First Deep Space Operational Experience with Simultaneous X- and Ka-bands Coherent Tracking

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ABSTRACT

International collaboration between the National Aeronautics and Space Administration (NASA) and the Italian Space Agency (ASI) resulted in the development of spacecraft and ground instrumentation to enable a set of Radio Science experiments on the Cassini mission that include a search for gravitational waves, a solar conjunction experiment, atmospheric occultations and gravity field measurements of Saturn and several of its satellites. Key to these experiments is the addition of a Ka-band translator to the Cassini payload to augment the telecommunications system at X-band and the Radio Science downlink at S-band, the most sophisticated radio system in deep space to date.

The Deep Space Network instrumented one 34-meter diameter beam-waveguide station in California with systems capable of simultaneous transmission and reception at X- and Ka-bands along with special antenna pointing techniques. Upgraded high-stability digital open-loop receivers augmented the tracking receivers. In order to fully take advantage of the superior stability radio link at Ka-band where the effect of interplanetary plasma noise is less than the effect at X-band, modifications were made to the frequency and timing subsystem and advanced water vapor radiometers were developed and installed as part of a media calibration system to calibrate the tropospheric effect. A multi-frequency scheme can be used to model and calibrate the intervening media of charged particles.

The first formal operational use of this new Radio Science system took place between November 2001 and January 2002 where the Cassini spacecraft was in solar opposition and a 40-day search for gravitational waves was conducted. Two additional opportunities of such searches are planned at oppositions to be followed six months later by solar conjunction experiments measuring the relativistic deflection of the radio beams as they pass near the sun.

This paper describes the new DSN science capability and highlights of the engineering work that lead to its development. It will also discuss experience with operations along with statistics and data quality.

Introduction

Radio Science investigators examine changes in the phase, amplitude, and other characteristics of a radio signal to study the atmospheres, rings and gravitational fields of the planets and their satellites as well as the sun, and conduct experiments based on the theories of relativity. The latter, such as the search for gravitational waves and improving on the accuracy of the bending parameter (gamma) drove the requirement for a higher frequency link, Ka-band, to minimize as well as fully calibrate the effect of interplanetary plasma.

An agreement between the National Aeronautics and Space Administration (NASA) and the Italian Space Agency (ASI) for solar system exploration with the Saturn-bound Cassini spacecraft resulted in the development of advanced Radio Science instrumentation for the spacecraft and ground stations based on coherent Ka-band links augmenting the telecommunications system at X-band and the Radio Science downlink at S-band, giving the mission the most sophisticated radio system in deep space to date. Italian scientists joined the Radio Science Team to collaborate on experiments with emphasis on utilizing the Ka-band links towards a search for gravitational waves and the solar conjunction experiment as well usage during the Saturn tour.

The search for gravitational waves

Gravitational waves are propagating, polarized gravitational fields which change the distance between separated test masses and shift the rates at which separated clocks keep time. Propagating at the speed of light, these waves are characterized by a dimensionless strain amplitude equal to the ratio of change in distance to the distance between test masses. Gravitational waves are extremely weak; only waves generated by extremely massive objects such as astrophysical objects undergoing extremely violent dynamics are potentially detectable.

In the Doppler tracking method of searching for gravitational waves, the earth and distant spacecraft act as free test masses. A highly stable radio signal transmitted from the ground station is phase-coherently transponded at the spacecraft and received on the ground. By comparing the frequencies of the transmitted and received signals the Doppler tracking system measures the relative dimensionless velocity between the earth and the spacecraft. A gravitational wave incident on the system causes Doppler perturbations of order of the relative velocity which is of the order of the strain amplitude. The waveform is replicated three times in the tracking record with a zero sum of these three perturbations. The limit at the high frequency band is set by the stability of the frequency standard driving the link and by the finite signal-to-noise ratio on the downlink.

