Characterizing DSN System Frequency Stability with Spacecraft Tracking Data

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Abstract— This paper describes a recent effort in characterizing frequency stability performance of the ground system in the NASA Deep Space Network (DSN). Unlike the traditional approach where performance is obtained from special calibration sessions that are both time consuming and require manual setup, the new method taps into the daily spacecraft tracking data. This method significantly increases the amount of data available for analysis, roughly by two orders of magnitude; making it possible to conduct trend analysis with reasonable confidence. Since the system is monitored daily, any significant variation in performance can be detected timely. This helps the DSN maintain its performance commitment to customers.

One challenge with using spacecraft data as input is that the measurements also include other contributions outside of the DSN ground system. Therefore, the model of expected performance, to be compared with actual measurements, needs to include the effects of flight communications equipment and Earth's atmosphere. Solar plasma effect must be accounted for, especially when the spacecraft signal, en route to Earth, traverses the region under the influence of the Sun's plasma. The spacecraft's trajectory must be accurately modeled; otherwise the non-modeled Doppler would be misinterpreted as the ground system instability.

To make it possible to process the continual stream of daily incoming data without much effort and to quickly understand the results, the processing needs to be automated and the data summarized at high level. This paper will discuss various considerations in data gathering, input validation, handling anomalous conditions, computation, and presenting the result in a visual form that makes it easy to spot items of exception/deviation so that further analysis can be directed and corrective actions followed. The paper also describes the model of expected performance and how well the actual measurements compare to it.

I. INTRODUCTION

The National Aeronautics and Space Administration (NASA) relies on the Deep Space Network (DSN) to communicate and operate its fleet of spacecraft that venture in and beyond the solar system. The DSN is comprised of 13 antennas dedicated to spacecraft tracking. These large antennas – three of 70 m and ten of 34 m – need to operate with as little vibration as possible, despite their incredibly large apertures.[1] In addition to providing typical telemetry, tracking and command functions for spacecraft telecommunications, the DSN also serves as a scientific instrument. For radio science investigation, the received signal from a spacecraft contains a lot of information on the medium through which the signal passes. By examining the signal's carrier frequency and amplitude, radio scientists can better understand the characteristics of the intervening medium, be it a planetary atmosphere or a passing gravitational wave.

To support these scientific investigations, the DSN ground system needs to be very frequency stable. The requirement on the Allan deviation – a measurement of fractional frequency stability with respect to the signal carrier – is a few parts of 10^{-15} at a 1000-s integration time. The interest of this work is on the characterization of frequency stability metrics to ensure that the DSN can meet its commitment to users.

In Section II, we will discuss the advantages (and challenges) of this new approach compared to the traditional method, which relies on special calibration measurements. Section III focuses on data processing and its automation. Section IV describes the model of expected Allan deviation. Section V presents findings from actual measured Allan deviations.

II. ADVANTAGES AND CHALLENGES

Traditionally, the DSN relies on a special calibration effort to measure the system frequency stability performance; however, there are several challenges with this traditional approach.

First and foremost is the difficulty in scheduling the antenna time for calibration activities. Antenna time is always in demand for spacecraft tracking. The calibration sessions typically must run for several hours in order to adequately quantify the performance at long integration times, such as 1000 s. Also, the calibration requires manual

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[1] The DSN has three additional antennas devoted to radio astronomy studies and educational program; however, they are not part of this study.

setup and oversight, which can further limit test opportunities due to limitations in personnel availability.

Historically, there was only enough opportunity to conduct one calibration measurement on each antenna annually. If the measurements produced questionable results, it was quite a challenge to repeat the test. In contrast, by using operational spacecraft tracking data available daily, we can tap into an abundant amount of data and produce a timely assessment on the system performance. For example, if an antenna experiences poor performance a few days before a scheduled radio science experiment, the problem would be detected and corrective action applied to make the equipment ready in time for the experiment.

