Pointing-Vector and Velocity Based Frequency Predicts for Deep-Space Uplink Array Applications

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Abstract— Uplink array technology is currently being developed for NASA's Deep Space Network (DSN) to provide greater range and data throughput for future NASA missions, including manned missions to Mars and exploratory missions to the outer planets, the Kuiper belt, and beyond. Here we describe a novel technique for generating the frequency predicts that are used to compensate for relative Doppler, derived from interpolated earth position and spacecraft ephemerides. The method described here guarantees velocity and range estimates that are consistent with each other, hence one can always be recovered from the other. Experimental results have recently proven that these frequency predicts are accurate enough to maintain the phase of a three element array at the EPOXI spacecraft for three hours. Previous methods derive frequency predicts directly from interpolated relative velocities. However, these velocities were found to be inconsistent with the corresponding spacecraft range, meaning that range could not always be recovered accurately from the velocity predicts, and vice versa. Nevertheless, velocity-based predicts are also capable of maintaining uplink array phase calibration for extended periods, as demonstrated with the EPOXI spacecraft, however with these predicts important range and phase information may be lost. A comparison of the steering-vector method with velocity-based techniques for generating precise frequency predicts specifically for uplink array applications is provided in the following sections.

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1. INTRODUCTION

Coherent arraying of antennas transmitting uplink signals to a spacecraft is a novel concept that will greatly increase NASA's deep-space communications capabilities in the future [1, 2, 3, 4, 5]. Typically, deep-space missions require the capability to command the spacecraft right after launch, during cruise, and after encountering the target, in order to provide two-way communication and ranging. In addition, in-flight reconfiguration may be required to accommodate unforeseen changes in mission objectives. The use of antenna arrays enables much greater data-rates, greater effective operating distance, and cost-effective scaling for more demanding future missions through a highly flexible design philosophy, via the inherently parallel architecture of antenna arrays.

The DSN uplink arrays are arrays of N microwave antennas operating at X-band, transmitting signals that add coherently at the spacecraft, thus providing a power gain of N^2 over a single antenna. However, earth rotation and consequent relative motion between the spacecraft and the transmitting antennas requires the generation of extremely accurate frequency predicts for each antenna in order to cancel differential Doppler and enable coherent combining at the spacecraft. This gain can be traded off directly for N^2 higher data rate at a given distance such as Mars, providing for example HD quality video broadcast from earth to a future manned mission, or it can provide a given data-rate for commands and software uploads at a distance N times greater than currently possible with a single antenna.

2. UPLINK ARRAY FREQUENCY PREDICT ALGORITHMS

The requirement to maintain coherence of the uplink array carriers at the spacecraft make it necessary to refine the existing single-antenna predicts, and even develop a new approach to generate greatly improved frequency predicts specifically for arraying applications. With the relatively long baselines formed by the Apollo complex (258m to 500m), it was found necessary to refine the positions of the antenna phase centers, after position errors as large as 60 cm were discovered in the DSN data-base. The long baselines lead directly to time-varying differential Doppler between the array antennas (due primarily to earth-rotation), hence any inaccuracy in the antenna position vectors can lead to significant frequency prediction errors. In a previous experiment, the position errors in the DSN data-base led to differential frequency errors of approximately 1 milli-Hz in the ITT frequency predicts (the official predicts supplied to the stations) used during the previous EPOXI Uplink Array experiment (February 8th, 2008). Accurate position vectors derived from previous VLBI measurements were used to yield much more accurate position vectors, and hence led to greatly improved frequency predicts for the uplink array.

The pointing-vector approach to frequency predicts is based on the observation that the differential Doppler frequencies are the most important components of the frequency predicts for array applications, instead of absolute frequency accuracy. In general, frequency predicts are designed to freeze the received frequency at the spacecraft at a predetermined value, by cancelling Doppler due to earth rotation and spacecraft trajectory dynamics. However, the Small Deep-Space Transponder (SDST) aboard EPOXI operates with a 100 Hz loop bandwidth, and therefore it can easily track out small deviations from the design frequency after signal acquisition: therefore, it is sufficient to relate the frequency predicts for the array antennas to the reference antenna predicts, which need to be accurate enough to enable tracking by the SDST.