After the orbital effects have been removed, the principal sources of variability are: frequency and timing system noise; propagation noise due to the solar wind as well as the ionosphere and troposphere; thermal noise in the receiver; un-modeled motion of the ground antenna; ground electronics; spacecraft transponder noise; spacecraft buffeting; gravitational radiation; and systematic errors.

Deflection of radio beam due to solar gravity

While searches for gravitational waves are conducted during solar oppositions where the effect of interplanetary plasma is at a minimum, another Cassini cruise experiment takes place during solar conjunctions. This experiment, in addition to studying characteristics of the solar corona, measures the deflection of a radio beam by the gravitational field of the sun. This effect is currently constrained to be within 0.001 of unity, the general relativistic value. The new technological developments driven by Cassini, specifically the introduction of Ka-band links will enable a test of General Relativity to a substantially greater accuracy; initial estimates show a potential improvement by two orders of magnitude. The Doppler observation should be such that the non-gravitational forces are minimized but the largest signal is obtained only at small impact parameters, where the radio beam is well within the solar corona undergoing strong frequency fluctuations. The available multiple links between the ground stations and the Cassini spacecraft will allow for nearly complete calibration of the plasma noise.

Development of the Cassini spacecraft

The Radio Science instrument on the Cassini orbiter is composed of the X-band telecommunications subsystem: a deep space transponder and traveling wave tube amplifiers; an ultra stable oscillator; and an S-band transmitter. In order to enable the levels of sensitivities sought by the Radio Science experiments, the Italian Space Agency (ASI) augmented the instrument with several flight elements at the heart of which is a Ka-band Translator (KaT). Since ASI supplied the Cassini High Gain Antenna, it was made compatible with transmission and reception at Ka-band as well as the other links.

The Ka-band Translator is a carrier-only transponder; no telemetry or range modulation is available at Ka-band. The KaT receives uplink at Ka-band and transmits a Ka-band signal at a frequency related to the uplink by a turn-around ratio of 14/15 at the assigned deep space channel assignments. The KaT is capable of generating a downlink signal with a stability measured by Allan deviation at 1000 seconds of 3×10^{-15}; pre-launch laboratory measurement of the Ka-band component showed stability of about 1×10^{-16}. Amplification of the output signal is accomplished through a Ka-band traveling wave tube amplifier producing an output power of 7.2 W when operating with one carrier and 5.7 W in the dual-carrier mode.

The KaT was designed and built by an Italian company under contract with ASI. Two units were manufactured allowing for one unit to remain in an Italian radio astronomy institute facility for testing of phenomena experienced by the unit in flight. Instrumenting the Cassini spacecraft with the Ka-band Translator led to the first ever experience with a coherent Ka-band link in deep space. Another first is the simultaneous uplink and downlink operations at X- and Ka-bands between a ground station and a planetary spacecraft.

Development of the Deep Space Network

Though their primary functions are to send commands and to receive telemetry from space probes, stations of NASA's Deep Space Network (DSN) have also been designed to be a world-class instrument for Radio Science research. As such, their performance and proper calibration directly determine the accuracy of Radio Science experiments. A 34-meter beam-waveguide antenna at the DSN complex in Goldstone, California (designated DSS-25, see Figure 1) was specifically upgraded with a suite of instrumentation for Ka-band uplink and downlink operations. This large upgrade task affected all the stations' subsystems that are relevant to acquisition of Radio Science data. These subsystems include monitor and control, antenna mechanical, microwave, receiver-exciter, transmitter, tracking, spectrum processing, and frequency and timing. A new subsystem was added at a location adjacent to this station, a media calibration technique based on advanced water vapor radiometers.

