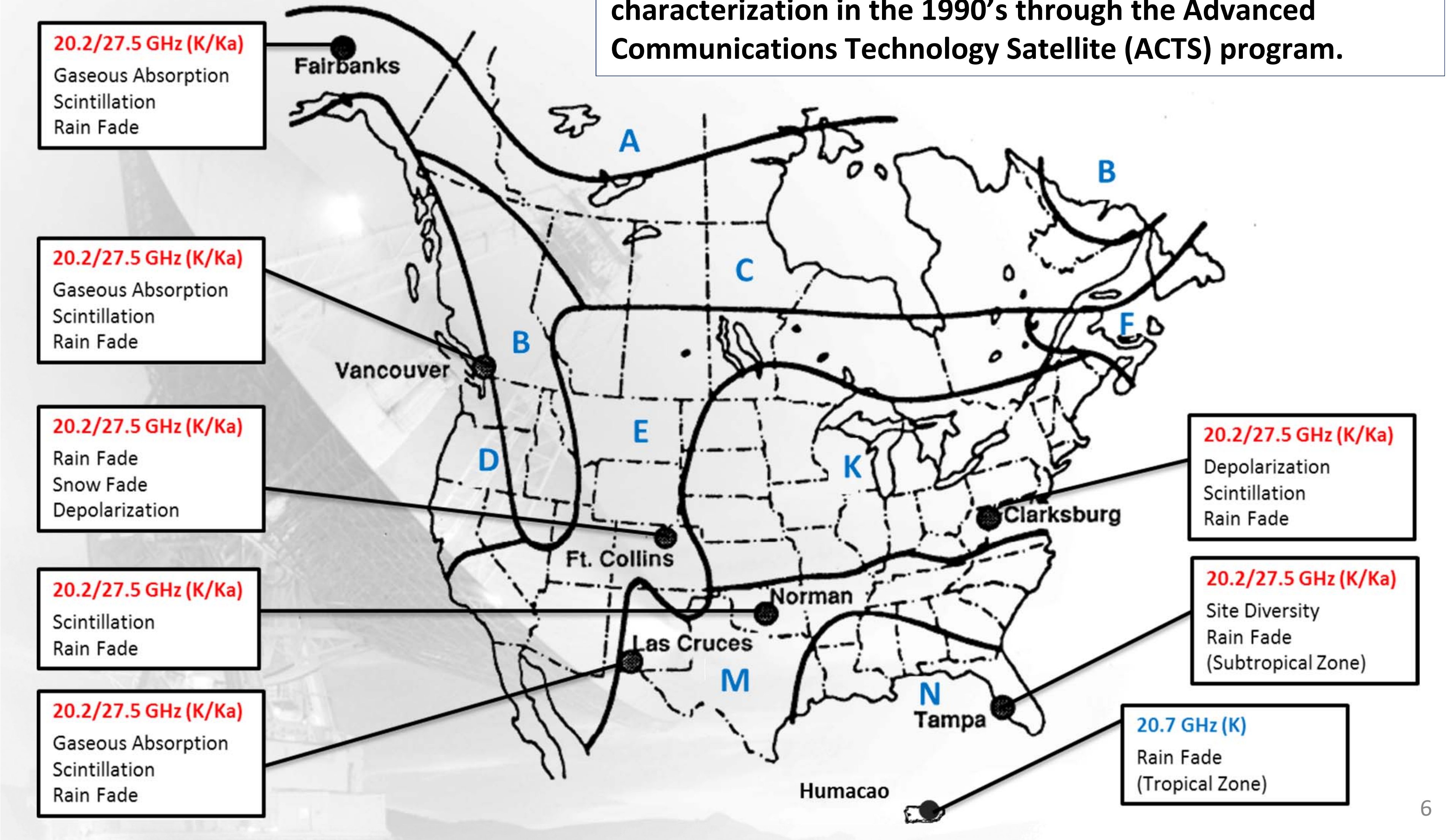
PROPAGATION STUDIES

Task History

RF Propagation Program History

Advanced Communications Technology Satellite (ACTS)

GRC opened up the Ka band spectrum through propagation characterization in the 1990's through the Advanced Communications Technology Satellite (ACTS) program.



Current NASA Network Characterization Sites

In the post-ACTS era, NASA propagation activities have primarily focused on site characterization of NASA operational networks throughout the world.

Propagation Data Collected by NASA

Location	Satellite Used	Frequency: Station Years	Measurements Performed/Lessons Learned
Fairbanks, Alaska	ACTS	20.2 GHz : 5 yrs. 27.5 GHz : 5 yrs.	Rain Attenuation Scintillation
British Columbia, Canada	ACTS	20.2 GHz : 5 yrs. 27.5 GHz : 5 yrs.	Rain Attenuation Scintillation effects
Fort Collins, Colorado	ACTS	20.2 GHz : 5 yrs. 27.5 GHz : 5 yrs.	Rain and snow effects Polarimetric radar
Tampa, Florida	ACTS	20.2 GHz : 5 yrs. 27.5 GHz : 5 yrs.	Rain Attenuation (Subtropical Zone) Site Diversity
Norman, Oklahoma	ACTS	20.2 GHz : 5 yrs. 27.5 GHz : 5 yrs.	Rain Attenuation Scintillation Snow on Antenna
Clarksburg, MD	ACTS	20.2 GHz : 5 yrs. 27.5 GHz : 5 yrs.	Rain Attenuation Scintillation
Ashburn, VA	ACTS	20.2 GHz : ~1 yr.	Depolarization
Humacao, Puerto Rico	UFO 09	20.7 GHz : 1.5 yrs.	Rain Attenuation (Tropical Zone)
Goldstone, California	ANIK F2 CIEL 2	20.2 GHz : 7 yrs. 12.45 GHz: 4 yrs.	Phase Decorrelation Total Attenuation
Las Cruses, New Mexico	ANIK F2	20.2 GHz : 12 yrs. 27.5 GHz : 5 yrs.	Phase Decorrelation (6 yrs.) Total Attenuation (12 yrs.) Atmospheric Profiles (3 yrs.)
Guam, USA	UFO 08	20.7 GHz : 5 yrs.	Phase Decorrelation Rain Attenuation (Tropical Zone) Site Diversity
Canberra, Australia	OPTUS D3	11.95 GHz: 3 yrs.	Phase Decorrelation
Madrid, Spain	EUTELSAT 9A	11.95 GHz: 1 yr.	Phase Decorrelation
Svalbard, Norway	N/A	22.234 GHz: 3 yrs. 26.5 GHz: 3 yrs.	Gaseous Absorption (Low Elevation Angles) Cloud Attenuation
Milan, Italy	Alphasat	19.7 GHz: 1 yr. 39.4 GHz: 1 yr.	Total Attenuation

PROPAGATION EXPERIMENT REQUIREMENTS

Atmospheric Propagation Effects at Ka-band and Above

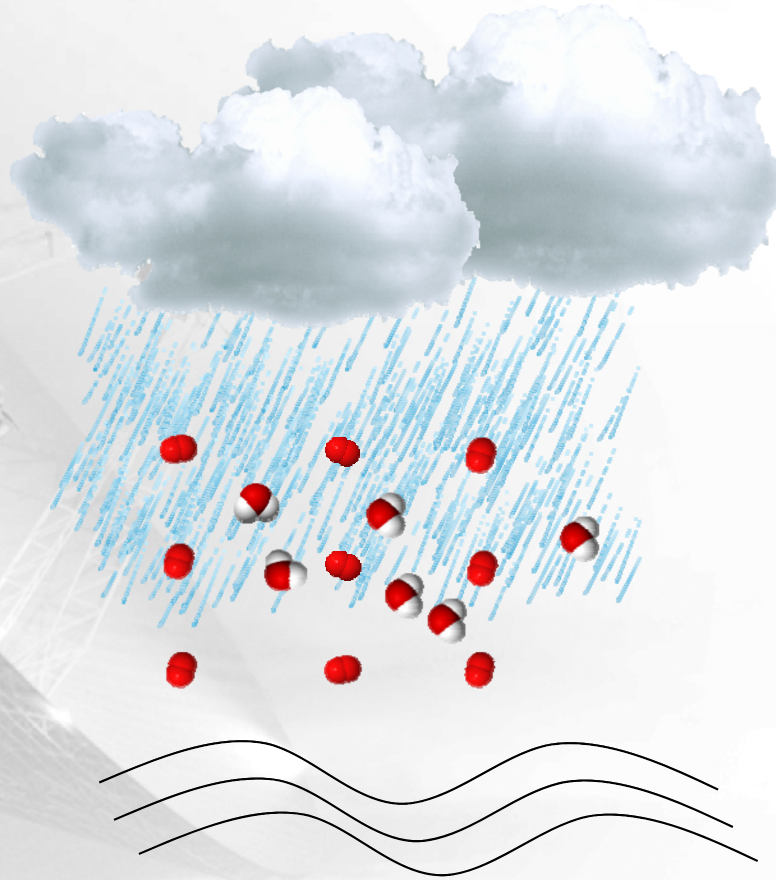
- Rain, rain, go away!

