Ka-Band Atmospheric Noise Temperature Measurements Using a 34-Meter Beam-Waveguide Antenna

David Morabito, Bob Clauss, and Michael Speranza
Jet Propulsion Laboratory
California Institute of Technology

Tenth ACTS Propagation Studies Workshop
November 19, 1997
Background

- NASA’s Deep space missions have used 960 MHz, 2.3 GHz, and 8.4 GHz for spacecraft communication downlinks
- Ka-band (32 GHz) is being considered as a downlink frequency for future flight projects
  - Ka-band provides an advantage of 11.6 dB (14.5 ratio) over X-band (8.4 GHz) in the spacecraft EIRP using the same transmitter output power and same antenna size
  - This downlink advantage is reduced to ~7 dB due to higher atmospheric noise, decreased ground station antenna efficiency and increased weather susceptibility at Ka-band
  - The higher Ka-band versus X-band downlink advantage can reduce cost, power, mass and volume of future space missions
  - In order to quantify this advantage, it is important to carefully characterize atmospheric effects at specific sites
- The Deep Space Network is supporting work to characterize the Ka-band atmospheric noise contribution at each of its three complexes
Surfsat- 1

- Surfsat-1 was launched on November 4, 1995 on a Delta-II Rocket
  - Carries an experiment to evaluate X/Ka link advantage and transponders to test Space VLBI ground stations at X and Ku bands
  - Is in a sun synchronous polar orbit (937 km by 1494 km)
  - Is observable 2-3 times near sunrise and sunset from the DSN R&D 34-m beam waveguide antenna DSS 13 in Goldstone near Barstow, Calif.
- Link experiment work deferred - Signal level data at X-band and Ka-band not yet fully modeled due to unanticipated dynamic motion of spacecraft
- Total Power Radiometer (TPR) data acquired from 192 tracking passes were processed to produce zenith atmospheric noise temperatures at Ka-band
Atmospheric Noise

At microwave frequencies, atmospheric attenuation is a significant source of external noise in earth-space communication systems.

Opacity (or absorption) in earth’s atmosphere at mm and cm wavelengths is primarily due to the combined effects of water ($\text{H}_2\text{O}$) and oxygen ($\text{O}_2$)

- $\text{O}_2$ is well distributed in the atmosphere and is relatively steady during a pass (8 km scale height)
  - $\sim 2\text{K}$ at X-band (8.4 GHz)
  - $\sim 4.5\text{K}$ at Ka-band (32.0 GHz)

- $\text{H}_2\text{O}$ vapor is concentrated in the lower 2 km near surface and is the principle variable component in atmosphere (2 km scale height)
  - $>0.2\text{ K}$ at X-band (8.4 GHz)
  - $>3\text{ K}$ at Ka-band (32.0 GHz)

- $\text{H}_2\text{O}$ hydrometeors
  - variable on time scales of minutes
Data Acquisition

● Surfsat-1 tracking data were acquired at DSS-13 in Goldstone, California
  - Passes occurred within 3 hours of sunrise or sunset
  - Passes were typically 5 to 20 minutes in duration
  - 418 total tracks between launch (November 1995) and December 1996
  - Elevation angles ranged from 7 deg (8.2 air masses) up to 90 deg (one air mass) depending upon particular track across sky

● Total Power Radiometer (TPR) data were acquired for noise floor calibration of received signal strength data
  - 20 MHz filter bandwidth at X-band (8.4 GHz); 30 MHz at Ka-band (32 GHz); 5 sec integration time
  - Spacecraft signal was not in filter bandpass

● WVR and surface meteorological data also acquired
  - WVR 31.4 GHz averaged brightness temperature over BWG tip curve time period was converted to 32 GHz for intercomparison.
  - Surface meteorological data converted to estimates of atmospheric noise temperature using model of Ulaby, Moore and Fung.
Model and Fit Strategy

- TOP measurements are “raw data” (192 data sets used in study).