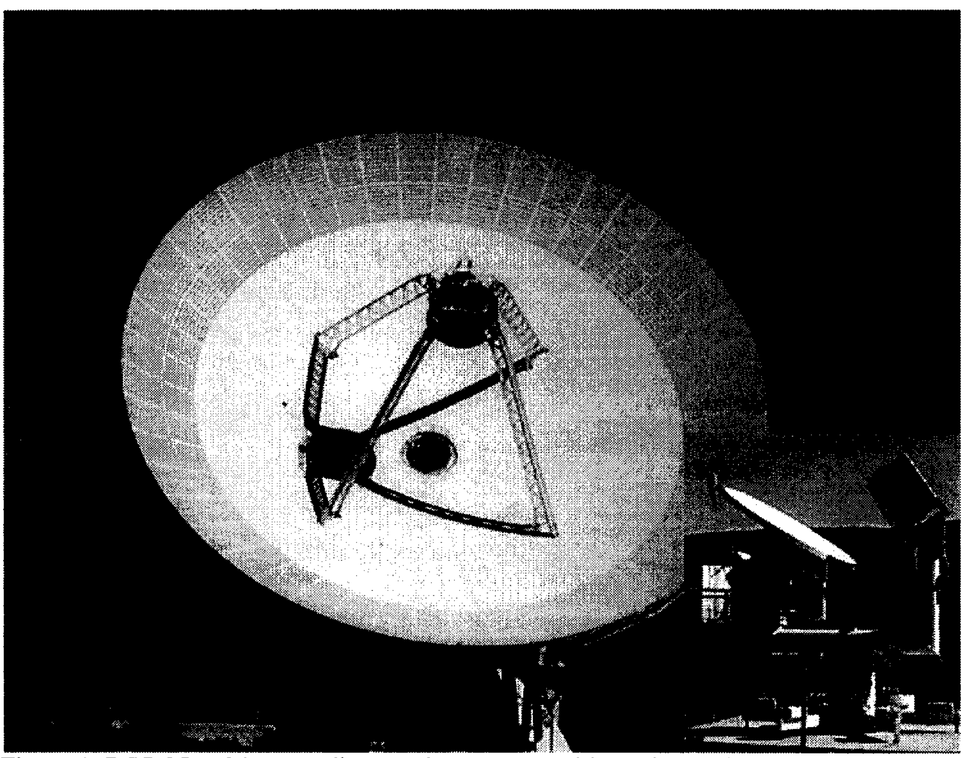

Figure 1: DSS-25, a 34-meter diameter beam-waveguide station at the Goldstone complex of the Deep Space Network. The inset is the Advanced Water Vapor Radiometer adjacent to DSS-25 for media calibration.

The surface of a DSN antenna collects the incoming energy transmitted from the spacecraft and focuses it onto the feed horn. The subreflector is adjusted in the axial and angular positions in order to correct for gravitational deformation due to the motion of the antenna between zenith and the horizon. The primary surface is a paraboloid that was modified for optimized illumination and signal stability. When transmitting, the antenna surface forms a narrow microwave beam that is directed to the spacecraft. Prior to the introduction of Ka-band, the DSN has utilized conical scanning algorithms to point the antennas. In CONSCAN, a pointing error is estimated during circular motion of the antenna compared to a prediction of the spacecraft location; but jitter resulting from this motion, although acceptable at S- and X-bands, would be too large at Ka-band frequencies. An alternate method was developed for pointing during Ka-band passes. This method introduced a monopulse tracking coupler in a single feed horn that is excited by eight symmetrically placed Ka-band waveguides, each of which is connected through combiners to generate circular polarization. An algorithm computes the aziumthal error based on the sum and differences of incoming signals and produces pointing updates.

In addition to monopulse pointing, DSN operations at Ka-band frequencies also necessitated special handling of the aberration effect, which occurs between the uplink and downlink beams. Given that the location of the spacecraft is moving in the right-ascension/declination coordinate system, the Ka-band downlink beam must be pointed, at any instance in time, to the spacecraft location one round-trip light time earlier, while the uplink beam must be pointed where the spacecraft will be located one round-trip light time later. This would result in an offset angle of about 15 milli-degrees at the distance to Saturn. While this effect is small at S- and X-bands, the effect at Ka-band, with the significantly narrower beamwidth at the 34-meter antenna, can cause a loss as large as 10 dB. The aberration correction points the receive beam at the predicted spacecraft position and the transmit beam at another position consistent with the predicted location of the spacecraft at the time of beam arrival.