$A_{cloud} = f(T, \rho_{liq})$

$A_{rain} = f(RR, DSD)$

$A_{gas} = f(T, P, H)$

$A_{scint} = f(T, H, wind)$



$$\mathbf{A_{total} = A_{gas} + \sqrt{(A_{rain} + A_{cloud})^2 + {A_{scint}}^2}}$$

Characterization Techniques

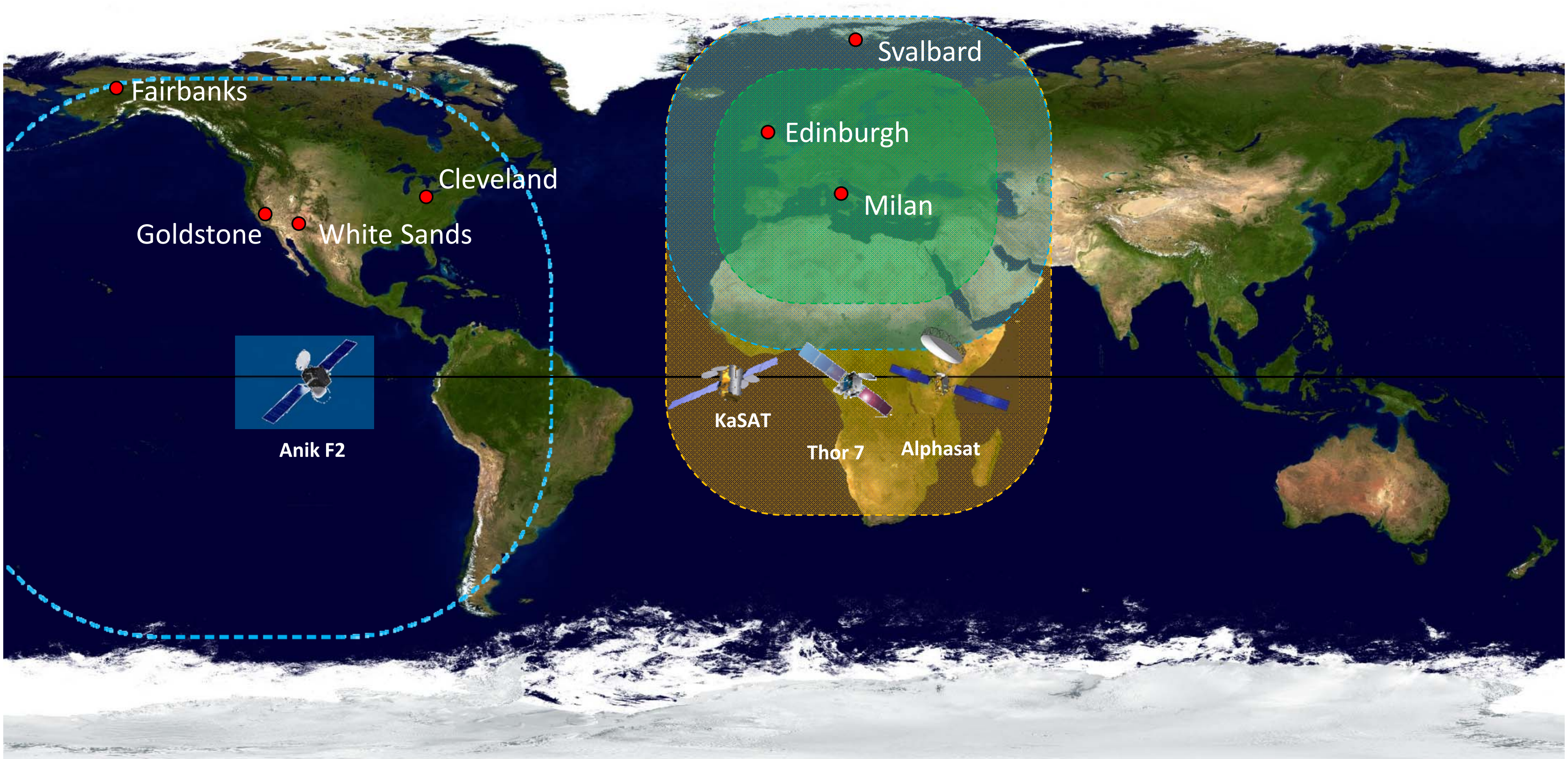
Desired Measurement	Reason for Measurement	Technology	Pros/Cons
Attenuation	Characterization of link margin availability as a result of losses through the atmosphere. Dominant atmospheric mechanism for defining system link	Beacon Receiver	• Provides DIRECT power loss measurement of atmosphere in all conditions (clear sky, cloudy, rain, snow, etc.) • Difficulty in scaling results from one frequency to another, unless known site-dependent scaling factor data exists. • Requires source signal
		Radiometer	• INDIRECT power loss measurement of atmosphere in only clear sky/cloudy conditions. • In combination with Beacon Receiver, provides reference attenuation level • Does not require source signal
Brightness Temperature	Desire to determine atmospheric noise temperature contribution to low receiver noise systems (high G, low T systems)	Radiometer	
Phase	Desire arraying capability at a particular site for link margin availability	Interferometer	• Provides DIRECT measurement of atmospheric-induced phase fluctuations • Requires source signal (beacon, quasar, downlink)
		Water Vapor Radiometer	• INDIRECT measurement of atmospheric phase fluctuations • Reliant on local radiosonde database and models to extract phase from water vapor content • Limited to longer integration times (>2 sec) • Does not require source signal
Depolarization	Provide double the data capacity through us of dual polarization receive/ transmit	Beacon Receiver	
Scintillation	Important for low elevation angle links	Beacon Receiver	

Step 1: Identify Signals of Opportunity

KaSAT: 19.68 GHz Beacon

Thor 7: 20.198 GHz Beacon

Alphasat: 19.701 GHz Beacon
39.402 GHz Beacon



Anik F2: 20.199 GHz Beacon

Step 2: Link Budget Estimates

Example: Alphasat Q-band Beacon

Parameter	User Inputs		Calculated	
Frequency of Operation	39.402	GHz		
Wavelength			0.008	m
Effective Isotropic Radiated Power (EIRP)			**26.50**	**dBW**
Propagation Channel Parameters				
Transmitter → Receiver Range	38600	km		
Gaseous Absorption Loss	0.5	dB		
Rain Attenuation	0.0	dB		
Pointing Loss	0.0	dB		
Polarization Loss	0.0	dB		
Free Space Loss			216.08	dB
Receive Antenna Parameters				
Antenna Diameter	0.6	m		
Illumination Taper Factor	70	deg		
Half Power Beamwidth			0.888	deg
Antenna Efficiency	60	%		
Antenna Gain			45.66	dB
Noise Temperature Contributions:				
Cosmic Background Noise Temperature	2.8	K		
Atmosphere Physical Temperature	290	K		
Antenna Noise Temperature (Clear Sky)			34.03	K
Antenna Noise Temperature (Rain)			34.03	K
Receiver Noise Temperature	800	K		
System Temperature			834.03	K
			29.21	dBK
Boltzmann's Constant			-228.60	dBW/K·Hz
Noise Spectral Density			-199.39	dB
Gain over Noise Temperature Ratio (G/T)			**16.44**	**dB/K**
Received Carrier Power (C)			**-144.43**	**dBW**
Carrier to Noise Density (C/N0)			**54.96**	**dBHz**

Obtained from Satellite Operator

Estimates from Models/Experience

$$FSPL = \left(\frac{4\pi d}{\lambda}\right)^2$$

Parameters fixed by virtue of experimental setup

Can adjust antenna size to obtain desired dynamic range…

Trades: Tracking Requirements

Dominant parameter to define dynamic range performance of receiver

Receiver Noise Temperature primarily determined by LNA performance…

Good LNA: ~ 600K

Not So Good LNA: ~ 1000-1200K

Parameter determined from system design (limited improvement)

~ -115 dBm power level at antenna flange

End Result: Provides dynamic range estimate of receiver

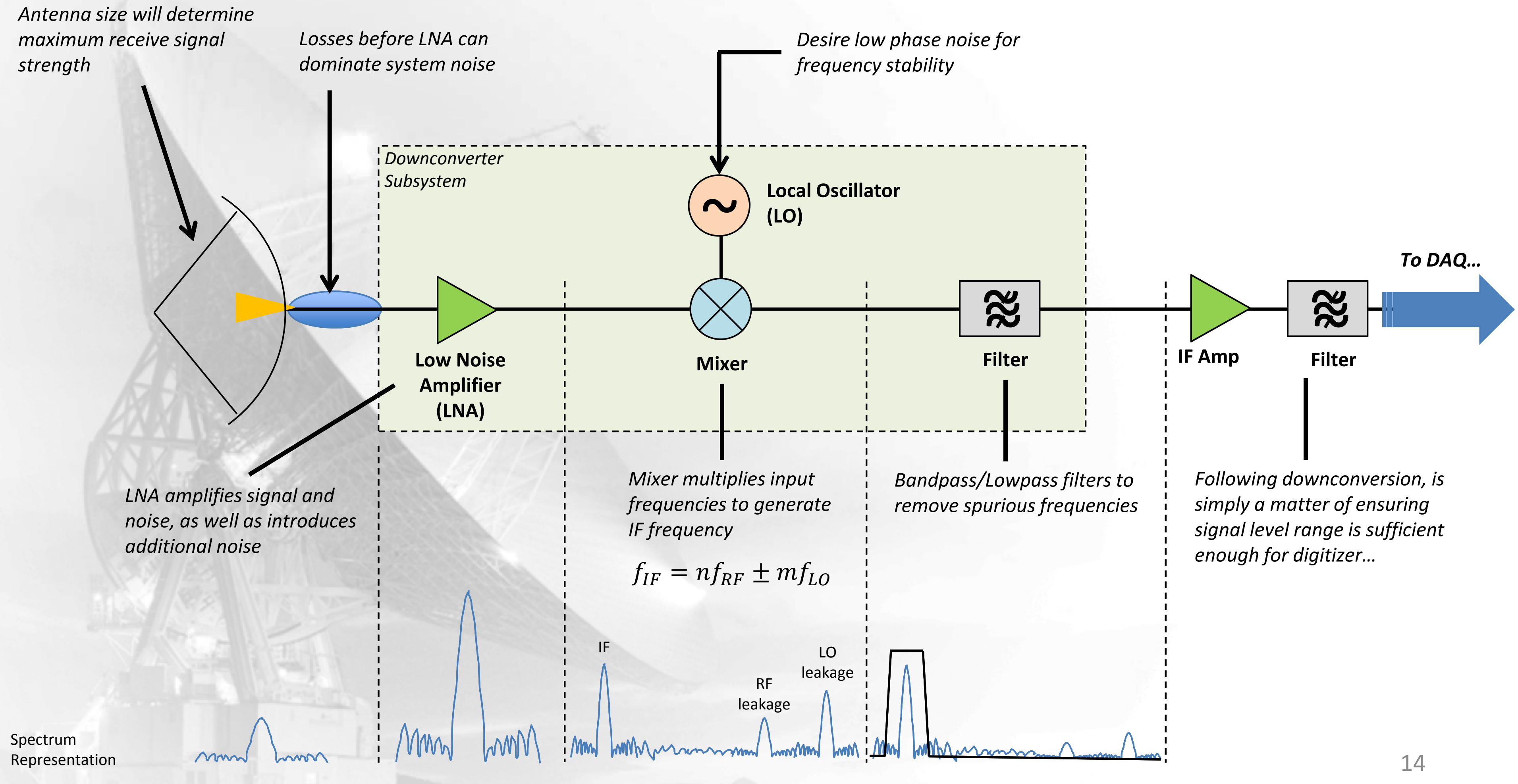
$$Dynamic\ Range = \left(\frac{C}{N_0}\right) - (Meas.BW) - (Tracking\ Threshold)$$