The second difficulty with the calibration is that the test configuration cannot capture contributions from certain elements in the system. The effect of antenna motion/vibration is not included because the test signal does not get radiated onto the antenna dish; rather, the signal is internally re-routed from the transmitting uplink to the receiving downlink prior to radiation. The noise contribution from the station frequency reference (e.g., the hydrogen maser) is also excluded. In a configuration with zero-roundtrip light time, any frequency perturbation in the station reference will cause a glitch on the uplink and an identical and opposite glitch on the downlink, resulting in a cancellation. A third effect not captured is the filter response to different operating frequencies. Calibration is typically done with the test signal fixed at one frequency, in the interest of simplifying the test procedures and minimizing the execution error. As such, the effect of the filter distortion on true spacecraft signal, which would move across the operating bandwidth under the influence of Doppler, is not captured.

In contrast, with the new approach, the spacecraft signal is radiated (on the uplink) and received (on the downlink) by the antenna. Thus, the antenna motion and vibration are part of the observed carrier frequency. With finite, non-zero round-trip light time – on the order of 10,000 s for Cassini spacecraft that orbits around Saturn – noise in the frequency reference is reflected in the uplink and downlink at different times and is thus no longer canceled.

There are however some challenges with using spacecraft tracking data. The received signal contains not just the contribution from the DSN ground system but also those from spacecraft telecommunication equipment, the Earth atmosphere, and the interplanetary plasma. The measurements are sensitive to spacecraft trajectory model error as well. The more accurate we can model the spacecraft trajectory, the less there will be residual Doppler error; thus, the better chance we have to qualify the system frequency stability

Because of these benefits and challenges, it is best to view both new and traditional methods as complementary – rather than one against the other so that together they can establish a better understanding on the system performance.

III. Data Processing

A. Setup

Cassini spacecraft tracking data are used as an input source. This choice takes advantage of the abundant data offered by daily Cassini tracks. Occasionally, the spacecraft transmits multiple downlinks at S-, X-, and Ka-band to support the mission's radio science experiments. The multi-frequency configuration offers an opportunity to examine the system performance differently from the single downlink passes. In the case of simultaneous X- and Ka-band reception, both signals share certain common noise sources such as spacecraft antenna, ground antenna and frequency reference. When we look at the differential X- and Ka- band data, there are fewer noise contributors. This difference enables us to isolate and estimate the magnitude of certain error components.

B. Processing

The automation script is activated once a day. It first searches for new data files from the Cassini mission in the DSN data repository. The consecutive phases of the received signal are differenced and converted to fractional frequency. The script then looks for an appropriate predicted frequency file for that pass and uses it to remove the two-way Doppler so that the Doppler effect does not mask the smaller frequency fluctuation that the system tries to measure.

This first round of processing provides a preliminary glimpse of the system stability performance; but the result is often not accurate enough for the final validation due to remaining error in the trajectory model. A second round of Doppler compensation is done several weeks later when the mission navigation team supplies a more accurate model of spacecraft trajectory. The new model is created by leveraging on tracking data received from recent tracks. Figure 1 shows a sample improvement in the Allan deviation between preliminary and post refinement processing. The improvement is typically at a long integration time, near and above 100 s.

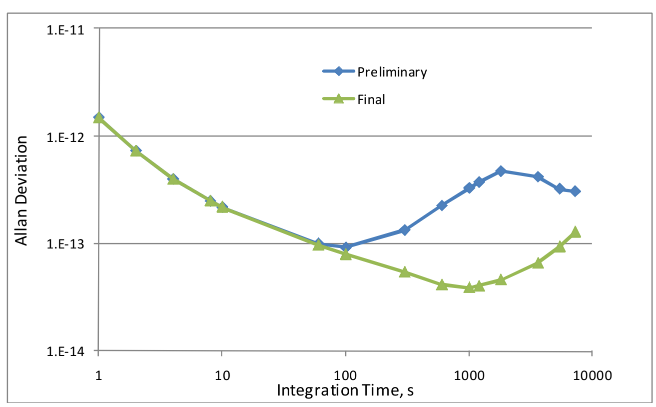

Figure 1. Allan deviation with pre- and post-refinement processing

C. *Data validation*

After the Doppler has been removed from data input, the residual frequency measurements are ready for Allan deviation computation. However, the data are not always valid and exceptions in the input data set need to be identified and corrected. Some of these exceptions are caused by planned events, others unplanned. The script tries to mitigate these impacts through detection and correction.