As part of the Cassini Radio Science upgrade task, the open-loop receivers throughout the Network were replaced. The DSCC Spectrum Processing (DSP) Assembly was replaced with the Radio Science Receiver (RSR). The Radio Science Receiver down-converts, filters, digitizes, and records the radio signal received by the DSN from the spacecraft. Scientists use this data to reconstruct small changes in phase, frequency, amplitude, and/or polarization of the radio signal due to the propagation media or the motion of the spacecraft

Spacecraft KaT Anomaly

Early in-flight tests of the Cassini Ka-band Translator showed anomalous behavior that required intense attention from the Radio Science Systems Group (RSSG). When powered on, the KaT's free-running downlink frequency was in a region outside the channel allocation. This region, designated "bad state," was as much as 13 MHz away from the nominal region. With the problem persisting daily during the test periods, the RSSG experimented with various conditions to solve the problem. Among other ideas, the RSSG commanded the spacecraft to cycle the power to the KaT off and back on; that always brought the signal into a "good state," at least for a short time.

The original plan called for turning the power off at the conclusion of the tests until the next planned test opportunity months later. Based on empirical observations, however, the RSSG decided to change the plan and leave the unit powered on. The same conclusion was independently reached by engineers from the Italian Space Agency and the KaT manufacturer based on their ability to devise a theoretical explanation for the observed behavior.

Towards improving daily operations and stabilizing the device for the long term, a technique of sweeping the uplink signal to the KaT was developed. After many modifications, a strategy that utilized an optimum uplink power level and frequency sweep rate as well as the direction of the sweep, was selected. A sweep in the negative direction allowed the KaT to lock onto the uplink signal and remain locked for the duration of the pass.

The developed operational strategies described above were not only consistent with the theory of the behavior but eventually led to near normal operations of the KaT, after formalizing them into operational procedures. The support of the capable Italian engineers and scientists investigating the anomaly were instrumental in stabilizing the Ka-band Translator.

Remote Operations

In the early 1990s, the DSN granted a limited set of configuration control of the subsystem that specifically receives and records the radio signals in "open-loop," i.e., Radio Science Receiver, to be conducted remotely from JPL by the Radio Science Systems Group. This arrangement helped the station staff concentrate on the daily tasks associated with the primary functions of tracking, command, and telemetry services. It also allowed the RSSG to make real time science decisions affecting the configuration of the instrument. This tool proved to be essential during cases of spacecraft-related anomalies.

Media Calibration System

Also as part of the DSS-25 Radio Science Upgrade Task, a new system was developed and installed adjacent to the station (see Figure 1), an advanced media calibration system (MCS). The MCS is based on two advanced water vapor radiometers. A meteorological suite of instruments and a microwave profiler, supplemented the radiometers. Collectively, the MCS can enable the calibration of the troposphere from the Radio Science data to very high accuracy.

The operation of the MCS was the responsibility of the RSSG and was conducted remotely from JPL. The system developers advised the RSSG on the operations and conducted spot checks of data quality. The acquisition of MCS data was practically flawless.

Operational Experience

The first deep space operational experience with simultaneous X- and Ka-bands coherent tracking reflected the culmination of implementing advanced technologies on the Cassini spacecraft and the Deep Space Network. The Radio Science Systems Group, responsible for acquiring the science data, developed expertise with all the new systems, monitored the implantation and testing and handled anomalies. The goal of the operations for the test period was to conclude how to operate the KaT; the operations, in essence, attended to the use a ground system to diagnose problems with a spacecraft half a billion miles away. The goal of the operations during the two experiments to date was to maximize the quality and quantity of data at all available bands.