The pointing-vector based predicts posses several advantages over alternative approaches. Calculation of projected geometric distances (which are needed for array phase alignment) from dot products are numerically more stable than calculations with differences of large frequency quantities. Another advantage is the inherent geometric consistency of the predicts. Frequency predicts can be calculated from derivatives of projected geometric distances, and these same geometric distances can be calculated from frequencies. Note that the pointing based predicts are primarily constrained to be geometrically consistent and then, if possible, to stop the phase at the spacecraft. Other predicts are designed to stop the phase as a primary constraint and consider geometric consistency to be secondary. Absolute frequency differences between the pointing based predicts and other predicts of up to 20 Hz, and differential phase differences as high as 100 degrees, have been observed. It is not clear which predicts actually freeze the phase at the target, but all predicts are well within the operational parameters of SDST transponders.

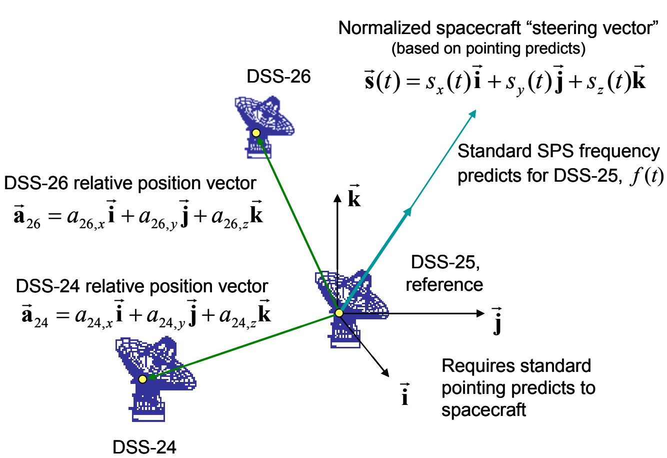

Figure 1. Components of pointing-vector based frequency predicts.

Referring to Fig. 1, the position vectors from the reference antenna, DSS-25, to the array antennas (DSS-24/26) have been determined to 7 decimal point accuracy (in meters), using very accurate VLBI derived solutions. These position vectors refer to the phase-centers of the antennas, which are defined as the intersection of the azimuth and elevation axes. The antennas must be pointed towards the spacecraft to within a small fraction of their 70 millideg beamwidths, however this is accomplished routinely using operational pointing predicts derived from earth and spacecraft ephemerides.

Using any adequate single-antenna frequency predict for DSS-25 as reference, the differential frequencies for the auxiliary array antennas can be obtained by forming the inner product of the normalized pointing vector and the position vector from the reference antenna, as shown in Fig. 5, for each predict-point in time. The single-antenna frequency estimates already contain large Doppler due to relative motion between the reference antenna and the spacecraft. Converting relative velocities to Doppler frequencies at X-band generally requires the use of the relativistic Doppler equation: $f = \sqrt{(1 - v/c)/(1 + v/c)}\, f_c$. The instantaneous pathlength difference to the target between the reference and the auxiliary antennas can be converted to an instantaneous phase difference via multiplication by $2\pi / \lambda$, where $\lambda \cong 4$ cm is the wavelength of the nominally 7.18 GHz carrier. Referring to Fig. 5, the instantaneous pathlength difference can be determined as $f_{\Delta,Q}(t) = \frac{2\pi}{\lambda}\vec{\mathbf{a}}_Q \cdot \frac{\partial}{\partial t}\vec{\mathbf{s}}(t)$ for the Q-th auxiliary antenna, where Q = 1, 2, 3, in the fixed reference-frame of the array. The frequency difference between the Q-th antenna and the reference antenna, in this reference frame, is given by the rate of change of the pointing vector: $f_{\Delta,Q}(t) = \frac{2\pi}{\lambda}\vec{\mathbf{a}}_Q \cdot \frac{\partial}{\partial t}\vec{\mathbf{s}}(t)$. Finally, the frequency predict for the Q-th antenna is the sum of the reference antenna predict and this frequency difference: $f_Q(t) = f(t) + f_{\Delta,Q}(t)$.

The Navigation and Ancillary Information Facility (NAIF) at JPL offers an information system named "SPICE" to assist scientists in planning and interpreting scientific observations from space-borne instruments. SPICE is also widely used in engineering tasks needing access to space geometry. SPICE is focused on solar system geometry, time, and other related information. The SPICE system includes a large suite of software mostly in the form of subroutines, which customers use to read SPICE files and to compute derived observation geometry, such as altitude, latitude/longitude, and illumination angles. SPICE data and software may be used within many popular computing environments. The software is offered in FORTRAN, C and IDL®, with a MATLAB® environments.

