IPN Progress Report 42-199 • November 15, 2014

Advanced Calibration Technique for Accurate Three-Way Spacecraft Ranging

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ABSTRACT. — Ranging measurements produced by the Deep Space Network (DSN) are used for determining spacecraft (S/C) position. For the past 40 years, two-way ranging measurements, where a single station performs uplinks and downlinks, have been contributing to accurate deep-space navigation. The performance of ranging measurement has been steadily improving and currently provides accuracy at the 1-m level in one-way distance for systematic errors. Unlike two-way ranging, three-way ranging, where different stations are used for uplink and downlink, is not used in the navigation data acquisition due to a larger systematic error. The large systematic error in three-way ranging is mainly due to the Deep Space Station (DSS) not being able to correctly calibrate internal DSS delays, and the DSN currently commits three-way ranging measurement with a 1-sigma systematic error of 100 m in one-way distance. As an S/C travels farther away from Earth, the DSN must prepare for conditions of long round-trip light time (RTLT), where conventional two-way ranging measurement is no longer feasible. The new method was developed to reduce unmodeled biases in the DSS delay for three-way ranging, to 2 m maximum in one-way distance from the existing 100 m of systematic error.

I. Introduction

Interplanetary spacecraft (S/C) navigation uses three primary types of measurements for orbit determination: Doppler, differential one-way range (delta-DOR), and ranging. Doppler is a measurement of the S/C range rate using the Doppler shift of the signal, delta-DOR is a measurement of the angular position of the S/C, and ranging is a measurement of the S/C distance.

For ranging, the Deep Space Station (DSS) modulates a ranging code on the uplink carrier and transmits it to the S/C, where it is demodulated and retransmitted back to the DSS. The DSS measures the round-trip phase delay between transmission and reception of the ranging code. The measured two-way phase delay allows the determination of the time delay between the DSS and the S/C [1]. In July 2015, for the Pluto encounter, the round-trip light time (RTLT) of New Horizons Pluto Charon (NHPC) will reach 11 hours, and it will no longer be feasible for a single DSS to receive any return two-way signal within the view period.

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

For improved navigation, ranging is still needed, which requires three-way range reception where the rising station receives the setting station's ranging returns.

The new method was developed to reduce unmodeled biases in the DSS delay for three-way ranging, to 2 m maximum in one-way distance from the existing 100 m of systematic error. This article describes current and new methods of calibrating the DSS delays and the test results from five S/C tracks.

This article describes:

- Existing and new methods of calibrating the DSS delays
- Error contribution analysis
- Test results from five S/C tracks
- Data delivery impacts
- DSN operation revision
- Future considerations

II. DSS Ranging Measurement and Calibration

Navigation uses the DSN-provided measurement and calibration data to determine the topocentric range, which is the time delay for the ranging modulation to propagate from the DSS reference location through the propagation media to the S/C reference location and back:

$$\text{Topocentric Range} = (\text{Range Measurement}) - (\text{S/C Delay}) - (\text{DSS Delay}).$$

The DSS reference location is at the intersection of the antenna elevation and azimuth axes. The S/C reference location is at the aperture plane of the S/C antenna. The ranging measurement includes DSS and S/C delays, which must be removed in order to determine the topocentric range. There is no direct method to measure a DSS delay that is the sum of the delay between the uplink ranging assembly (URA) and the DSS reference location and the delay between the receiver and ranging processor (RRP) and the DSS reference location, as shown in Figure 1.

III. DSS Delay Calibration and Error

A. Two-Way Ranging

For two-way ranging, the DSS transmits a modulated ranging code onto the uplink carrier, and the same DSS measures the round-trip phase delay between transmission and reception of the ranging code. The DSN performs two independent measurements to determine a DSS delay: station calibration and Z-height correction (ZCR) [2]:

$$\text{DSS Delay} = (\text{Station Calibration}) - \text{ZCR}.$$

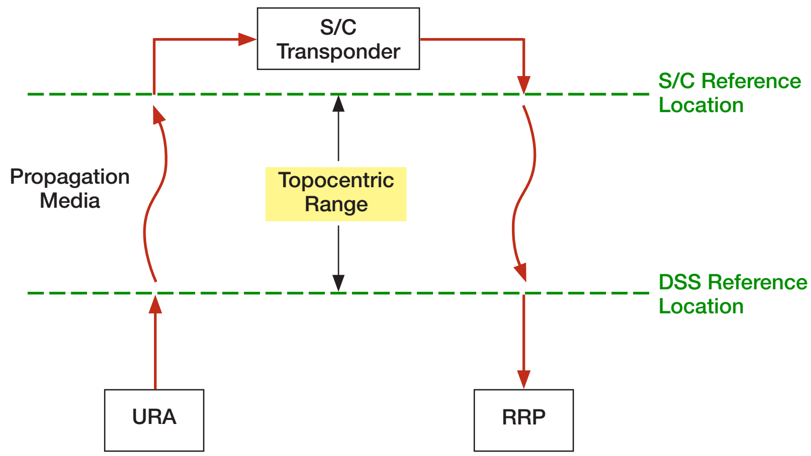

Figure 1. Topocentric range.

