Atmospheric-Induced Effects
Observed on Deep Space Ka-band Carrier Signals

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1. ABSTRACT

Atmospheric loss fluctuations due to water vapor and liquid water contribute to fluctuations in 32 GHz (Ka-band) signals. Signal degradation due to the weather, principally rain fades, is a major concern for Earth orbiting satellites, which operate at high microwave frequencies. One program that was initiated to quantify the rain fade problem, was the Advanced Communications Technology Satellite (ACTS), whose propagation experiments included statistical measurements on rain fade depths and fade durations. Since NASA deep-space missions operate at much weaker received signal levels, and hence tend to operate at lower margins, it becomes more important to characterize and understand propagation effects at these high microwave frequencies. Such knowledge is useful for developing optimum telemetry data return strategies that are unique to Ka-band. In addition to rain fading, other atmospheric-induced effects on a spacecraft signal’s SNR include scintillation and increased thermal noise.

This paper will report on atmospheric induced effects observed on received Ka-band carrier signals of deep-space missions. Signal amplitude and phase were extracted from open-loop and closed-loop receiver data acquired during turbulent and nominal weather passes. These data were analyzed in order to extract fluctuation information and compare against model predictions. In addition to long time scale rain fades, it is also important to characterize fluctuation effects at Ka-band on short time scales (~1 sec) that are comparable to that of telemetry data frames, in order to develop strategies that maximize data return at high data rates. This work will be useful to prepare for and plan future Ka-band experiments and operations on spacecraft that will have Ka-band telemetry links, such as the Mars Reconnaissance Orbiter (MRO), which will launch in August 2005. MRO expects to use high data rates with frame rates of about 400 frames/sec.

2. INTRODUCTION

There was a rich amount of work done previously using Earth orbiting Ka-band spacecraft such as the ACTS, and some European satellites on studying Ka-band effects due to weather. The NASA ACTS propagation experiment included slant path attenuation statistical measurements for several sites in the US and Canada for use in low margin Ka-band satellite communication systems [1]. The data from the ACTS propagation experiment was also used to examine scintillation models [2]. This study made use of beacon measurements at 1/sec and 20/sec using widely separated frequencies for elevations down to 8 deg and was used to test old models and develop new ones. An examination of the data indicates scintillations with time scales of several seconds, as is expected for Ka-band due to troposphere. Signal level changes as high as 5 dB over 6 seconds were observed [2]. Typical seasonally averaged magnitudes of scintillation typically ranged from 0.1 dB for cold dry
winters upwards to a maximum of about 0.7 dB for the warm moist summers \[2\] for the ACTS Fairbanks, Alaska site at the 27.5 GHz beacon frequency at an 8 deg elevation angle.

Previous propagation studies using deep space links focused on atmospheric induced fluctuations on system operating noise temperature at Ka-band \[3\], and on atmospheric induced fluctuations on received Ka-band signal amplitude and phase \[4\].

During the opposition of the Cassini spacecraft between December 2002 and January 2003, the Cassini Radio Science Team conducted the Gravitational Wave Experiment (GWE). During this experiment, very phase-stable carrier signals were transmitted up to the spacecraft by ground stations of the NASA Deep Space Network. These signals transited through the solar system, were received by the spacecraft, coherently turned-around by the spacecraft, and transmitted back to the DSN ground stations. The purpose of this experiment was to attempt to detect any gravitational waves that may have transited through the solar system at that time, causing a unique signature in the signal phase \[5\].

The period of opposition (where the spacecraft is opposite the direction of the Sun as seen by the Earth) was chosen for such an experiment because media effects due to charged particles of the solar wind are minimal. The choice of a Ka-band link was beneficial to this experiment in that it would result in less contributed effects due to charged particles than X-band. However, the Ka-band frequency link is more susceptible to troposphere effects that can result in significant fading due to rain, and scintillation. However, during the usually cold dry nighttime conditions characteristic of the wintertime in the Goldstone desert climate, smaller degradation on Ka-band signal links is expected. The occurrence of any significant propagation effects on the signal during the experiment provided an opportunity to study these effects. During the GWE, there were very few cases of significant signal fluctuations associated with turbulent weather. There were instances of rapid signal amplitude fluctuations that appeared to be associated with mechanical response of antenna pointing system to weather as well as a classic rain fade event.

In addition to the Cassini GWE data, previous data sets acquired using Ka-band from the Mars Global Surveyor spacecraft \[6\] were further studied to complement the Cassini data set study. Rain fade events were studied as well as scintillation. The measured amplitude scintillation was compared against predictions of scintillation derived from surface meteorological data using models provided in Otung \[7\].

3. OBSERVATIONS

The Cassini GWE observation period spanned 40 days during opposition. The Cassini spacecraft was configured to accept X-band and Ka-band uplink signals, and downlink X-band coherent with the X-band uplink, Ka-band coherent with the X-band uplink (turnaround frequency ratio of 3.8) and Ka-band downlink coherent with the Ka-band uplink. The primary ground station used to uplink and receive the carrier signals was DSS-25, a 34-meter beam-waveguide (BWG) antenna located at the NASA Goldstone Deep Space Tracking Complex near Barstow, California. The DSS-25 station accommodated uplink and downlink X-band and Ka-band signals. The antenna used Ka-band monopulse tracking to actively point to the spacecraft with ~2 millideg accuracy. The RF signals output from the low-noise amplifiers were down-converted to IFs near 300 MHz, and were then input into the receivers. The prime data for Cassini were open-loop receiver data recorded on Radio Science Recorders (RSRs) that were configured to record the carrier signals at a rate of 1000 samples/second for both in-phase and quadrature channels. The data were processed with tools used to estimate average power and scintillation.