For planned events, the processing script scans through the mission planning sequence for events known to affect the quality of the observed carrier frequency. An example is the activation of a spacecraft reaction control sequence. Such an action changes the relative velocity between the spacecraft and the Earth tracking antenna, and thus affects the observed carrier frequency. To prevent this error from affecting the frequency stability assessment, the portion of affected data is excluded from the Allan deviation computation. Another example is the handling of possible solar plasma effect. As a spacecraft moves closer to the Sun–Earth line of sight, its signal traverses the region affected by the solar varying plasma. The signal frequency and power are then subjected to distortion. While there is no corrective action to this phenomenon, by correlating the expected Sun–Earth–Probe (SEP) angle against the stability measurement, we can explain the reason for the observed increase in the frequency instability.

For unplanned events, such as occasional data missing or out of bounds, the script would try to replace it with a statistically equivalent data point. The processing determines the average and standard deviation of measurements throughout the pass. Data points that are missing or significantly exceed the three-sigma range are replaced with the average value. To protect the data integrity against the potential of introducing many artificial replacements, the data correction is limited to only occasional missing one-second data point rather than gaps of several seconds.

IV. PERFORMANCE MODEL

The model for expected stability includes the effects from the DSN ground system, the spacecraft communications flight equipment, the Earth atmospheric plasma, and the solar plasma. The total instability is the root-sum-square of all contributing factors. Reference [1] provides a good detailed description on the noise budget expected for the observations.

The DSN ground system portion includes contributions from the antenna, the microwave low-noise amplifier, the transmitter, the receiver, and the frequency reference. Among these elements, the antenna contribution seems to be the largest. The estimates are based on a collection of measurements – some from special calibration sessions with the traditional method discussed earlier in Section II; others from specific measurements at component level, [2] and [3].

The flight equipment includes the spacecraft antenna, the receiver, and the transmitter. Due to a lack of concrete data on the stability measurement of flight equipment, we model this effect as 20% of the typical published value for the stability of a spacecraft oscillator. The value of an oscillator instability is indicated in [4]. Because we only process data in a two-way configuration – a configuration where the ground system generates an uplink and receives the turned-around downlink from spacecraft - the effect of spacecraft frequency reference (i.e., the oscillator) is not included.

For media contribution, troposphere effect on the uplink and downlink are treated as two independent, non-correlated factors due to the long round-trip light time relative to the atmospheric changing time constant. The interplanetary plasma effect is treated similarly. Numerical values for the model are based on [5].

Signal-to-noise ratio (SNR) of the received signal carrier power also affects the estimation of carrier frequency. The higher the SNR, the less noise there is. The Cassini spacecraft generates a relatively high SNR, about 45 dB carrier power to noise spectral density; thus, the thermal effect is quite small, which enables us to observe other effects better.

Table 1 shows various contributing noise sources, their estimates, and the expected total. It was computed with a large SEP angle where the solar plasma effect is relatively small. The ground system contribution dominates at the 1-s integration time. At 10 s, media effect is slightly larger than ground system. At 100 s and 1000 s, the media effect and the spacecraft contribution are the dominant factors.

TABLE I. MODEL OF EXPECTED ALLAN DEVIATION

Contributing Elements	σ(1s)	σ(10s)	σ(100s)	σ(1000s)
Thermal SNR	1.8E-13	1.8E-14	1.8E-15	1.8E-16
DSN Ground System	6.9E-13	1.2E-13	2.2E-14	4.9E-15
Spacecraft System	5.7E-14	2.8E-14	2.8E-14	2.8E-14
Media	9.1E-14	1.5E-13	5.3E-14	2.8E-14
Total	7.2E-13	2.0E-13	6.4E-14	4.0E-14

V. RESULTS

Figure 2 shows a sample of observed Allan deviation in January 2009 at one of the 34-m antennas (Deep Space Station DSS-25). The data show a good consistent behavior and reasonably agree with the model. The variations at 1-s, 10-s and 1000-s integrations are small – with the maximum value being no more than 50% of the minimum value. Variation at the 100-s integration, however, is much greater where the maximum value is about 300% higher than minimum value.