The first formal science support of the Cassini mission with DSS-25 started with the first Gravitational Wave Experiment (GWE1). The Cassini GWE consists of three data-taking intervals, approximately centered on solar oppositions, during November 2001-January 2002, December 2002-January 2003, and October 2003-December 2003. During GWE1, Radio Science data were acquired around-the-clock using the DSN's DSS-45 in Australia for X-band up- and downlink; DSS-65 in Spain for X-band up- and downlink; and the new DSS-25 in California for three coherent radio links: X-band uplink/X-band downlink; X-band uplink/Ka-band downlink; Ka-band uplink/Ka-band downlink.

Because of the stringent requirements on pointing of the spacecraft antenna for Ka-band observations, the Cassini spacecraft was oriented using reaction wheels, versus thrusters, and configured as a "quiet spacecraft," i.e., all other instruments and subsystems were kept in a quiescent state with no articulation nor large changes in power. Other than this aspect of the spacecraft operations, Radio Science operations concentrated on the ground stations, since the spacecraft elements of the Radio Science instrument are RF devices with no configuration to manipulate. The most one can do is command the spacecraft power subsystem to turn power on or off for a particular instrument.

In order to diagnose a problem on a distant spacecraft, the ground system had to be flexible in order to allow for the maximum number of attempts of various ideas. This is especially true for long round-trip light times. To that end, the Radio Science Receiver (RSR) came to the rescue. A new digital receiver, the RSR has a sizable selection of bandwidths and improved real time monitoring tools over its predecessor. There was extensive real-time use of the FFT displays, time history displays and log files. Engineers were also able to use a very wide bandwidth (100 kHz) on one RSR channel for searching for the Ka-band signal during anomaly testing and reserve another channel at a very narrow bandwidth for recording the data while minimizing the data volume.

During GWE1 operations, there were many cases of system "debugging." Those included the aberration correction mechanism, the monopulse system, and the stability of the thermal environment of the Ka-band transmitter at DSS-25. For monopulse, for example, it was discovered that the subreflector could not be frozen in place, as is often done with Radio Science experiments to minimize the phase shift associated with the subreflector motion; the monopulse algorithm expected a moving subreflector. The opportunities to test the end-to-end ground system with a spacecraft signals (coherent X- and Ka-band) were very limited. As a result, the period of testing with the spacecraft prior to formal transfer from the engineering developers to the operations staff with the spacecraft short and the learning period for all involved spilled into the experiment time frame. In support of these issues, several engineers from the development side traveled to DSS-25 to study the problems during GWE1. This reflected the commitment of the DSN to successful mission support and resulted in improved quality and quantity of acquired data.

Despite the initial KaT anomalies, the steep learning curve with the new systems at the ground stations, the data quality was excellent and the statistics for data quantity were impressive.

Data Quality

Figure 2 shows the spectrum of test data of the ground system electronics to illustrate their excellent stability. It displays the power spectrum of fractional frequency fluctuations versus Fourier frequency. For frequencies greater than about 0.003 Hz, the spectrum is dominated by thermal noise in the system. By ≈ 0.001 Hz there is a change in the spectral shape, indicating that we are detecting the instrumental noise. The electronics noise is as low as 2.3E-16 at 1000 second Allan deviation.

Two hours per pass were selected at high elevation angle for statistical analysis of the data quality. The pre-detection "open-loop" signal samples recorded at 1 kHz data rate were passed through a digital phase lock loop to estimate the carrier frequency as a function of time. We then removed an approximate orbit from these data by solving for a mean frequency, the Fourier component at the earth rotation frequency, and a linear trend in the frequency.

These residuals were then analyzed to produce power spectra and Allan deviation at integration times of 10, 100, and 1000 seconds. Additionally, for DSS-25 tracks, the downlink plasma contribution was isolated by taking the X-band frequency and subtracting (880/3344) times the Ka-band frequency. (For this quick look analysis, we did not attempt to correct for tropospheric scintillation using the new media calibration system).