$$= 55dBHz - 10Hz - 10dB$$

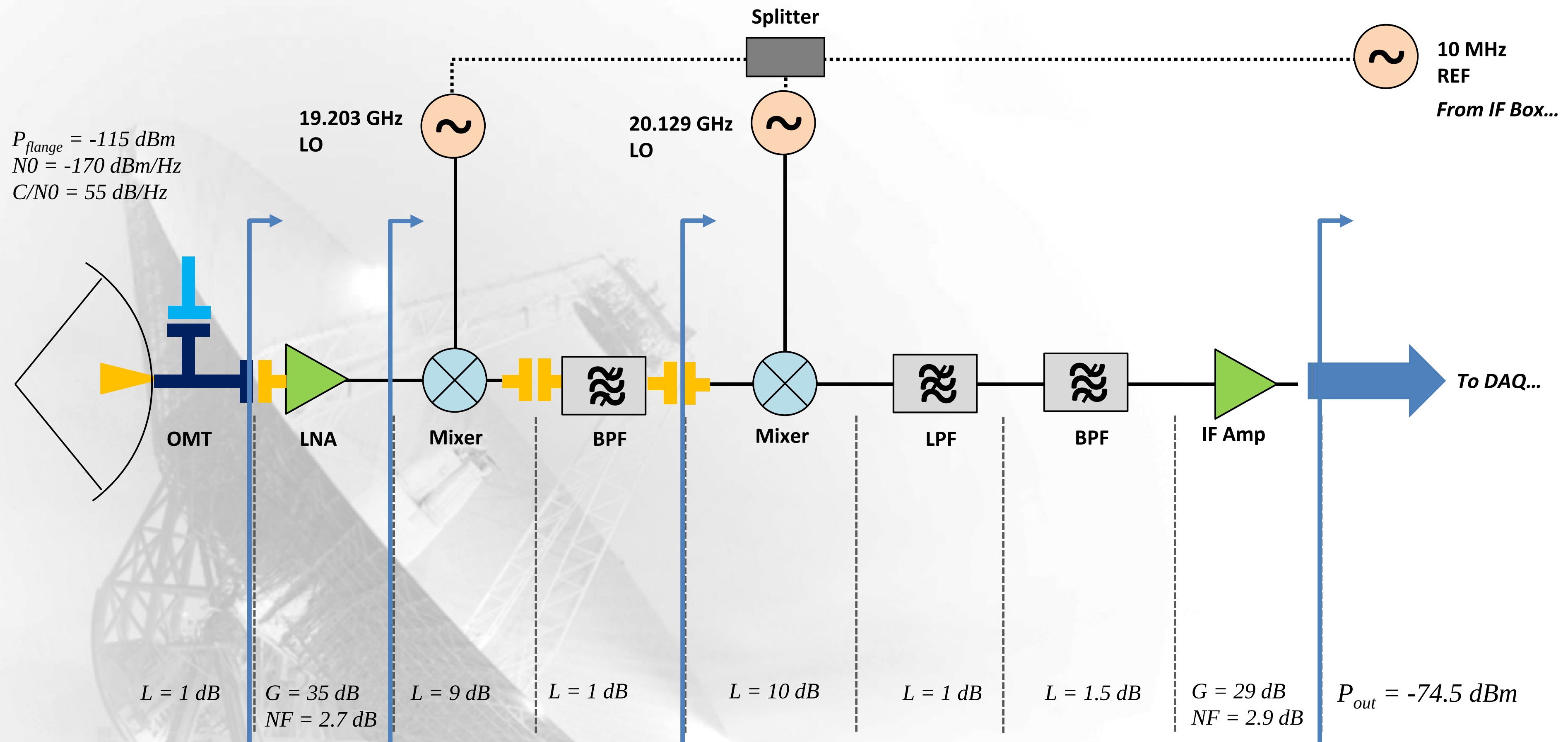
$$= 35dB$$

Step 3: System Design

The role of the propagation terminal hardware is simply to provide a means to convert the receive beacon frequency to a more manageable intermediate frequency (IF) for digitizing…



Step 3: System Noise Temperature



T_{Rx} = 365.1 K 679.8 K 680.6 K 681.7 K

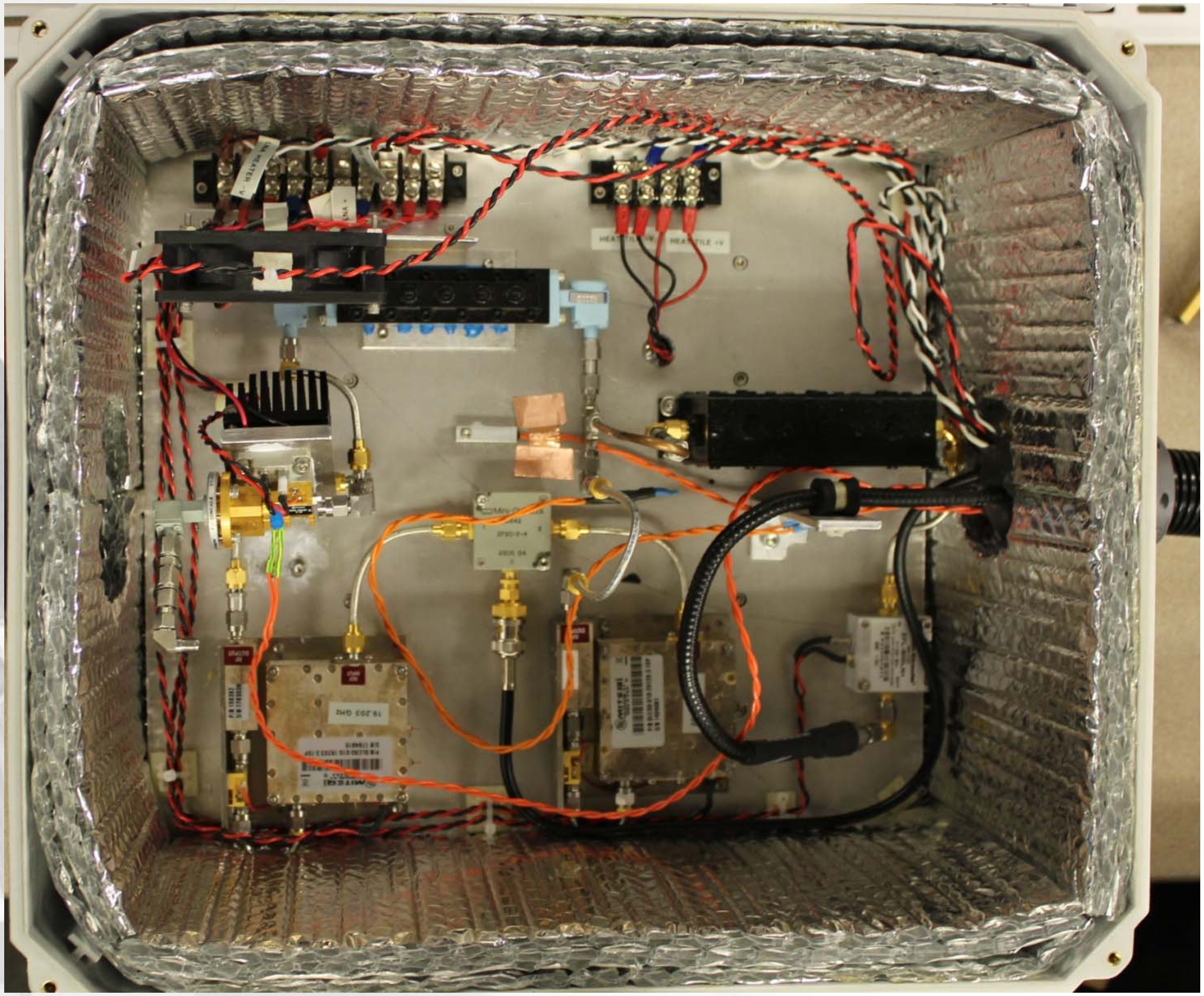
$$T_{Rx} = T_1 + T_1(L_1 - 1) + T_{LNA}L_1(NF_{LNA} - 1) + T_2\frac{L_1}{G_{LNA}}(L_2 - 1) + T_2\frac{L_1 L_2}{G_{LNA}}(L_3 - 1) \ldots$$

Q-band RF Front End

Physical Layout

Hinge Side

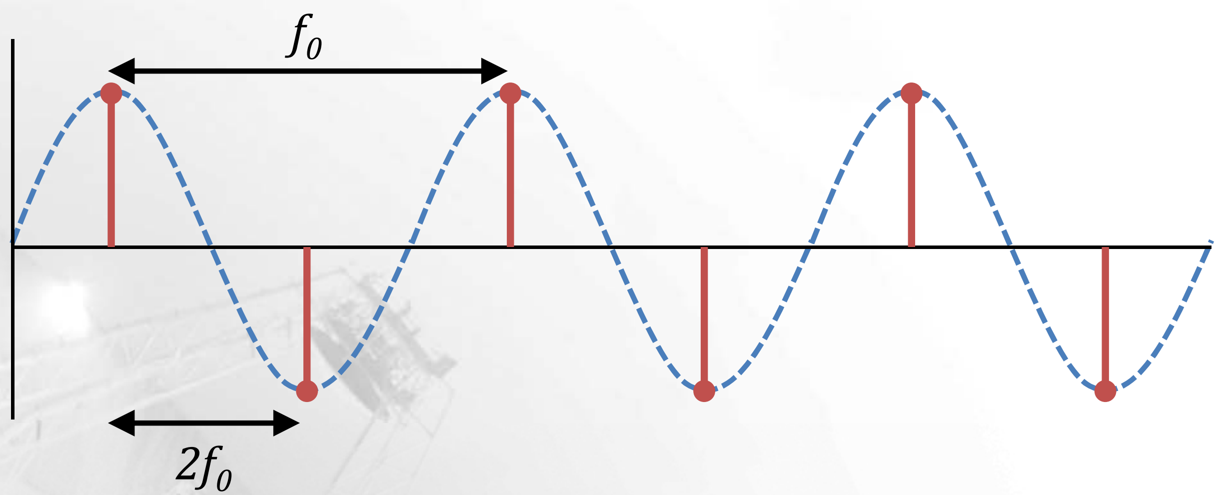
Antenna Side



Cable Side (To Power Box)

DIGITAL SIGNAL PROCESSING

Nyquist-Shannon



The well-known **Nyquist-Shannon Sampling Theorem** states that a continuous-time function must be sampled at a rate of at least $2f_0$ *Hz*, where f_0 is the highest frequency component of the signal (i.e. a sampling rate of $2f_0$ *Hz* will ensure that no aliasing occurs).