- Pre-fit Top’s are estimated from raw TOP measurements by removing non-atmospheric dependent effects;
  \[ \text{ATOP}(\theta) = \text{TOP}(\theta) - \text{TOP}(0) - \text{T}_{\text{atm}}(\theta) - \text{T}_{\text{equipment}} \]

- The remaining signature in ATOP is atmosphere dependent;
  \[ \text{ATOP}(\theta) = \text{Bias} + \left[ \frac{T_{\text{cb}}}{L_{\text{atm}}} + \text{T}_{\text{atm}}(\theta) \right] / L_{\text{ant}} \]
  \[ T_{\text{cb}} \] is effective cosmic background (2.5K at X-band; 2.0K at Ka-band)
  \[ T_{\text{atm}}(\theta) = T_{\text{O}_2} \left[ 1 - \exp(-\tau_{\text{O}_2} A(\theta)) \right] \exp(-\tau_{\text{H}_2\text{O}} A(\theta)) + T_{\text{H}_2\text{O}} \left[ 1 - \exp(-\tau_{\text{H}_2\text{O}} A(\theta)) \right] \]
  \[ L_{\text{atm}}(\theta) = \exp \left[ (\tau_{\text{O}_2} + \tau_{\text{H}_2\text{O}}) A(\theta) \right] , A(\theta) \text{ is airmass number } (\sim 1/\sin(\theta)) \]


- Ka-band data from 1 airmass (90 deg elev) to 5.5 airmasses (10.5 deg elev) are fit. X-band model derived from Ka-band fit for this study.

- Bias and \( \tau_{\text{H}_2\text{O}} \) are solve-for parameters from least-squares fit. \( \tau_{\text{O}_2} \) calculated from surface model

- Post-fit residuals are computed by removing the fitted model from pre-fit residuals. Scatter of these residuals is a measure of goodness of fit and/or “bumpiness” of atmospheric variations over pass.
Error Sources

- BWG Top measurement error sources
  - gain instability (-0.1K)
  - thermal noise (0.005K)
  - atmospheric fluctuations (variable; dependent upon weather conditions)
- Model uncertainty believed to be below ±0.5K in elevation dependent signature of non-atmospheric antenna model (tripod scatter and backlobe pickup)
- Selection effect - near-dawn or near-dusk observations only
- WVR and BWG intercomparisons
  - ±0.5K absolute calibration error of each system
  - BWG and WVR spatially sampling different atmosphere
  - 31.4 GHz to 32 GHz correction accounts for water vapor and oxygen but not for water droplets
For each pass, an Atmospheric Noise Temperature at zenith, $T_{atm}(90)$ was estimated from available BWG Tip Curve, WVR, and surface model meteorological data.

Statistics on these estimates over all available passes are presented below:

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>RMS</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Number of Passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>BWG</td>
<td>10.6 K</td>
<td>4.0 K</td>
<td>7.3 K</td>
<td>56.2 K</td>
<td>192</td>
</tr>
<tr>
<td>WVR</td>
<td>11.0 K</td>
<td>2.0 K</td>
<td>8.1 K</td>
<td>16.5 K</td>
<td>115</td>
</tr>
<tr>
<td>MODEL</td>
<td>9.4 K</td>
<td>1.8 K</td>
<td>6.1 K</td>
<td>16.2 K</td>
<td>173</td>
</tr>
</tbody>
</table>
Example of ‘Clear’ Weather Data
96-150b Raw Top Data and Post-Fit Residuals

X-BAND

Ka-BAND

0.28K RMS

0.18K RMS
Example of Cloudy Weather Data

96-073d Raw Top Data and Post-Fit Residuals

UTC Minutes

Temp, K

UTC Minutes

Temp, K

Temp, K

Temp, K

Temp, K

16.1K RMS

3.3K RMS
BWG versus WVR
Concurrent Data Acquired During Tip Curve Periods

BWG and WVR $T_{atm}(90^\circ)$ are in general agreement
- typically within $\pm 0.5\, K$ absolute uncertainties of each system
- larger differences could be explained by both systems sampling different spatial areas of sky

A linear fit of the 115 common data points yields

$$T_{BWG} = 0.96 \, T_{WVR} - 0.12\, K$$

$\pm 0.04 \pm 0.40\, K$

0.76K rms scatter about fitted line
Cumulative Distribution

Ka-BAND

810-5 is internal JPL DSN document used by flight projects

Tatm, K
CONCLUSIONS

- BWG Ka-band TPR Data Acquired During Surfsat-1 Provides Valid Estimates of Atmospheric Noise Temperatures
- BWG and WVR Estimates are in Agreement within Uncertainties of Both Systems