After the DSN database had been corrected, it was observed that the above procedure was equivalent to and could be carried out more efficiently using NAIF range predicts directly, together with the improved position vectors, to obtain identical results. This is not surprising since pointing vectors should be the same as normalized range vectors. Therefore the actual frequency predicts for DOY-179 used during this experiment, were computed using NAIF range predicts every 22 seconds. The frequency predicts for the reference antenna, DSS-25, were also derived in this manner, for the DOY-179 experiment. Until recently the NAIF range and velocity predicts were not consistent with each other. Relative range and velocity estimates are obtained through Chebyshev expansion polynomial evaluations but the relative velocity was not constrained to equal the derivative of the relative position. The inconsistency was not significant for single antenna applications but manifested itself as a diurnal accumulated phase error (between instantaneous range and velocity predicts) of up to 100 degrees for array applications. As a result, an average velocity (from which frequency predicts were derived) consistent with range was estimated by computing the difference in range every 22 seconds. While the discrete difference is but an approximation of the range derivative, it is accurate enough for trajectories in which the magnitude of the relative velocity is dominated by Earth rotation. The range-velocity inconsistency has since been eliminated in version N62 of the SPICE toolkit released March 2008. No compensation for tropospheric delay was implemented for the DOY179 experiment.

3. SIMULATION AND EXPERIMENTAL RESULTS

For comparison during the experiment, and to provide some degree of verification, three other sets of frequency predicts were derived using different techniques. These were: SPS predicts derived with development software; official ITT predicts using operationally approved software; and Custom predicts using "forward" and "backward" predicts were first derived, then averaged to obtain the final result. The key features of these techniques are as follows:

a) The ITT predicts are generated from modified versions of the NAIF kernels which take into account general relativity effects such as path length increases from gravitational effects of massive bodies. Tropospheric compensation based on a seasonal zenith delay model and Chao Mapping Function [7] model is supported by both ITT and SPS but was not used in this experiment.

b) For the Custom Predicts, SPICE Routines from NAIF were used in developing a FORTRAN program to provide the various parameters of interest in support of the EPOXI experiment. Directions (AZ-EL), geometric path lengths, RF phases, and Doppler frequency shifts for DSN Stations to EPOXI were evaluated. In implementing the program, as shown in Fig. 2, a forward pass from the transmit station (Tx) to the spacecraft (Sx), and a backward pass from spacecraft (Sx) back to the station (Tx) were first computed. The pass involved the calculation of distance R and time delay LT to the target spacecraft, as well as the velocity v at the target. These values were then used in calculating the transmit frequency F_t at the given time T_0 at the transmit station needed to provide the given frequency F_r at the spacecraft at calculated time T_r.. The actual values used in processing were then obtained by averaging over the forward and backward passes which provide the most accurate results. In this way, a set of ephemeris data at the desired range of UTC times are calculated. The main NAIF routine utilized is SPKEZR which returns the state (position and velocity) of a target body relative to an observing body, optionally corrected for light time (planetary aberration) and stellar aberrations. Tropospheric compensation was not added.

c) SPS predicts used the same algorithms as the ITT predicts, except that operational constraints are relaxed, so that the most recent updates of ephemerides and kernels are used, which however may not be approved for operational applications.

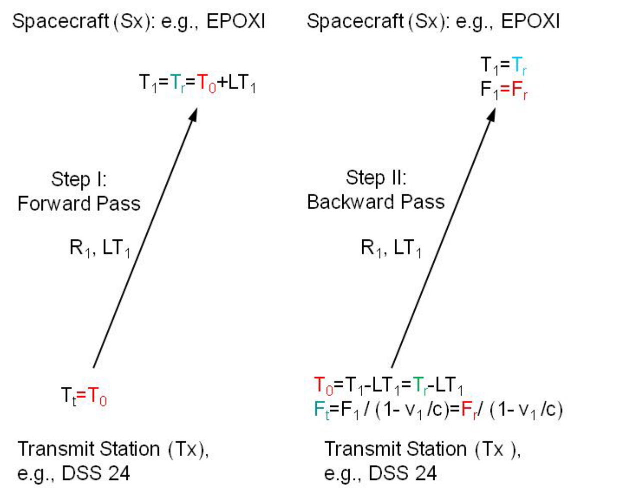

Fig. 2. Graphic representation of steps in time/distance calculations from Ground Station to the Spacecraft.

