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

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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.
- The Deep Space Network is supporting work to characterize the Ka-band atmospheric noise contribution at each of its three complexes.
Background

- Ka-band provides an advantage of 11.6 dB (14.5 ratio) over X-band (8.4 GHz) in the spacecraft EIRP.
- This downlink advantage is reduced to -7 dB due to higher atmospheric noise, decreased ground station antenna efficiency and increased weather susceptibility.
- This higher 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.
Surfsat-1

- Surfsat-1 was launched on November 4, 1995 on a Delta-11 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
DSS 13 R&D Beam Waveguide (BWG) Antenna

- R&D 34-m BWG antenna constructed as a prototype for the evolving DSN BWG subnet
- Provide stable environment for feed, receiver and electronics development
- Provide easy access to multiple development stations at feed ring located in the pedestal room
- Lower maintenance costs compared to non-BWG antennas
- Less susceptible to weather, for example, lower attenuation during rain
- Unique radio science and radio astronomy facility
Atmospheric Noise

- At microwave frequencies, atmospheric attenuation is a significant source of external noise in earth-space communication systems.
- Absorption in earth’s atmosphere at these frequencies is primarily due to the combined effects of H\textsubscript{2}O and O\textsubscript{2}.
  - O\textsubscript{2} is well distributed in the atmosphere and is relatively steady during a pass (8 km scale height).
  - H\textsubscript{2}O vapor is concentrated in the lower 2 km near surface and is the principle variable component in atmosphere (2 km scale height).
  - H\textsubscript{2}O droplets variable on time scales of minutes.
Data Acquisition

● Surfsat-1 tracking data were acquired at DSS-13
  – 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

● Water Vapor Radiometer (WVR) and surface meteorological data were 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)
- Pre-fit Top’s are estimated from raw TOP measurements by removing non-atmospheric dependent effects;
  \[ \Delta T_{\text{op}}(\theta) = T_{\text{op}}(\theta) - T_{\text{ant}}(\theta) - T_{\text{equipment}} \]
- The remaining signature in ATOP is atmosphere dependent;
  \[ \text{ATOP}(\theta) = \text{Bias} + \left[ \frac{T_{\text{cb}}}{L_{\text{atm}}(\theta)} + T_{\text{atm}}(\theta) \right] / L_{\text{ant}} \]

where

- \( T_{\text{cb}} \) is effective cosmic background (2.5K at X-band; 2.0K at Ka-band)
- \( T_{\text{atm}}(\theta) = T_{\text{O2}} \left[ 1 - \exp(-\tau_{\text{O2}} A(\theta)) \right] \exp(-\tau_{\text{H2O}} A(\theta)) + T_{\text{H2O}} \left[ 1 - \exp(-\tau_{\text{H2O}} A(\theta)) \right] \)
- \( L_{\text{atm}}(\theta) = \exp \left[ (T_{\text{O2}} + \tau_{\text{H2O}}) A(\theta) \right] \), \( A(\theta) \) is airmass number (\( \sim 1/\sin(\theta) \))

Model and Fit Strategy

- 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 ±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
Results

- 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

Temp, K

Temp, K

UTC Minutes

UTC Minutes

0.28K RMS

0.18K RMS
Example of Cloudy Weather Data
96-073d Raw Top Data and Post-Fit Residuals

UTC Minutes

Temp, K

3.3K RMS

Temp, K

Temp, K

16.1K RMS

Temp, K

UTC Minutes
BWG versus WVR
One Airmass Atmospheric Noise Temperature Concurrently Acquired During Tip Curve Periods
**BWG versus WVR**

**One Airmass Atmospheric Noise Temperature**

- BWG and WVR $T_{atm}(90°)$ are in general agreement
  - typically within ±0.5K absolute uncertainties of each system
  - larger differences could be explained by both systems sampling different spatial areas of sky
  - 31.4 GHz to 32 GHz correction of WVR accounts for water vapor and oxygen but not for water droplets

- A linear fit of the 115 common data points yields

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

$$\pm 0.04 \quad \pm 0.40K$$

0.76K rms scatter about fitted line
Cumulative distributions at specific tracking sites are used by planners of future flight projects to assess 900/0 or 95°/0 weather effects for spacecraft-to-ground link budgets.

BWG, WVR and 810-5 cumulative distribution curves are plotted here for the common BWG tip curve periods of the studied data sets.

810-5 is internal JPL DSN document currently used by flight projects.
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
  – The WVR is used to calibrate atmospheric effects for geodetic systems
  – This work verifies the 0.5K accuracy of the atmospheric noise temperatures measured by the BWG