Propagation Terminal Design and Measurements

James Nessel
NASA Glenn Research Center
Advanced High Frequency Branch

November 16, 2015
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.
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.

**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
As NASA Networks continue their current transition to Ka-band and future transition to higher frequency allocations (e.g., for the next generation SBR), propagation data collection will influence SCaN Network architecture through optimal understanding of system margin requirements and compensation of existing assets to enhance Network operational availability.

GRC/GSFC data collection in Guam is providing short baseline site diversity data for practical implementation of Ka-band in tropical environments.

GRC/GSFC data collection in Svalbard is providing critical characterization of Ka-band performance at low elevation angle polar sites for NEN upgrades.

GRC/JPL data collection at DSN sites are providing characterization of turbulence effects for the practical implementation of Ka-band uplink arrays for DSN upgrades.

GRC/GSFC/AFRL data collection in White Sands is providing availability measurements of Ka/Q/V/W-band potential for RF Space-Ground Links.
PROPAGATION STUDIES

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

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

- Rain, rain, go away!

\[ A_{\text{cloud}} = f(T, \rho_{\text{iq}}) \]

\[ A_{\text{rain}} = f(RR, DSD) \]

\[ A_{\text{gas}} = f(T, P, H) \]

\[ A_{\text{scint}} = f(T, H, \text{wind}) \]

\[ A_{\text{total}} = A_{\text{gas}} + \sqrt{(A_{\text{rain}} + A_{\text{cloud}})^2 + A_{\text{scint}}^2} \]
## Characterization Techniques

<table>
<thead>
<tr>
<th>Desired Measurement</th>
<th>Reason for Measurement</th>
<th>Technology</th>
<th>Pros/Cons</th>
</tr>
</thead>
</table>
| 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 use 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

Fairbanks
Goldstone
White Sands
Cleveland

Svalbard
Milan
Edinburgh

Anik F2: 20.199 GHz Beacon
### Step 2: Link Budget Estimates

**Example: Alphasat Q-band Beacon**

#### Parameter Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>User Inputs</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of Operation</td>
<td>39.402 GHz</td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>0.008 m</td>
<td></td>
</tr>
<tr>
<td>Effective Isotropic Radiated Power (EIRP)</td>
<td>26.50 dBW</td>
<td></td>
</tr>
</tbody>
</table>

#### Propagation Channel Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter → Receiver Range</td>
<td>38600 km</td>
</tr>
<tr>
<td>Gaseous Absorption Loss</td>
<td>0.5 dB</td>
</tr>
<tr>
<td>Rain Attenuation</td>
<td>0.0 dB</td>
</tr>
<tr>
<td>Pointing Loss</td>
<td>0.0 dB</td>
</tr>
<tr>
<td>Polarization Loss</td>
<td>0.0 dB</td>
</tr>
<tr>
<td>Free Space Loss</td>
<td>216.08 dB</td>
</tr>
</tbody>
</table>

#### Receive Antenna Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna Diameter</td>
<td>0.6 m</td>
</tr>
<tr>
<td>Illumination Taper Factor</td>
<td>70 deg</td>
</tr>
<tr>
<td>Half Power Beamwidth</td>
<td>0.888 deg</td>
</tr>
<tr>
<td>Antenna Efficiency</td>
<td>60 %</td>
</tr>
<tr>
<td>Antenna Gain</td>
<td>45.66 dB</td>
</tr>
</tbody>
</table>

#### 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
- 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

#### Equations

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

#### Notes

- **End Result:** Provides dynamic range estimate of receiver

\[
\text{Dynamic Range} = \left( \frac{C}{N_0} \right) - (\text{Meas. BW}) - (\text{Tracking Threshold})
= 55dBHz - 10Hz - 10dB
= 35dB
\]

- **Parameters:**
  -脂肪 by virtue of experimental setup
  -Dominant parameter to define dynamic range performance of receiver
  -Parameter determined from system design (limited improvement)

- **Receiver Noise Temperature:**
  -Primarily determined by LNA performance...
  -**Good LNA: ~ 600K**
  -**Not So Good LNA: ~ 1000-1200K**

- **Trade-offs:** Tracking Requirements

- **Power Level:** ~1.15 dBm power level at antenna flange
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...