A comparison of the four techniques, namely ITT, Custom, SPS and Pointing-Based, is shown in Figs 3a, b, and c, for the third predict interval spanning 1500-1800 UTC on DOY-179. The dark blue curves refer to the DSS-24/25 baseline, and the pink curves to DSS-25/26. Note the excellent agreement between the pointing-vector based and the custom predicts: the peak difference is about 0.5 degrees for DSS-24/25, and about 2.25 degrees for DSS-25/26. These differences would not lead to any measurable power fluctuations at EPOXI, hence these predicts would yield essentially identical performance during the third interval.

However, both the SPS and ITT predicts accumulated phase linearly with respect to the pointing vector predicts, amounting to approximately -17 degrees and -25 degrees for ITT and SPS, respectively, along the DSS-24/25 baseline, and 20 degrees and 32 degrees for the DSS-25/26 baseline. It can be inferred that the developmental SPS and operational ITT predicts differ from each other by only -8 degrees and 12 degrees for the two baselines, hence either predict set would yield similar performance.

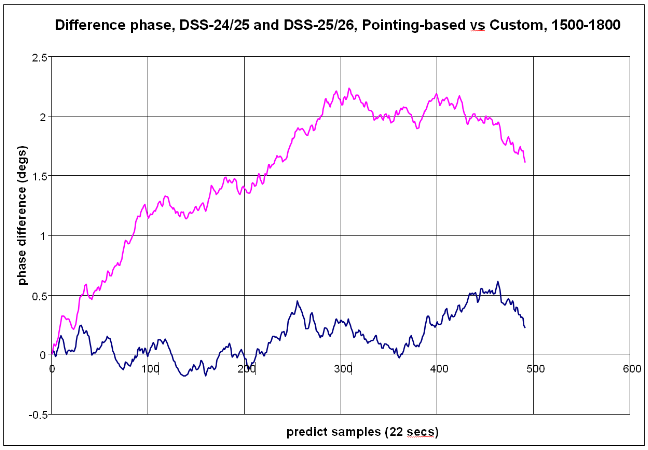

Figure 3a. Comparison of differential phase errors for Pointing-based and Custom frequency predicts for both baselines: third tracking interval.

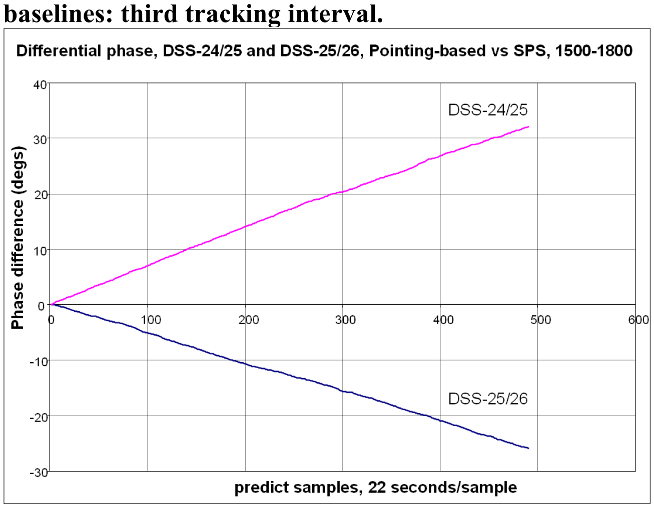

Figure 3b. Comparison of differential phase errors for Pointing-based vs ITT frequency predicts for both baselines: third tracking interval.

An example of the application of the Pointing-based frequency predicts is shown in Fig. 4, where stable combined power can be seen for both two-antenna combined power (e.g. 13:26:29 SCET) and three-antenna combined power (e.g. 13:40:53 SCET). Power dips and fluctuations are due to transmission of No-Op commands, phase-ramp calibration, and other experimental activities carried out during the track. However, the combined powers remained stable throughout the duration of the track, for more than five hours.

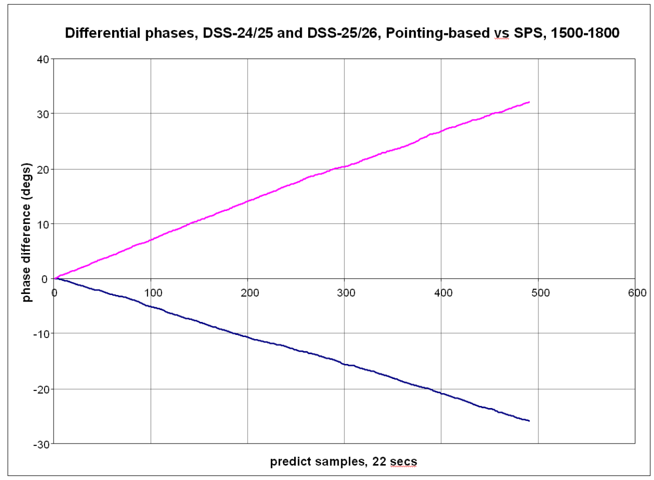

Figure 3c. Comparison of differential phase errors for Pointing-based vs ITT frequency predicts: third tracking interval.