The station calibration is the delay from the URA to the test translator (XLTR), and then to the RRP, as shown in Figure 2 by the blue path: the URA to A to B to the RRP. The XLTR converts the uplink signal to a downlink signal. The ZCR is a correction offset that accounts for delays in the signal path not included in the station calibration measurement. The station calibration is done for every ranging pass prior to the S/C tracking. The ZCR is the delay of the test translator minus the delay between A and the DSS reference location and between B and the DSS reference location, as shown in Figure 2. The XLTR delay values are measured periodically, and the delays between A and the DSS reference location and between B and the DSS reference location are the theoretical constants calculated from physical dimensions and group velocities and measurements.

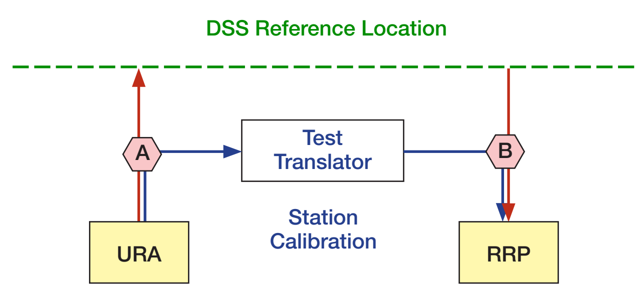

Figure 2. Two-way DSS delay calibration.

The DSN is currently capable of providing the DSS delay calibration to better than 4 ns (59 cm in one-way distance) accuracy: 2 ns for station calibration and 2 ns for ZCR.

B. Three-Way Ranging

For three-way ranging, the setting DSS transmits a modulated ranging code onto the uplink carrier, and the rising DSS measures the round-trip phase delay between transmission and reception of the ranging code returns.

There is no direct method to measure the DSS delay: $l_1 + l_4 + l_{10} + l_8$, as shown in Figure 3. In the existing method, the DSN measures station calibration delays for both uplink and

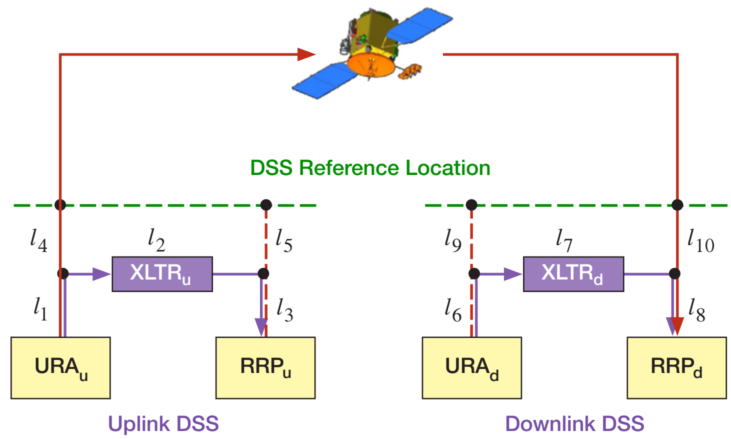

Figure 3. Three-way DSS delay calibration.

downlink DSSs, and the value used is the arithmetic average of the uplink and downlink station delays. The same averaging is done with the ZCR values. The DSN estimates total DSS delay as

$$= \left(\left(\text{Station Calibration} - \text{ZCR}\right)_{\text{uplink DSS}}\right)/2 + \left(\left(\text{Station Calibration} - \text{ZCR}\right)_{\text{downlink DSS}}\right)/2$$
$$= \left(l_1 + l_3 + l_4 + l_5\right)/2 + \left(l_6 + l_8 + l_9 + l_{10}\right)/2.$$

This estimation could provide the systematic error at a minimum if a path-delay of $(l_1 + l_4)$ is identical to $(l_3 + l_5)$ and $(l_6 + l_9)$ to $(l_8 + l_{10})$. However, another source of measurement difference for three-way ranging is the offset between master clocks at the two DSSs, plus the timing delays between the master clock and the URA/RRP at each DSS.

It should be possible to determine these delays with a few nanoseconds accuracy, but the infrastructure is not in place in the DSN to do so. For example, the measured offset between Global Positioning System (GPS) clocks at the three DSN sites will occasionally jump by 1 μs without explanation. The three-way ranging error caused by this time transfer uncertainty is at the 100-m level for one-way distance.