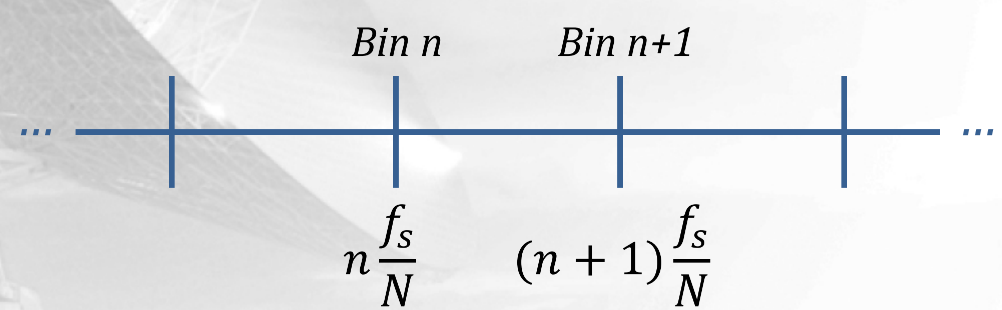
Frequency Detection

Detecting the measured frequency of the beacon can be done easily with an FFT, but there are much more accurate alternatives.

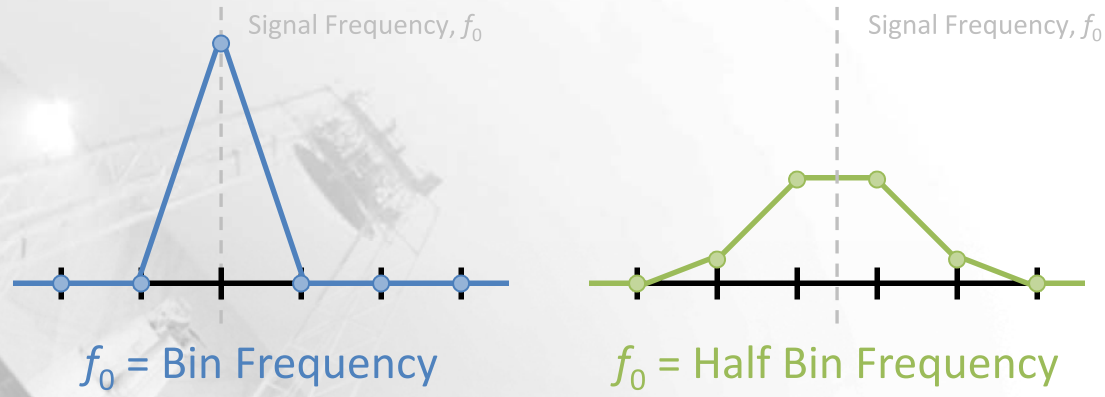
FFT Peak Search

- The FFT can be used to easily estimate the frequency of a signal by finding the peak bin, but it has a resolution is defined by $\frac{f_s}{N}$ (where f_s is the sampling frequency of the signal and N is the number of points) – this is the distance between two points in the FFT, and thus the finest measurement of frequency we can make by doing a simple peak search.

- In other words, while the actual signal frequency can vary continuously between $n\frac{f_s}{N}$ and $(n+1)\frac{f_s}{N}$, the bins of the FFT are discrete integer multiples of $\frac{f_s}{N}$. Therefore, if we want a fine resolution that can accurately measure frequency, we are forced to choose f_s and N such that $\frac{f_s}{N}$ is very small.



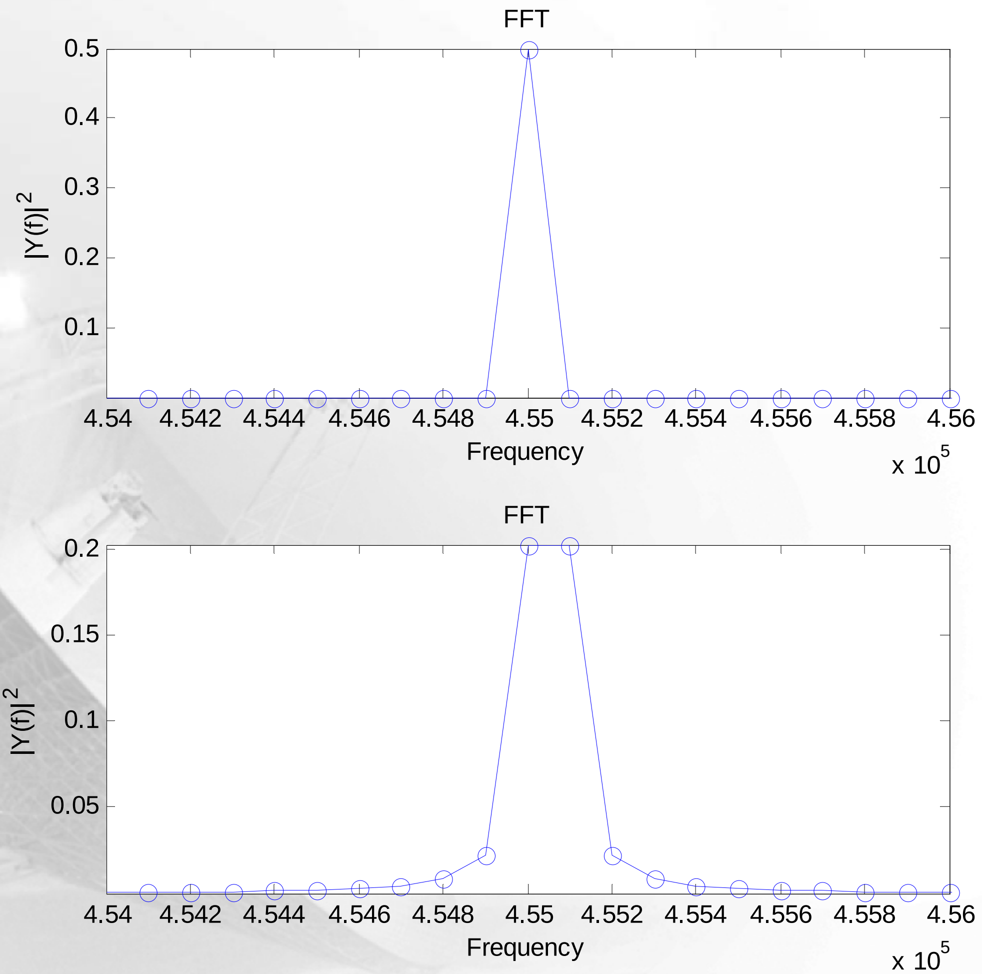
However, just doing a simple peak search ignores other information that the FFT provides.



When the frequency of a signal falls exactly into a **bin frequency**, that bin will contain all of the power of the signal. In all other cases, the power of the signal will also be **spread into multiple nearby bins**.

The worst case scenario occurs when the signal frequency is halfway between two bin frequencies, in which case the two bins on either side will have the same amount of power (in other words, there will be two matching peaks).