Antenna size will determine maximum receive signal strength

Losses before LNA can dominate system noise

Desire low phase noise for frequency stability

Downconverter Subsystem

Local Oscillator (LO)

Mixer multiplies input frequencies to generate IF frequency

\[ f_{IF} = n f_{RF} \pm m f_{LO} \]

Bandpass/Lowpass filters to remove spurious frequencies

Following downconversion, is simply a matter of ensuring signal level range is sufficient enough for digitizer...
Step 3: System Noise Temperature

\[ T_{Rx} = 365.1 \text{ K} \quad 679.8 \text{ K} \quad 680.6 \text{ K} \quad 681.7 \text{ K} \]

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

\[ P_{flange} = -115 \text{ dBm} \]
\[ N_0 = -170 \text{ dBm/Hz} \]
\[ C/N_0 = 55 \text{ dB/Hz} \]

\[ L = 1 \text{ dB} \]
\[ G = 35 \text{ dB} \]
\[ NF = 2.7 \text{ dB} \]

\[ L = 9 \text{ dB} \]
\[ L = 1 \text{ dB} \]

\[ L = 10 \text{ dB} \]
\[ L = 1 \text{ dB} \]

\[ L = 1 \text{ dB} \]
\[ L = 1.5 \text{ dB} \]

\[ G = 29 \text{ dB} \]
\[ NF = 2.9 \text{ dB} \]

\[ P_{out} = -74.5 \text{ dBm} \]
Q-band RF Front End

Physical Layout

Hinge Side

Antenna Side

Cable Side (To Power Box)
DIGITAL SIGNAL PROCESSING
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 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.

\[
\begin{align*}
\text{Bin } n & \quad \text{Bin } n+1 \\
\ldots & \\
n \frac{f_s}{N} & \quad (n + 1) \frac{f_s}{N} \\
\ldots & \\
\end{align*}
\]
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).
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.
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.
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.
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.
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)

\[ A_{total} = A_{gas} + A_{rain} + A_{cloud} \]

### 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

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

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

**Interannual Variability**
- 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

- **International Telecommunications Union**
  - Improve Global Maps/Models

- **Mission Designers**
  - JPL (DSN)
  - GSFC (NEN/SN)
  - Other NASA Network Users
  - SATCOM Industry
  - Other Government Agencies
  - International Space Agencies

- **Propagation Data**
  - Attenuation Statistics
  - Phase Statistics
  - Second Order Statistics
  - Atmospheric Models

- **Other Government Agencies**
  - International Space Agencies
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)

<table>
<thead>
<tr>
<th>Atmospheric Loss*</th>
<th>4.06 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Margin</td>
<td>3.84 dB</td>
</tr>
<tr>
<td>Total Margin</td>
<td>7.90 dB</td>
</tr>
</tbody>
</table>

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)

<table>
<thead>
<tr>
<th>Margin</th>
<th>Measurement</th>
<th>Model</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architecture</td>
<td>Single Site</td>
<td>Diversity Sites</td>
<td>Single Site</td>
</tr>
<tr>
<td>2.24 dB</td>
<td>99.0%</td>
<td>99.45%</td>
<td>97.5%</td>
</tr>
<tr>
<td>3.75 dB</td>
<td>99.5%</td>
<td>99.6%*</td>
<td>99.0%</td>
</tr>
<tr>
<td>7.90 dB</td>
<td>99.88%</td>
<td><strong>99.92%</strong></td>
<td>99.7%</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>MHz</td>
<td>28703.40</td>
</tr>
<tr>
<td>Data Rate</td>
<td>Mbps</td>
<td>300.00</td>
</tr>
<tr>
<td>Slant Range</td>
<td>km</td>
<td>2035</td>
</tr>
<tr>
<td>Modulation</td>
<td>SQPSK</td>
<td></td>
</tr>
<tr>
<td>Data Format</td>
<td>NE2.U</td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>RHCP</td>
<td></td>
</tr>
<tr>
<td>Boltzmann's Constant (k)</td>
<td>dB/Hz/K</td>
<td>-228.6</td>
</tr>
<tr>
<td>W</td>
<td>dB</td>
<td>13.01</td>
</tr>
<tr>
<td>TWTA Power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tx Antenna Gain</td>
<td>dB</td>
<td>30.00</td>
</tr>
<tr>
<td>Tx Antenna Pointing Loss</td>
<td>dB</td>
<td>-1.50</td>
</tr>
<tr>
<td>Tx Circuit Loss</td>
<td>dB</td>
<td>-0.02</td>
</tr>
<tr>
<td>EIRP</td>
<td>dB</td>
<td>43.91</td>
</tr>
<tr>
<td>Path Loss</td>
<td>dB</td>
<td>100.03</td>
</tr>
<tr>
<td>Atmospheric Loss</td>
<td>dB</td>
<td>-11.70</td>
</tr>
</tbody>
</table>

7 dB overprediction by not using LEO orbit
4 dB overprediction by model compared to measurement
Measurements predict availability of 99.99% vs. design requirement of 99% (not including excess margin)

• 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.