Forty-two tracks of three-way ranging measurements were evaluated to determine the magnitude of the systematic error in DSN measurement. These tracks were from 2008 DOY266 to 2013 DOY025 with the Cassini, Deep Impact Flyby (DIF), Mars Reconnaissance Orbiter (MRO), and NHPC S/C. The average systematic error from these tracks was determined to be 30.8 m in one-way distance, as shown in Figure 4. The largest systematic error in three-way ranging is due to the current inability to properly calibrate the station delay. In order to minimize the systematic error, there must be a DSS delay calibrated separately for the uplink (URA to DSS reference location of uplink DSS, $l_1 + l_4$) and another DSS delay for the downlink (DSS reference location to RRP of downlink DSS, $l_8 + l_{10}$). Currently, the DSN does not have a method to calibrate uplink and downlink delays separately to the 1-ns level. Also, time transfer between and within each DSS needs to be calibrated.

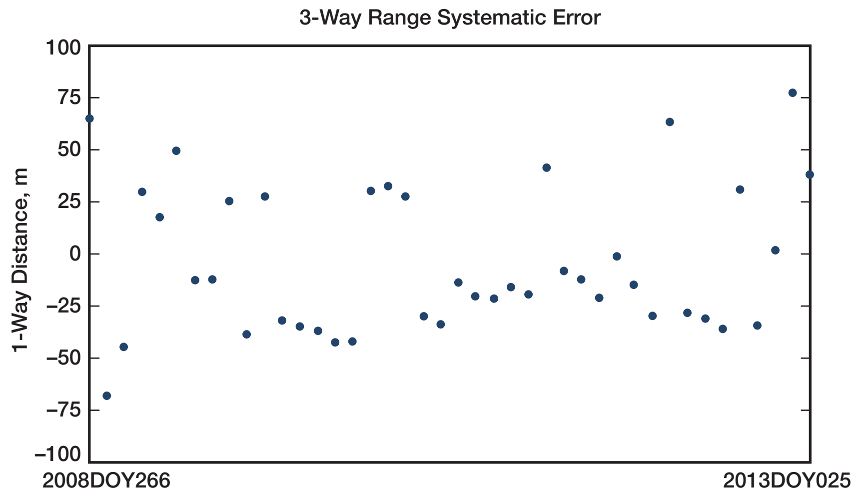

Figure 4. DSN three-way ranging error.

IV. New Method

New methods of the calibration include additional activities of:

- Performing the pre-calibration (pre-cal) activity utilizing both closed-loop receiver (RRP) and open-loop receiver (VLBI science receiver — VSR)
- Performing quasar observation during station overlap using the VSR. This measurement can be done as a nominal delta-DOR activity.

The basic step is that a standard ranging calibration is done at each station, the RRP is calibrated with the VSR, and a quasar observation using the VSR during delta-DOR activity enables calibration between stations. The quasar observation fully accounts for timing offsets between the DSS and the VSR. Previously it was demonstrated that two-way ranging using the open-loop VSR data agreed well with standard ranging using the RRP [3]. That technique is extended here to three-way ranging.

A. Pre-Cal Activity

Prior to S/C tracking, during the pre-cal activity, the DSN performs the station calibration delay. The station calibration delay path is from the URA to RRP via the XLTR. As shown in Figure 5, the new method utilizes the VSR to simultaneously measure the station calibration delay with the RRP to isolate for uplink delay of the uplink DSS and downlink delay of the downlink DSS. The VSR shares the same downlink path with the RRP up to the IF switch.

During the pre-cal, the following delays will be measured:

- Station calibration for uplink DSS, RRP path $l_1 + l_2 + l_3$
- Station calibration for uplink DSS, VSR path $l_1 + l_2 + l_4$

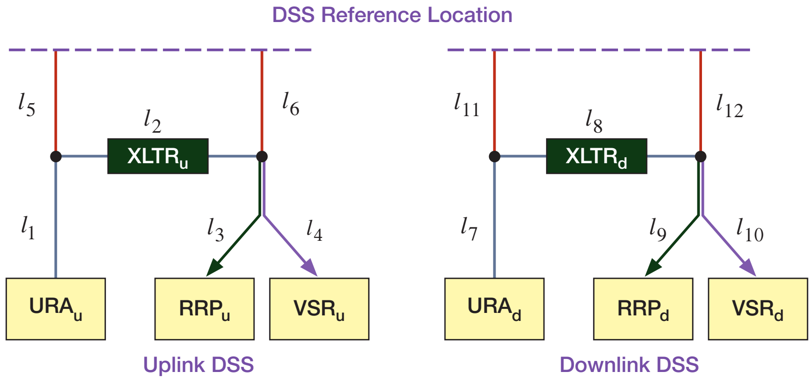

Figure 5. New pre-cal configurations.