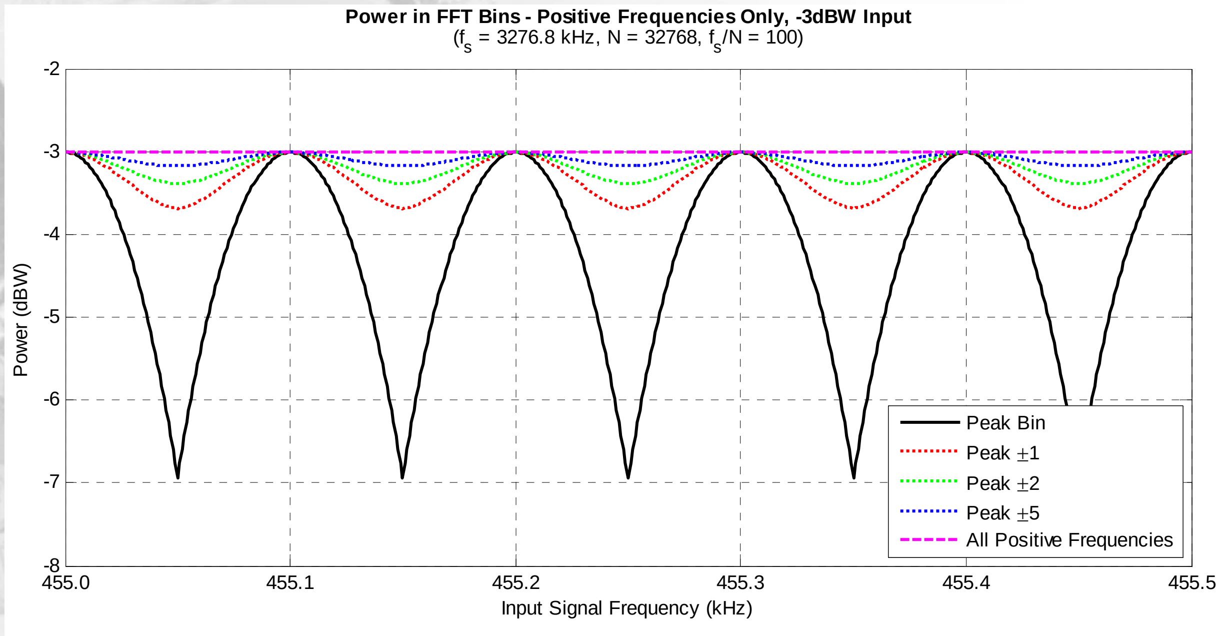
Bin Frequency vs. Half-Bin Frequency



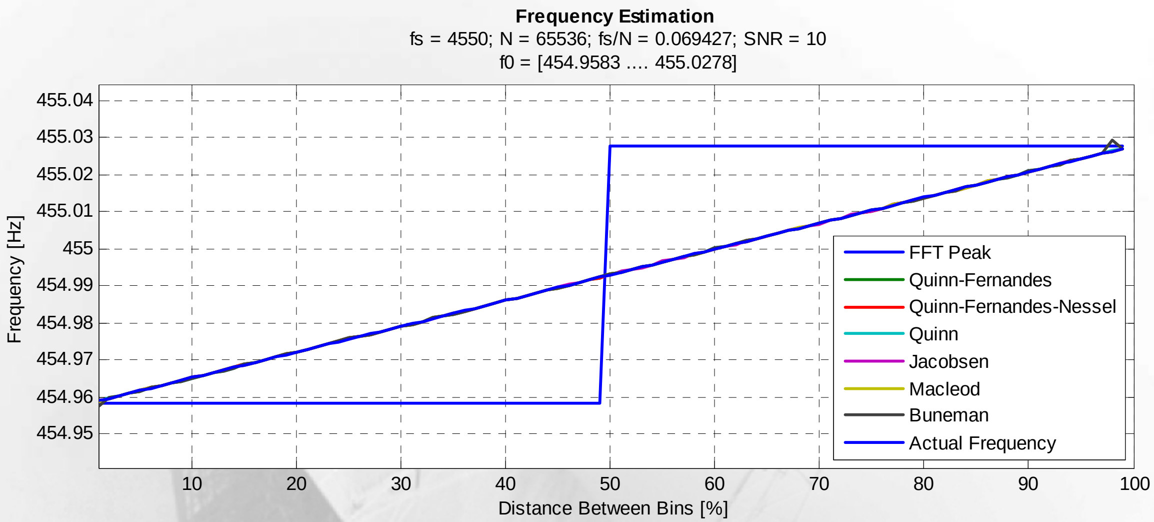
Scalloping

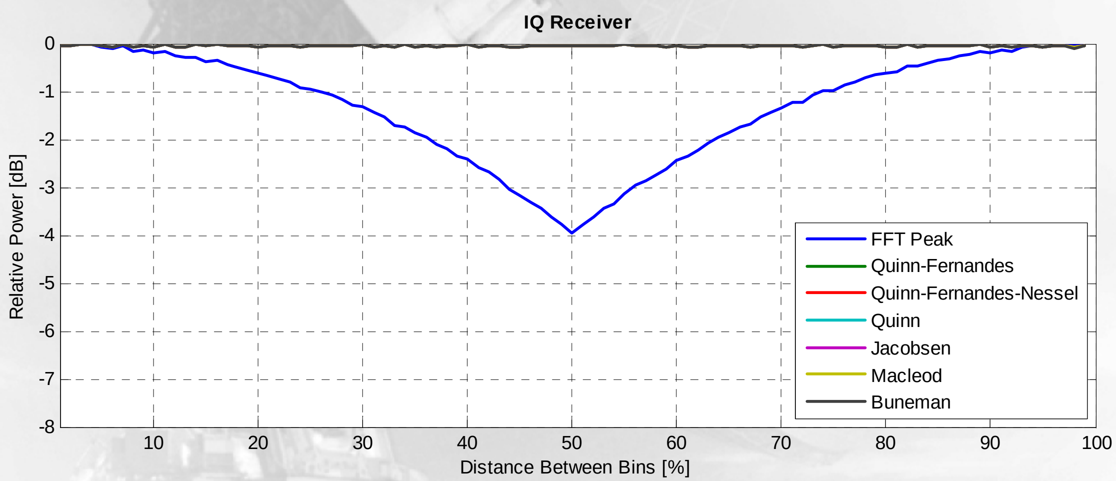
If we are only considering the power in the peak bin, we observe a **scalloping** effect: the power quickly drops off when we move away from a bin frequency, then comes back up again as we start approaching another bin frequency.

However, if we also consider ±1 bin on either side of the peak (red), or ±2 (green) or ±5 (blue), the scalloping effect is greatly mitigated, and we capture a majority of the signal power.



Frequency Estimates and IQ Power

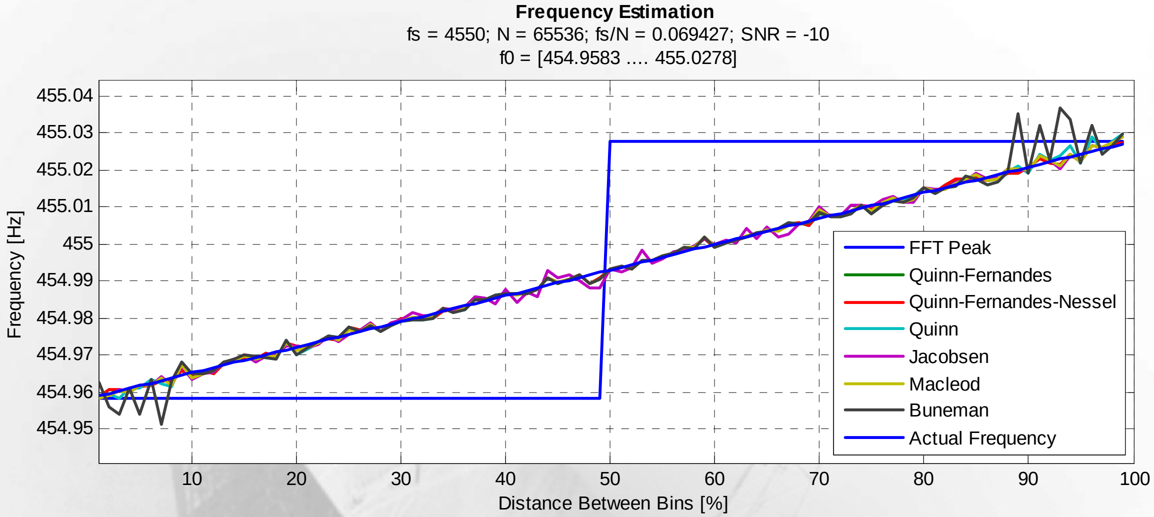


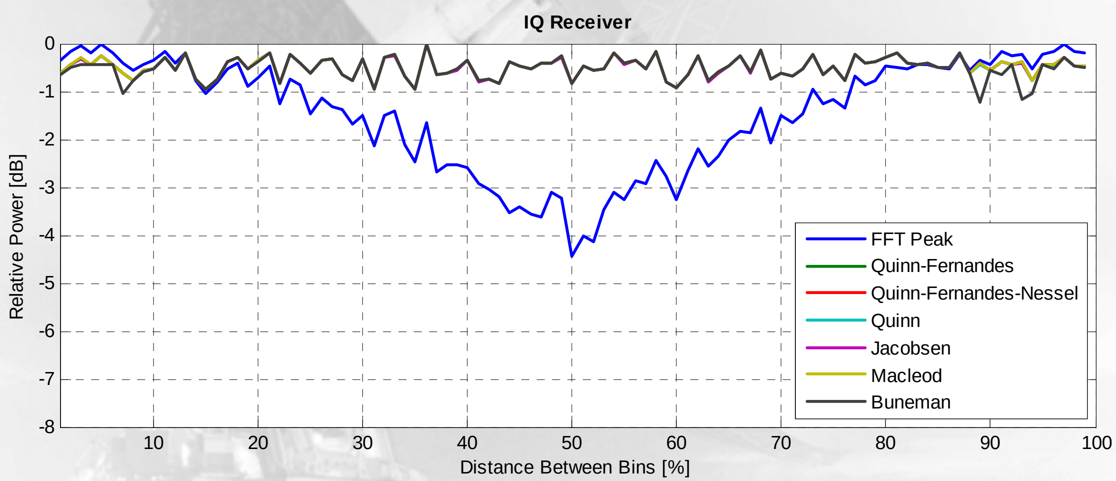


At a high SNR of 10 dB (as expected) all methods other than the FFT performed well, tracking the frequency as it varied from exactly one bin frequency to the next.

The estimators also eliminate the scalloping that occurs in the relative power of the IQ receiver if just the FFT Peak is used.

Frequency Estimates and IQ Power

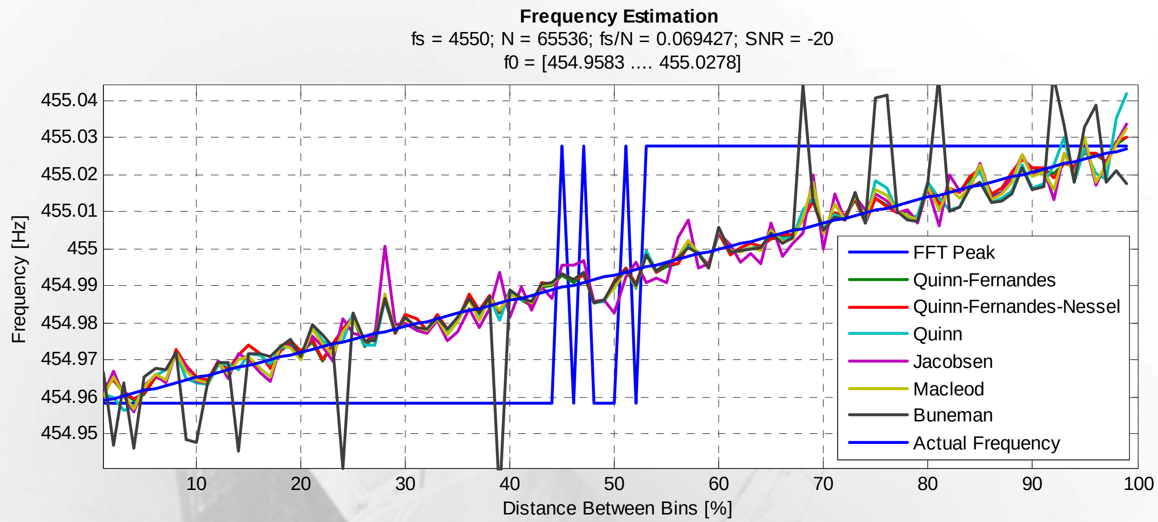


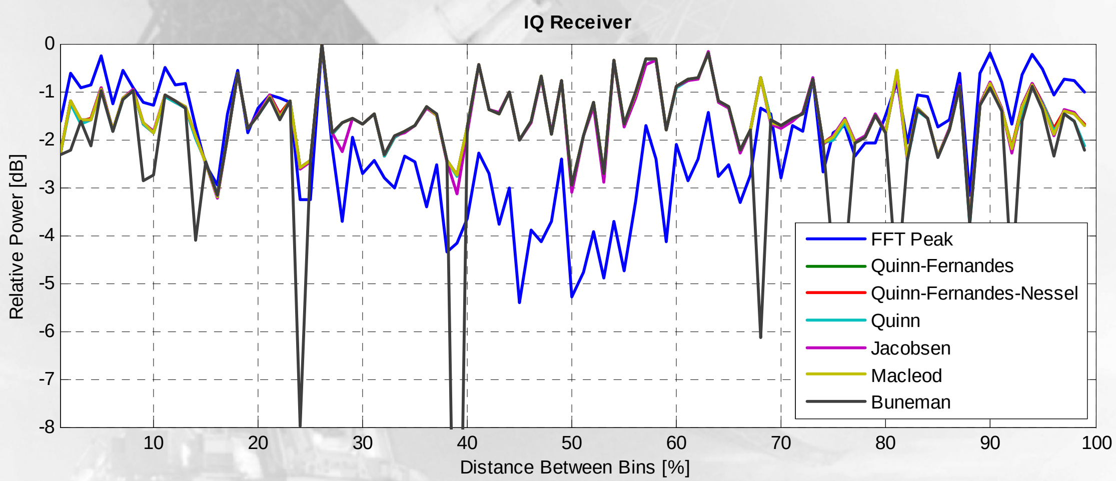


With the SNR decreased to -10 dB, more noise is apparent in the frequency estimations, but they continue to track the frequency linearly and avoid scalloping in the IQ receiver power.