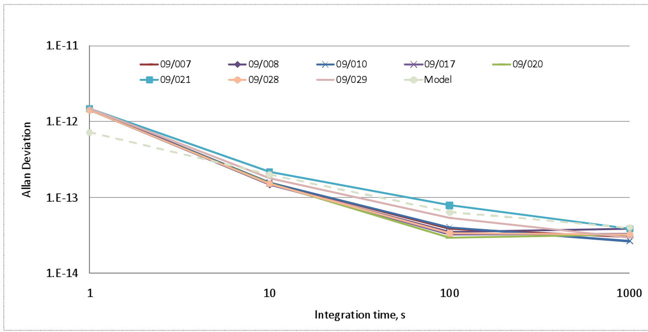

Figure 2. Observed frequency stability from Cassini spacecraft at a 34-m antenna, January 2009

Figure 3 shows the X-band Allan deviation observed and predicted, from January to November 2009. Also shown are the SEP angles. The influence of the solar plasma, when the SEP angle drops below 40 degrees, can be seen with a gradual increase in the observed Allan deviation of 1-s integration. The plasma influence starts earlier for longer integration times at 100–1000 s.

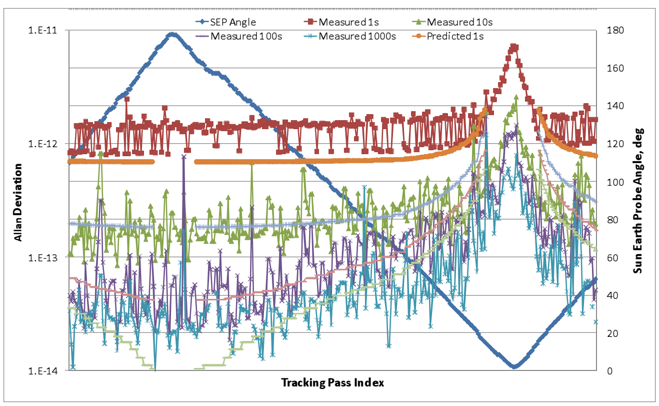

Figure 3. Observed and predicted Allan Deviation in 2009, with changing SEP angle

To aid with the data assessment, the results are visually presented in a form of dashboard, as in Figure 4. Each pass is displayed as a dot whose color (red or green) is tagged based on how the measured Allan deviation compared against the threshold. The dashboard layout shows the day of year (DOY) the data collected and the specific antenna (Deep Space Station, DSS) where tracking took place. This allows us to assess the relative performance among the antennas. To examine the pass that is of concern, one can click on each pass/dot to access more detailed data and plots. More general information on the performance dashboard design can be found in [6].

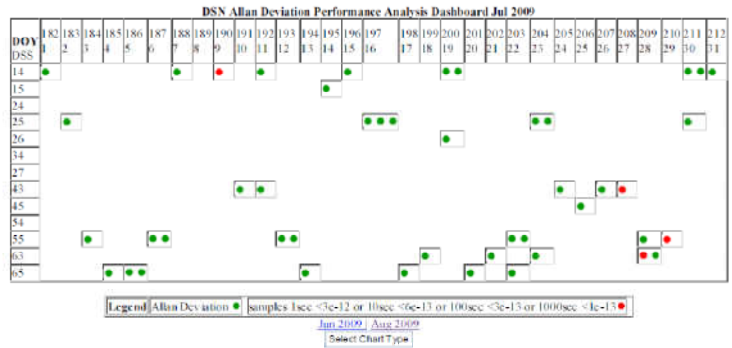

Figure 4. Dashboard of Allan Deviation for July 2009 performance

VI. SUMMARY

This paper has described a new analysis capability developed in the DSN to monitor the system frequency stability to ensure good support for radio science experiments. The data processing is automated, relying on daily tracking data from the Cassini spacecraft for performance assessment. A model on the expected performance (which includes all contributors from the ground to flight and intervening media) is discussed. The ground system contribution is dominant at 1-s integration, while spacecraft and media effects are quite significant at longer integration times of 100–1000 s.

Compared to the traditional reliance on relying on special calibration activities to assess the ground system performance – which happens infrequently and does not offer a complete picture of the ground system anyway - the new approach offers more timely examination of system performance; however, its measurements encompass more contributions outside of the ground system. Because there is no capability to independently measure the effect of media or spacecraft components, one can only approximate the contribution of the ground system, but not with great precision.

Overall, the results indicate a good agreement between measurements and the model; the largest deviation occurs at the 100-s integration. The data also show a good match to the model regarding the effect of solar plasma, especially near solar conjunction.

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