The Radio Science GWE included a full complement of troposphere calibration instrumentation used to characterize weather effects along the signal-path. Water vapor
Radiometers (WVRs) were co-aligned with the BWG antenna as it tracked the spacecraft. The particulars of the Cassini Media Calibration System are documented in [8-10].

Most of the GWE experiments were conducted during nominal weather conditions. However, there were a few experiments for which the effects on the Ka-band signals due to weather were significant. These include passes conducted on December 15, 2002 (2002/349) December 29, 2002 and December 31, 2002 (2002/365). During these experiments, examples of several suspected weather-induced fades were observed in the signal strength data. The objective for conducting an analysis of these experiments for weather effects were twofold; 1) to further characterize rain fades and check consistency with models, and 2) to assess scintillation and check validity with theory. For rain fades, the signal amplitudes were examined in detail near the occurrence of the fading. For scintillation, the entire pass RMS scatter was plotted in chunks of several seconds covering the expected scintillation scale time, and compared against predicted models.

4. RESULTS

Based on an examination of the Cassini GWE amplitude time series data, of about 438 hours of Goldstone data acquired during the nights of the 40 day GWE period, only about three passes were found that possessed significant fade features possibly attributable to weather. The signal-to-noise strength as a function of time for two of these passes is displayed in Figure 1. The amplitude measurements were extracted from the RSR open-loop samples from Cassini GWE passes conducted on 2002/349 (December 15, 2002) (Figure 1a) and 2002/365 (December 31, 2002), (Figure 1b).

During the experiment conducted on 2002/349, there were a few periods of minor fading. There was an active period between 08:30 to 08:45 UTC, which was examined at different time resolutions. Significant fade features of magnitudes of up to 5 dB were seen in the 2002/365 data set (Figure 1b), during which conditions were cloudy. During an 11 second period focused around the deepest fade, a very rapid slope of 4.5 dB was observed to have occurred in just 1 second. These fades appear to be very rapid and there is some evidence that they may be related response of the antenna pointing control system to weather changes, and not due entirely to weather.

The only significant example of a classic rain fade feature was seen in the SNR data time series for pass 2002/363. Figure 3 displays the received signal amplitude in dB extracted from sinusoidal fits of the open-loop data. Here the amplitude experiences a fade feature of up to 2 dB magnitude which very well matches the attenuation inferred from the WVR 31.4 GHz sky brightness temperature data. The received signal-to-noise (not shown) reached a maximum fade value of about 6 dB in SNR and exceeded 1 dB over ~ 2 hours, and exceeded 3 dB for about 1 hour. The signature of the SNR fade feature was in good agreement with the fade signature reconstructed from the combined thermal noise and attenuation contributions using the WVR data. This reconstruction removed a nominal elevation dependent background model using a single opacity value, and accounts for both thermal noise and attenuation contributions. This feature appears to be the only significant classic rain fade feature seen in the 438 hours of Cassini GWE amplitude data. The projected fraction of data lying below 3 dB fade depth is about 0.2 percent, which means a telemetry link with 3 dB margin could suffer lost data this fraction of the time.

Scintillation models such as the ITU-R model [3] can be used to predict scintillation as a function of aperture size, troposphere refractivity and turbulence scale height. These predictions can be used to compare against scintillation measurements derived from averages of signal amplitudes over selected time intervals. The measured scintillation was computed by taking a moving average where high pass filtering at a suitable cutoff frequency removes long
period trends. The samples were also low-pass filtered to remove very rapid fluctuations due to other noise sources. Even during passes when there were periods of turbulent weather along the signal path, the value of the amplitude noise was relatively small. For instance the measurement noise level or fluctuations in signal amplitude were about 0.12 dB for most of pass 2002/365, but the level of scintillation predicted from the model (typically 0.06 dB) lied well below this. The measured noise level of ~0.12 dB is consistent with the expected level of thermal noise fluctuations given the bandwidth and averaging time. Thus amplitude scintillation appears to not dominate the fluctuations in signal amplitude, which is not surprising given the cold nighttime winter conditions at the Goldstone site. A similar analysis conducted on other Ka-band data sets such those acquired from the Mars Global Surveyor Ka-band experiments [6] support this result.

5. FUTURE PLANS AND CONCLUSION

Ka-band (32 GHz) signals amplitudes which been recorded during the 2002-2003 opposition of the Cassini spacecraft during the Radio Science GWE have been analyzed to assess atmospheric effects. The amplitude data were examined for fading and scintillation in preparation for upcoming Ka-band telemetry demonstration experiments with Mars Reconnaissance Orbiter [11].

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7. REFERENCES


\[\text{Figure 1a - 2002/349 DSS-25 X up Ka down}\]
Figure 1b - 2002/365 DSS-25 X up Ka down

Figure 2 - December 29, 2002 Ka-Band Data