Buneman in particular begins to exhibit a noisier estimate near the bin frequencies (at the edges), whereas the other estimates are more consistent.

Frequency Estimates and IQ Power

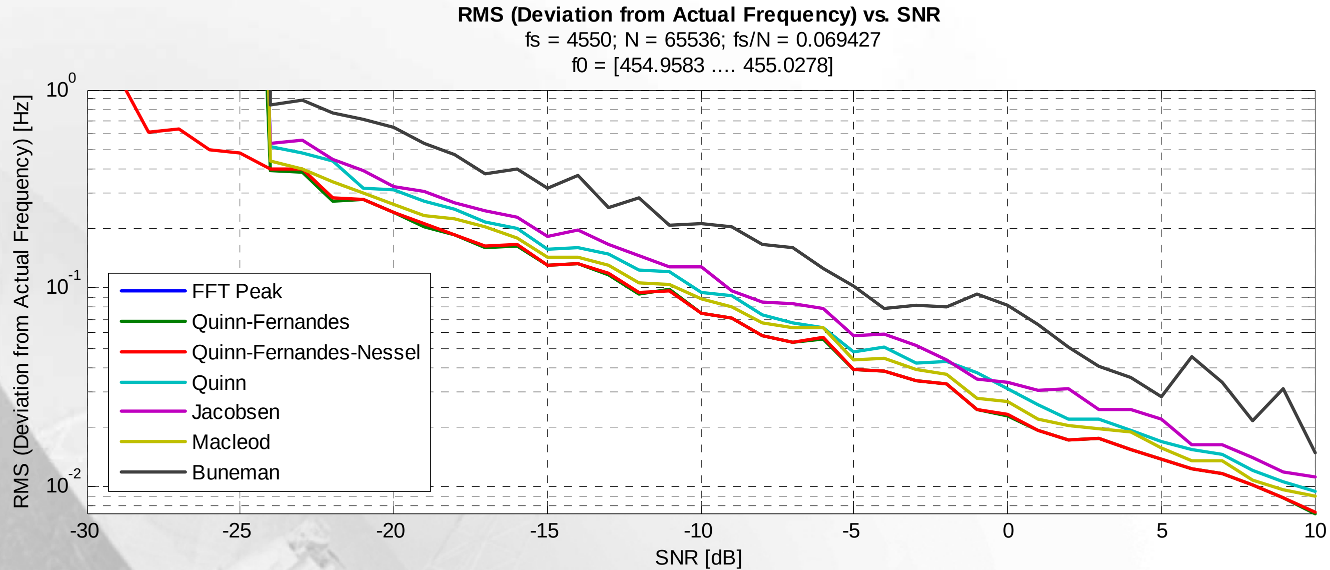




At -20 dB SNR, the noise is significant, but the estimators are still able to perform.

The FFT begins to oscillate around the halfway point because, when there are two peaks very similar in magnitude, the noise is large enough to make either one the maximum.

RMS Error vs. SNR



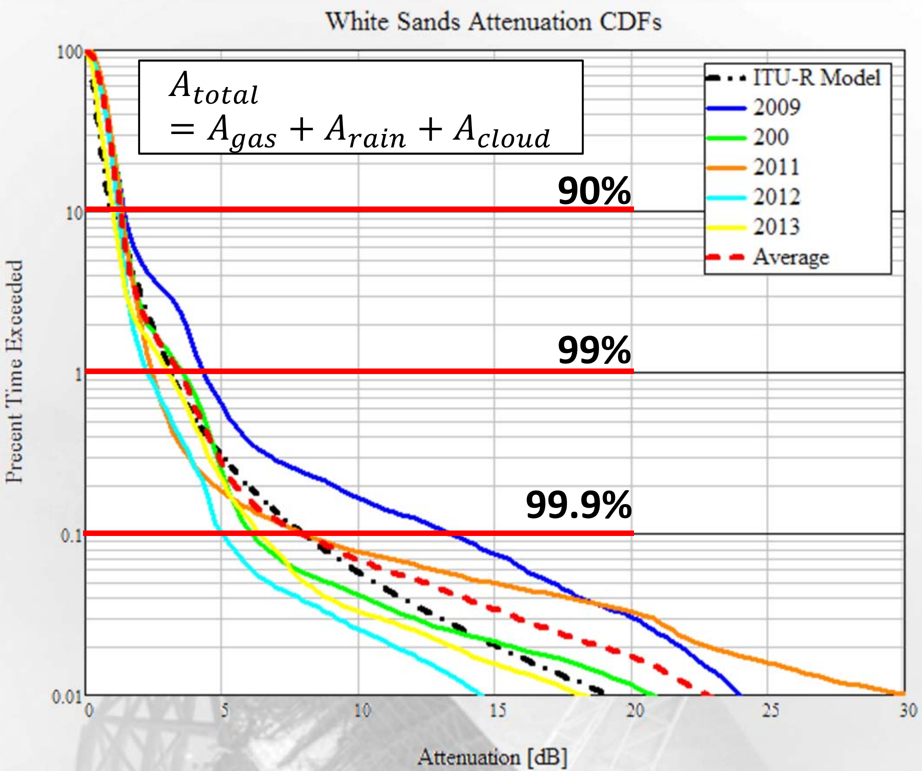
With SNR varying from -30 to +10 dB, each algorithm's error with respect to the actual frequency (RMS) is plotted on a semi-log scale above.

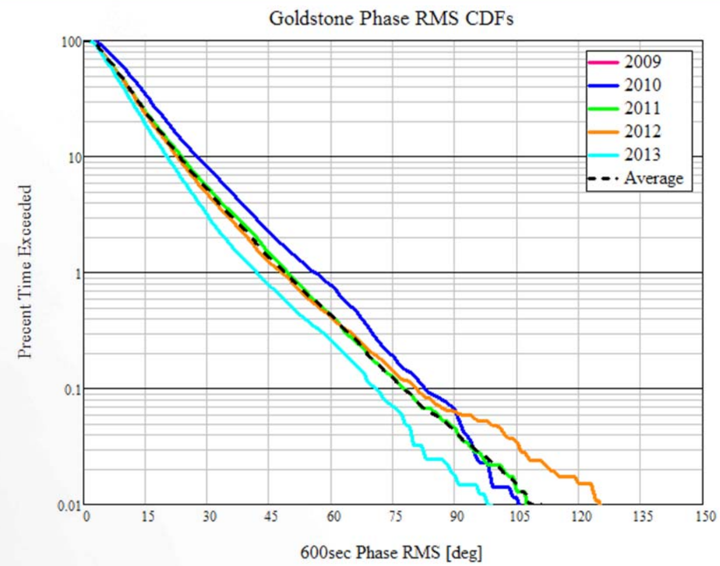
All six methods considered (excluding the FFT) exhibit an exponential increase in RMS error as the SNR decreases. At approximately -24 dB SNR, the noise at any point in the spectrum may exceed the peak of the FFT, and most of the methods therefore become unable to track the frequency. Quinn-Fernandes-Nessel manages to survive below this point because of the *a priori* information it is given on where to look for the peak.

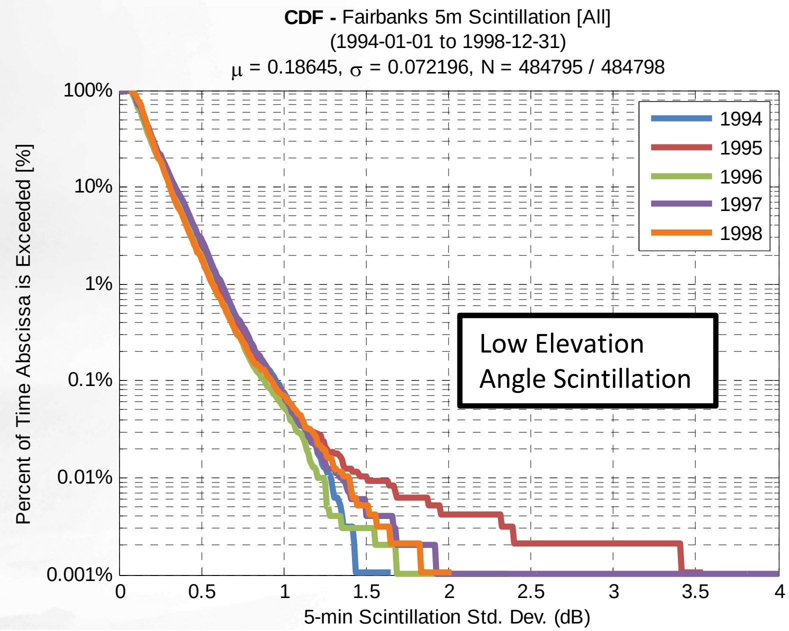
DATA PRODUCTS

Primary Data Products

Cumulative Distribution Functions (CDFs)