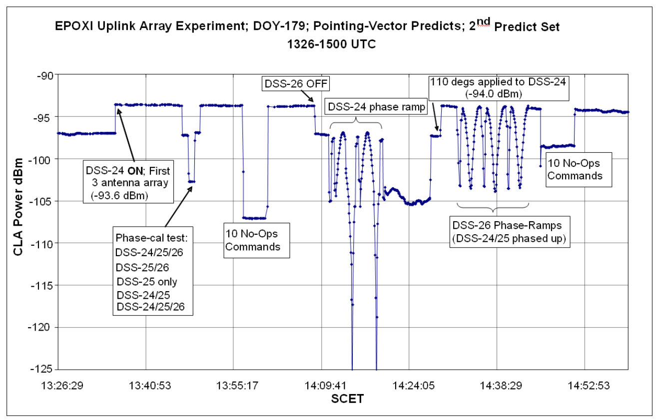

Figure 4. Real-time CLA data, Pointing-Vector based predict set.

The primary significance of this experiment was the demonstration of the ability to compensate for differential Doppler frequencies between all three baselines of a three-antenna uplink array, to an accuracy required to maintain coherence between the transmitted fields over time-scales typical of an operational pass. This will enable the use of powerful arrays to transmit commands and data to deep-space missions, greatly increasing NASA's future communications and command capabilities.

4. SUMMARY AND CONCLUSIONS

The first stable arraying of X-band carriers at interplanetary distances from up to three operational antennas was demonstrated experimentally with the EPOXI spacecraft, on June 27, 2008. The experiment was carried out under real-world conditions at the Goldstone Deep-Space Communications Complex, using the 34 meter BWG antennas located at DSS-24, DSS-25 and DSS-26 of the Apollo complex at Goldstone. The key component of this experiment was the determination of the differential Doppler frequency between all three Apollo stations, in order to effectively stop any phase rotation at the spacecraft, when all three antennas were transmitting. This meant that the frequency predicts currently employed by the DSN had to be improved by about two orders of magnitude, in order to reduce power cycling at the spacecraft. The approach taken was to assume that the current frequency predicts were accurate enough to enable carrier lock and phase tracking by the spacecraft, which typically operates with 100 Hz loop bandwidth, and to generate differential frequency offsets based on array-spacecraft geometry.

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REFERENCES

1. V. Vilnrotter, Dennis Lee, “Uplink Array Experiment with the Mars Global Surveyor (MGS) Spacecraft,” IPN-Progress Report 42-166, August 15, 2006.

2. V. Vilnrotter, D. Lee, R. Mukai, T. Cornish, P. Tsao, “Three-antenna Doppler-delay Imaging Of The Crater Tycho For Uplink Array_Calibration Applications,” IPN Progress Report 42-169, May 15, 2007.

3. L. Paal, R. Mukai, V. Vilnrotter, T. Cornish, and D. Lee, “Ground System Phase Estimation Techniques for Uplink Array Applications,” IPN Progress Report 42-167, November 15, 2006.

4. Vilnrotter, Mukai, Lee, “Uplink Array Calibration via Far-Field Power Maximization”, IPN Progress Report 42-164, February 15, 2006.

5. V. Vilnrotter, D. Lee, R. Mukai, T. Cornish, P. Tsao, “Doppler-Delay Calibration of Uplink Arrays via Far-Field Moon-Bounce Power Maximization,” Proceedings of the 11-th ISCOPS Conference, Beijing, May 15, 2007.

6. Acton, C.H.; "Ancillary Data Services of NASA's Navigation and Ancillary Information Facility;" Planetary and Space Science, Vol. 44, No. 1, pp. 65-70, 1996.

7. Chao, C. C., “The Tropospheric Calibration Model for Mariner Mars 1971,” JPL Technical Report 32-1587, pp. 61-76, 1974.

BIOGRAPHY

Philip Tsao *is a new member of the Communications Networks Group at JPL. He received a BEE from Georgia Tech in 1999 and an MSEE from Caltech in 2001 where he pursued research in collective robotics. From 2001 and 2005 he was a Systems Engineer with Raytheon Space and Airborne Systems where he supported radar software and mixed signal circuit design efforts.*

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