Figure 3 shows the Allan deviation at 1000-second integration time for the quick-look data from DSS-25. The upper circles are the Allan deviation from the high-elevation, uncorrected-for-troposphere, 2-way Ka-band data. The lower plot is the inferred two-way plasma noise at Ka-band. As intended, the Ka-band up- and downlink system reduced the plasma noise at solar opposition to a secondary noise source. The tropospheric noise level (not plotted) is consistent with the Ka-band data often being dominated by tropospheric noise. On days when the total Ka-band noise level is smallest, antenna mechanical noise is probably the leading noise source. These quick-look results can be compared with the previous best-sensitivity Doppler observations (Mars Global Surveyor, taken at X-band) having average Allan deviation ≈ 4E-14.

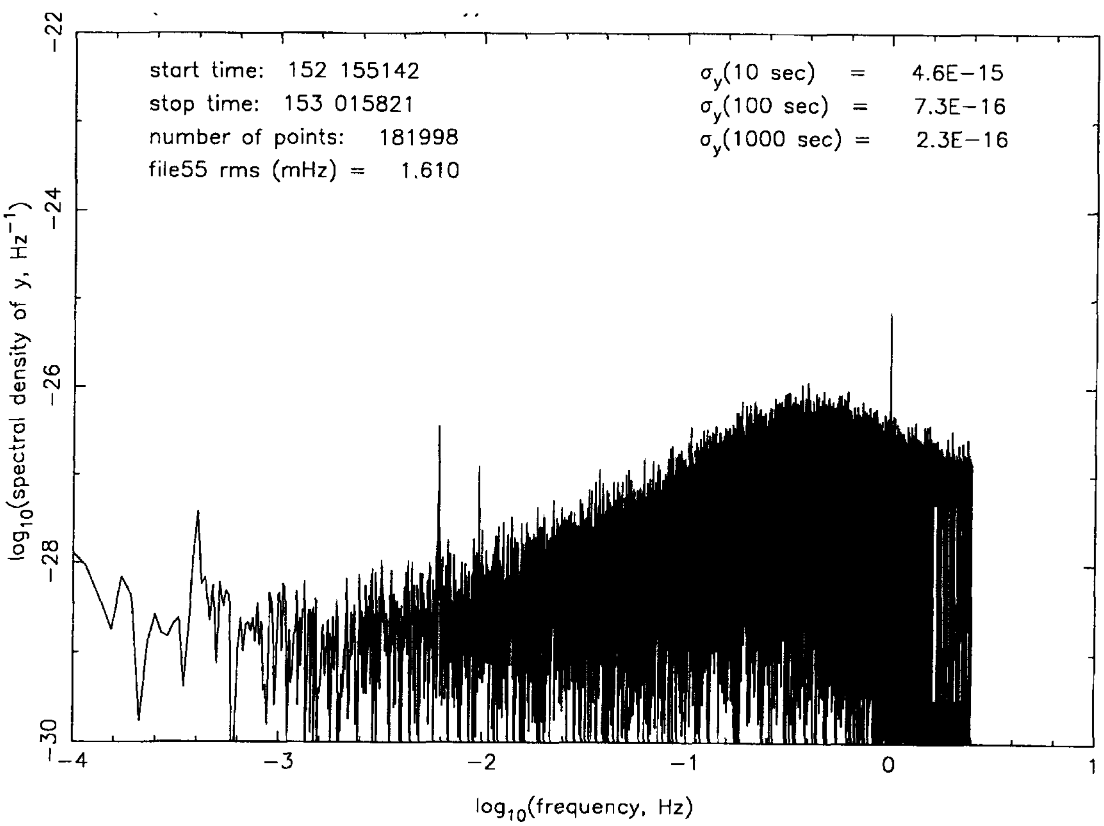

Figure 2: Spectrum of fractional frequency fluctuations in a controlled test, 2001 DOY 152-153. This test isolates the DSS-25 ground electronics, excluding the frequency and timing system, and indicates excellent frequency stability of this part of the apparatus.