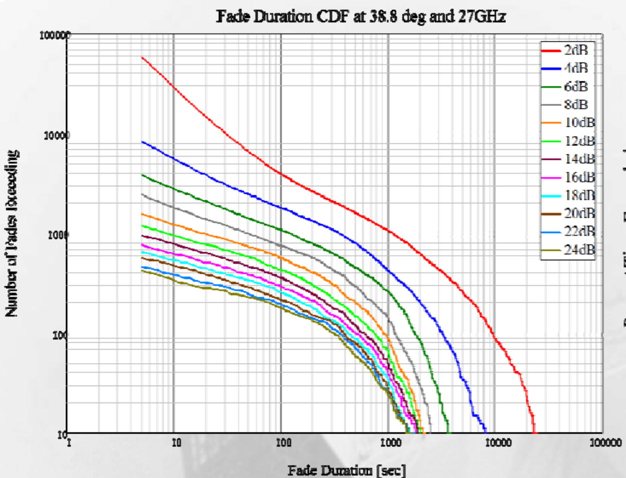


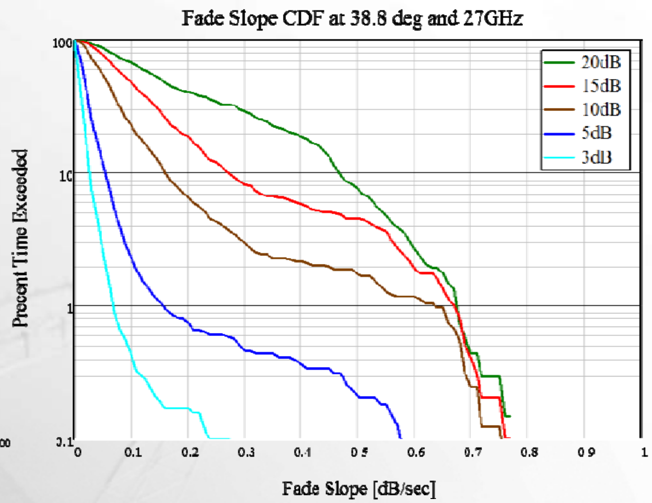


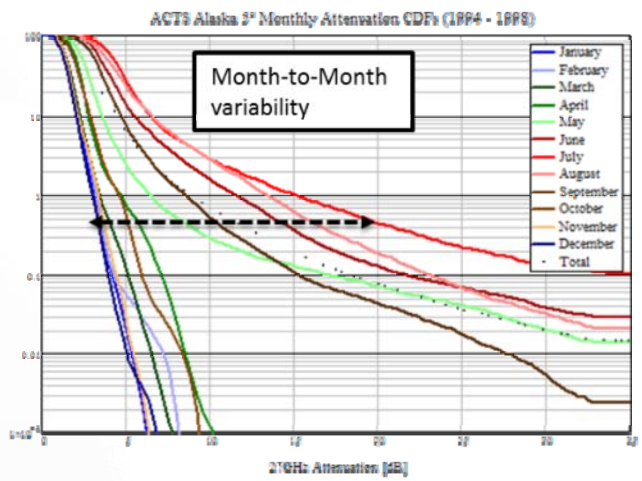
Availability (%)	System Outage (per year)
90%	36.5 days
99%	87.6 hrs
99.9%	8.76 hrs

Note: System outage time refers to average over given time interval (days, years, multiple years)

Example Higher Order Data Products







<u>Fade Duration</u>

- System outage and unavailability: store/forward requirements
- Sharing of the system resource: dynamic reassignment of system
- System coding and modulation: FEC, optimal modulation schemes

<u>Fade Slope</u>

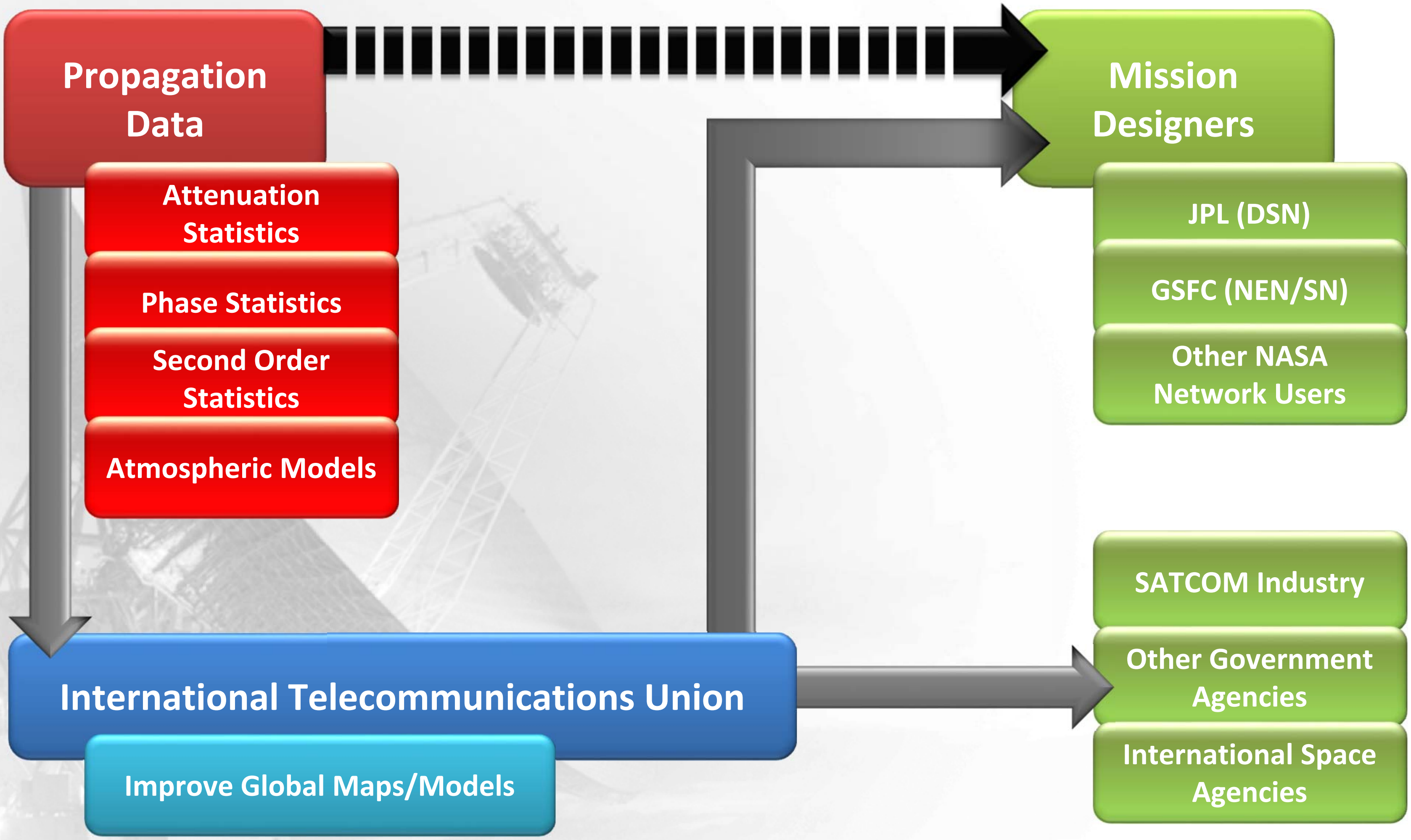
- Fade Mitigation Techniques
- Adaptive/Cognitive Systems
- Can provide short-term statistical prediction

<u>Interannual Variability</u>

- Fade Mitigation Techniques
- Seasonal Statistics
- Metric for design confidence level (i.e., probability of exceeding exceedence levels)

Where Does this Data Go?

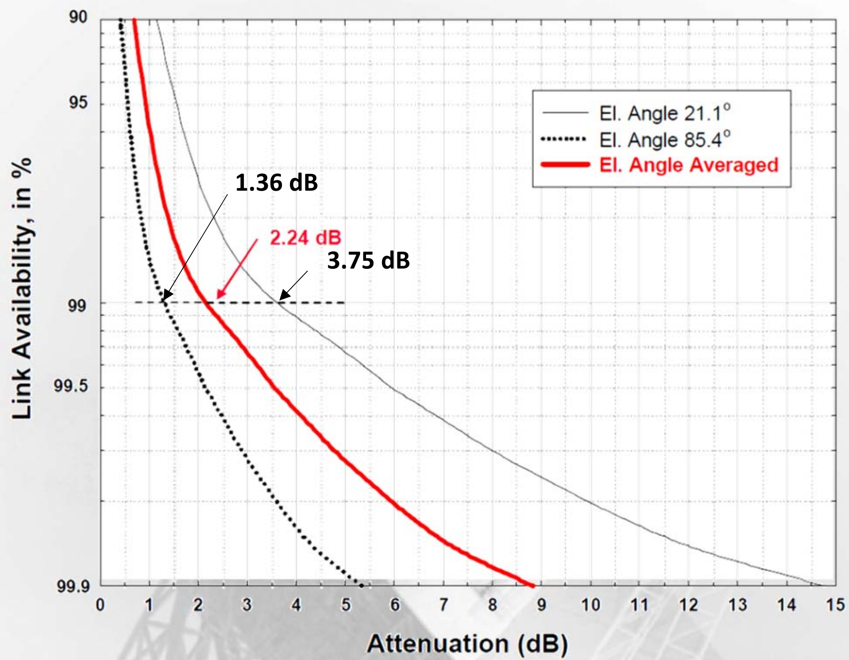
System Design Infusion Path

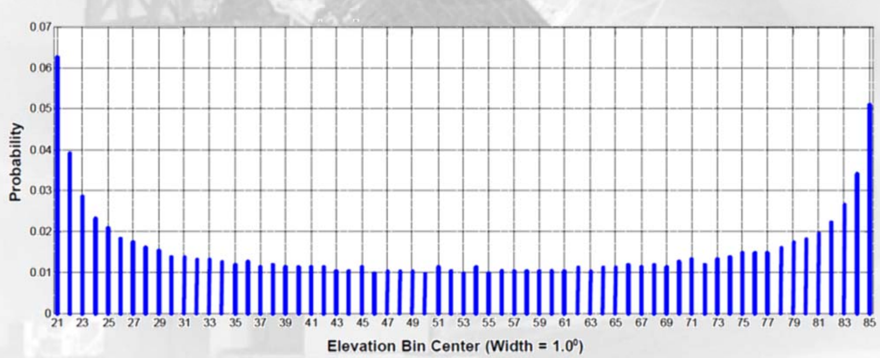


PROPAGATION DATA FOR MISSION DESIGN

Case Study #1

Solar Dynamic Observatory (SDO)





- Values used in SDO Downlink Margin Calculation (based on model)
- **Design Goal: 99% Availability** (*87.6 hrs/yr outage*)

Atmospheric Loss*	4.06 dB
Margin	3.84 dB
Total Margin	7.90 dB

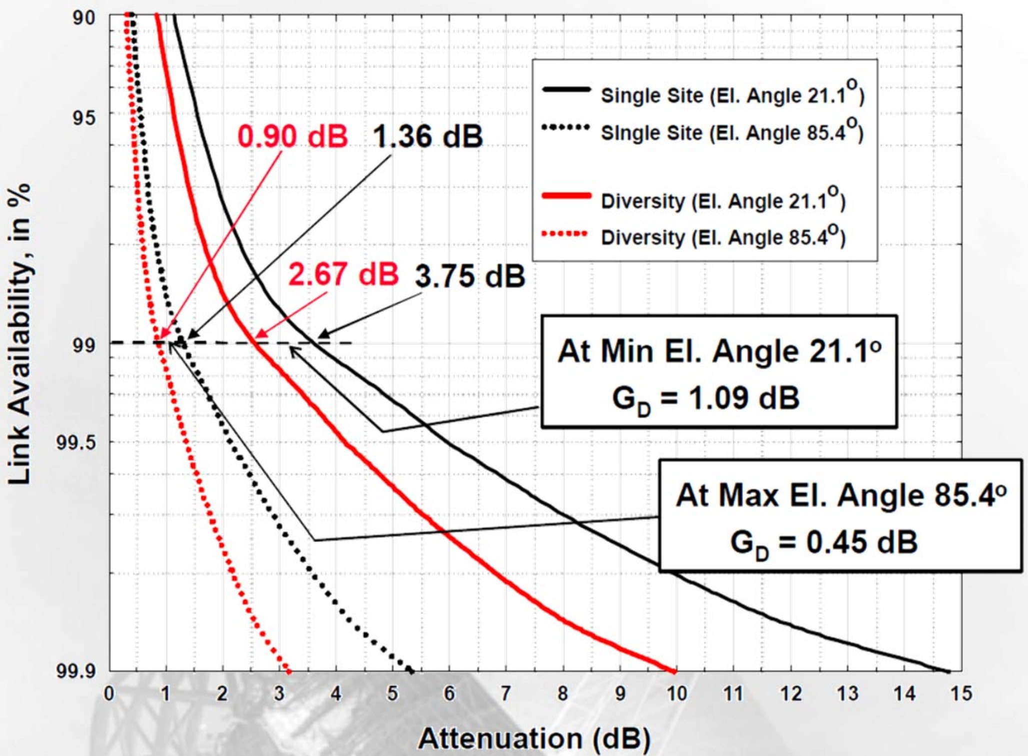
At 4.06 dB link margin: 99.6% (*35 hrs/yr outage*)

At 7.90 dB link margin: 99.88% (*10.5 hrs/yr outage*)

* *model based on worst case elevation angle conditions and did not account for inclined orbit*

Case Study #1

Solar Dynamic Observatory (SDO)



- Final SDO Architecture utilizes 2 ground station antennas for site diversity (STGT/WSGT, 3km separation distance)
- Analysis for Site Diversity Architecture
  - Conclusions: Diversity gain, on average, improves link margin by < 1dB (due to site geometry and average rain conditions)

Results from System Availability Analysis

- Over 5 year timespan…
  - 615.2 min. of system outage related to weather
  - Over 200 mins of downtime due to both dishes being completely full of snow (*not modeled in determining atmospheric-related outages*)

Margin	Measurement		Model		Actual
Architecture	Single Site	Diversity Sites	Single Site	Diversity Sites	Diversity Sites
2.24 dB	99.0%	99.45%	97.5%	*98.5%**	--
3.75 dB	99.5%	*99.6%**	99.0%	99.45%	--
7.90 dB	99.88%	***99.92%****	99.7%	*99.78%**	**99.98%**

** Values not available…estimates of availability based on diversity gain estimates*

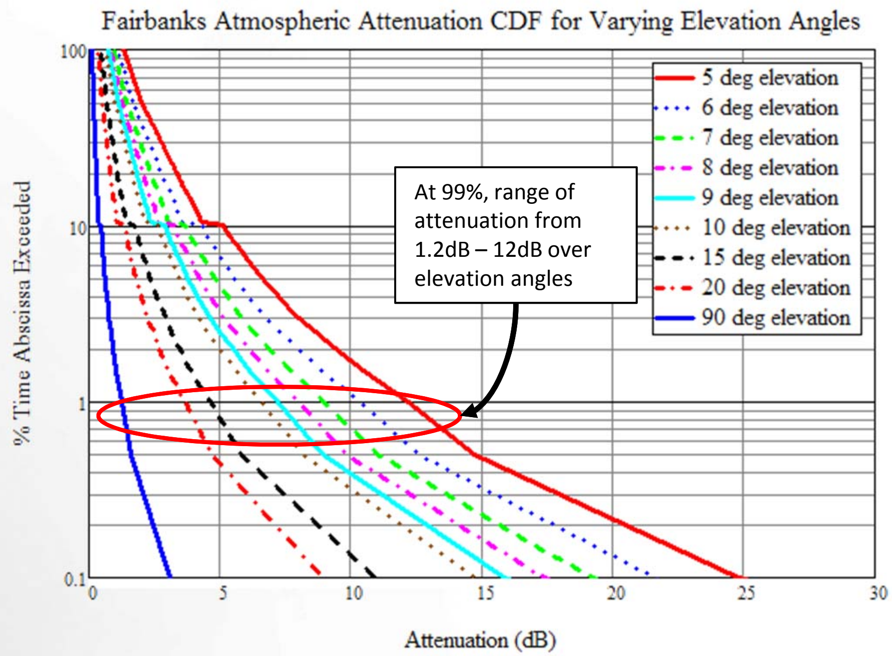
Case Study #2

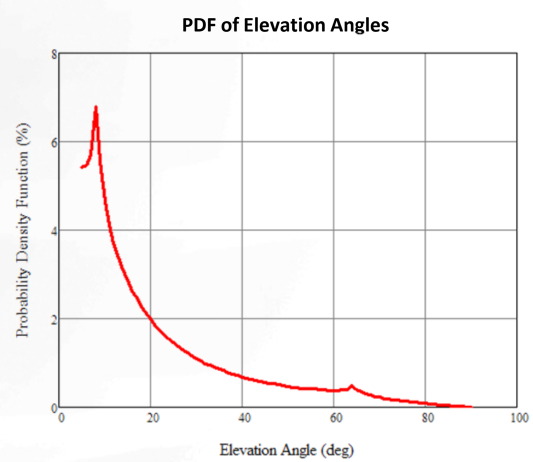
Joint Polar Satellite System (JPSS)

From ITU-R 618-11: Earth-Space Link Design

For non-geostationary systems, where the elevation angle is varying, the link availability for a single satellite can be calculated in the following way

1. Calculate the minimum and maximum elevation angles at which the system will be expected to operate
2. Divide the operational range of angles into small increments (e.g. 5° bins)
3. Calculate the percentage of time that the satellite is visible as a function of elevation angle in each increment
4. For a given propagation impairment level, find the time percentage that the level is exceeded for each elevation angle increment
5. For each elevation angle increment, multiply the results of (3) and (4) and divide by 100, giving the time percentage that the impairment level is exceeded at this elevation angle
6. Sum the time percentage values obtained in (5) to arrive at the total system time percentage that the impairment level is exceeded



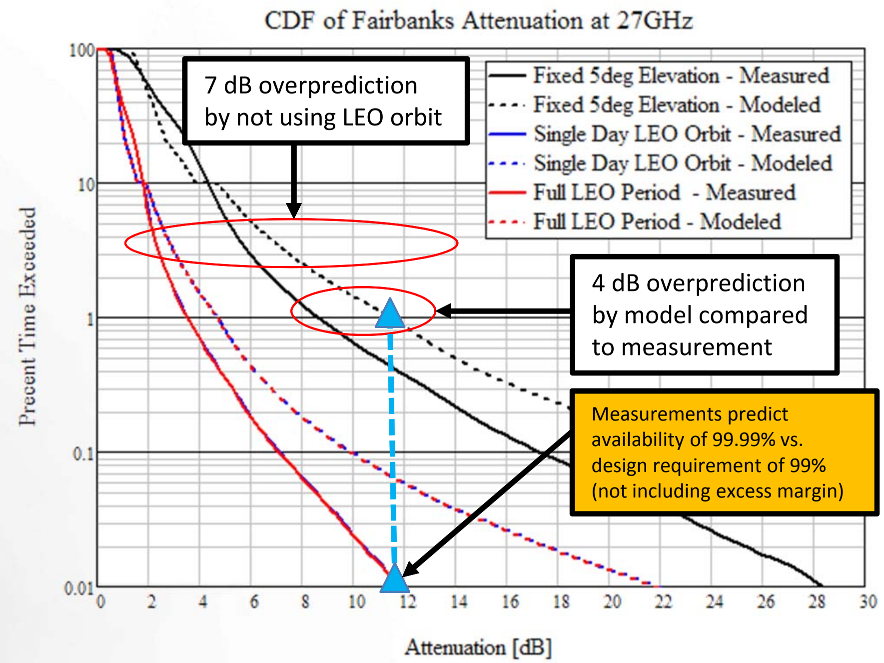


Case Study #2

Joint Polar Satellite System (JPSS)

JPSS-1 Link Budget

Parameter	Units	Value	Notes
Frequency	MHz	26703.40	
Data Rate	Mbps	300.00	150Mbps on I, 150Mbps on Q (includes R/S)
Slant Range	km	2835	Altitude=824km, 5° elevation angle
Modulation		SQPSK	Coding: Randomized, RS(255,223)
Data Format		NRZ-M	
Polarization		RHCP	
Boltzmann's Constant (k)	dBW/Hz-K	-228.6	
JPSS-1 to GN			
TWTA Power	W	20	TWTA power backed off for direct ground link
	dBW	13.01	
Tx Antenna Gain	dB	39.00	HGA specification
Tx Antenna Pointing Loss	dB	-1.50	Estimate
Tx Circuit Loss	dB	-7.00	Estimated Loss from TWTA to HGA, includes post TWTA attenuator
EIRP	**dBW**	**43.51**	Calculated EIRP from TWTA power, Antenna gain, Losses
Path Loss	dB	-190.02	Calculated from Frequency and Slant Range
Atmospheric Loss	dB	-11.70	99% Availability at Alaska
Polarization Loss	dB	-0.18	worst case estimate based on ARs of 2 dB S/C and 1.5 dB Ground
Rx Antenna Pointing Loss	dB	-0.20	From Ka-Band SMD IRD to Polar Sites
GN G/T	dB/K	28.20	From Ka-Band SMD IRD to Polar Sites
C/No	dB-Hz	98.21	
Constraint Loss (SC Tx)	dB	-0.23	
Implementation Loss (GN Rx)	dB	-3.10	
Eb/No	dB	10.11	
Theoretical Required Eb/No	dB	6.80	SQPSK, BER=10^{-8}, RS(255,223)
Margin	dB	**3.31**	



- JPSS-1 designed using ITU-R model for worst-case condition of constant 5 degree elevation angle at worst case site (Fairbanks, AK).
- Measurements from Fairbanks site (during ACTS) and Svalbard site indicate that model used for fixed elevation angle (geostationary conditions) overestimates measurements by approximately 4 dB.
- Furthermore, link margin does not take into account LEO architecture, which would reduce total atmospheric loss requirements by approximately 7 dB.
- **Total Atmospheric Loss Overdesign = 7 dB.**

THANK YOU!!!