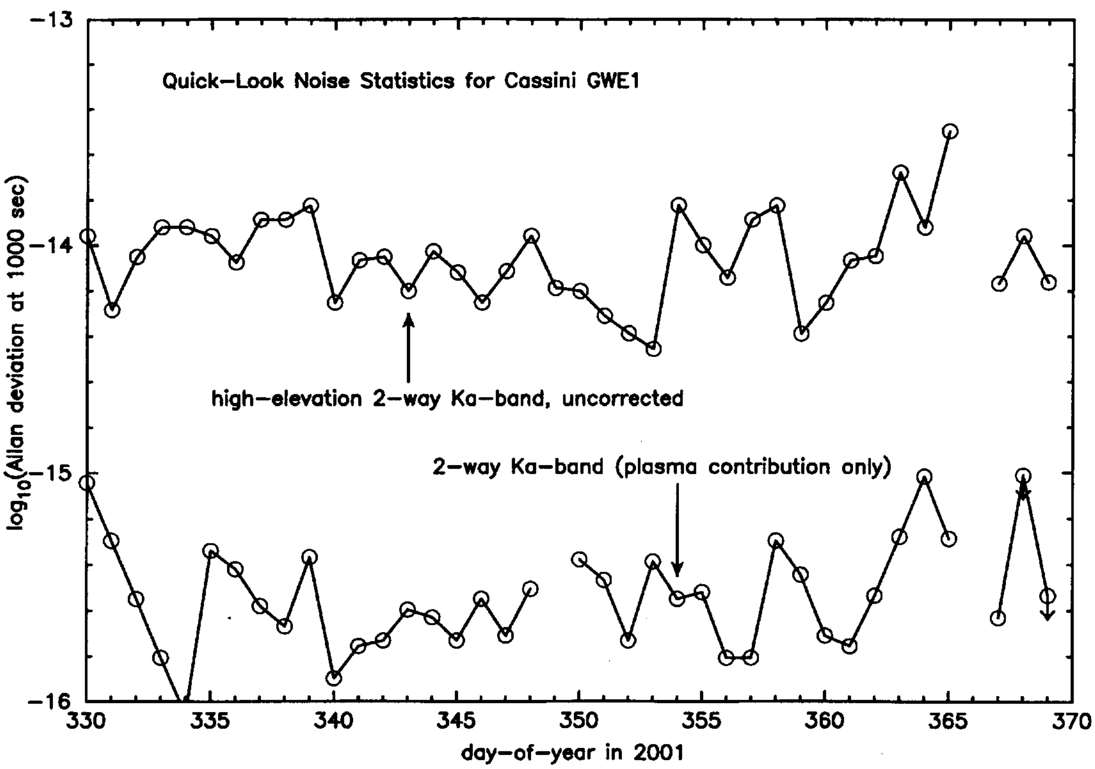

Figure 3: Allan deviation versus day-of-year for GWE1, showing the frequency stability of the total 2-way Ka-band signal (not corrected yet for tropospheric noise) and the contribution to the signal from the 2-way plasma, only.

Summary

Despite anomalies with spacecraft Radio Science components and the steep learning curve with the new systems at DSS-25, operations were very successful. The data quality was excellent and the statistics for data quantity, considering the various challenges, were impressive. This was due to the support, commitment, and hard work on the part of the entire Deep Space Network organization and the Cassini Program. The dedicated members of the Radio Science Systems Group were further motivated by the support and advise from the scientists, who are currently processing the data. The facility of remote operations allowed quick reaction to problems and superior tools for visibility and monitoring of the data and health of the instrumentation. The open communications between the various organizations cut short the time to address issues and make the experience very rewarding.