- Station calibration for downlink DSS, RRP path $l_7 + l_8 + l_9$
- Station calibration for downlink DSS, VSR path $l_7 + l_8 + l_{10}$

B. Delta-DOR Activity

Delta-DOR measures the geometric time delay between received radio signals from the S/C and from an angularly nearby quasar at two geographically separated DSSs [4]. A delta-DOR measurement provides an S/C angular position that complements the line-of-sight Doppler and range measurements. The quasar observation of the delta-DOR activity between the uplink DSS and the downlink DSS provides a differential delay between the VSR paths between two DSS: $l_{10} - l_4$. Note that only the quasar observation is actually needed for the purpose of three-way ranging calibration.

C. DSS Delay Determination

$$\text{DSS Delay} = (\text{Station Calibration}) - \text{ZCR} = l_1 + l_5 + l_{12} + l_9$$

Delays of l_5 and l_{12} are calculated/measured from physical dimensions and group velocities, and the ZCR value contains these delays. $l_1 + l_9$ can be derived from

$$(l_1 + l_2 + l_3) - l_2 + (l_4 - l_3) + (l_{10} - l_4) + (l_9 - l_{10}) = l_1 + l_9$$

where

- $(l_1 + l_2 + l_3)$ Station calibration for uplink DSS, RRP
- l_2 XLTR delay for uplink DSS, measured periodically from ZCR calibration
- $(l_4 - l_3)$ Differential station calibration for uplink DSS, VSR path to RRP path
- $(l_{10} - l_4)$ Obtained from quasar measurement during delta-DOR activity
- $(l_9 - l_{10})$ Differential station calibration for downlink DSS, RRP path to VSR path

D. Error Estimation

One-sigma systematic error due to DSN calibration and measurement is estimated as 14 ns (2 m in one-way distance). A breakdown of the error budget is:

- DSS delay calibration = 8 ns (4 ns for each DSS)
- Quasar measurement = 1 ns
- Reserve = 5 ns

V. Test Result

Five S/C tracks with DIF and NHPC using the new method were completed. The test results are also compared using the existing method, as shown in Table 1.

Table 1. Test results.

		Systematic Error, m	
Year/DOY	S/C	Existing Method	Proposed Method
2011 / DOY211	DIF	30.82	1.86
2011 / DOY240	DIF	34.33	1.71
2012 / DOY036	DIF	2.02	0.55
2012 / DOY040	DIF	77.38	0.22
2013 / DOY025	NHPC	38.0	1.01

Note that the numerical values in Table 1 are ranging offsets with respect to the two-way ranging data, for one-way distance in meters. The DSN currently provides accuracy of two-way ranging at the 1-m level in one-way distance for systematic errors [5].

VI. Data Delivery Impact

The new method will impact tracking data delivery. The entire 2013 DSN tracking data delivery for the Cassini, Dawn, Juno, M01O (Mars Odyssey 2001), Mars Atmosphere and Volatile Evolution (MAVEN), Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER), and MRO S/C are summarized and separated for each type of tracking data: one-way Doppler, two-way Doppler, three-way Doppler, and ranging. A summary of tracking time analysis for each S/C and tracking mode is shown in Table 2. Two- and three-way Doppler as well as two-way ranging data have been used as the main data for S/C navigation. Due to the instability of S/C oscillators and the corresponding error sources that could not be adequately modeled, one-way Doppler data have not been commonly used as the sole data type for S/C navigation.

One-way Doppler data are mostly acquired during the initial acquisition of an S/C, S/C in safe mode, tracking mode changes, delta-DOR tracks, or telemetry data replay-only track. A summary of track numbers for each S/C and each mode is shown in Table 3 to illustrate that two-way tracking supports are most commonly used for tracking mode. With the new method, additional pre-cal and quasar observation times are needed for station calibration. Current pre-cal times for two-way and three-way modes are 45 min and 60 min, respective-

Table 2. Tracking data delivery in 2013.

S/C	Track Time			
	One-Way Doppler	Two-Way Doppler	Three-Way Doppler	Two-Way Ranging
Cassini	1095:32:00	1801:47:00	449:57:00	1391:30:00
Dawn	51:24:00	548:39:00	25:07:00	287:13:22
Juno	188:05:40	2671:34:45	51:04:35	2459:51:00
M01O	2050:50:50	1611:24:00	578:36:40	1292:31:15
MAVEN	31:04:20	664:27:40	32:06:50	637:29:00
Messenger	253:48:20	2896:02:35	36:01:35	1567:00:00
MRO	1341:18:40	2957:01:30	436:16:50	283:45:45
Total	5012:03:50	13150:56:30	1609:10:30	7919:20:22
Distribution	18.1%	47.5%	5.8%	28.6%

Table 3. Track number distribution.

S/C	Total Number of Tracks	One-Way Only Track	Two-Way Only Track	Three-Way Only Track	Two- and Three-Way Track
Cassini	376	18	256	65	37
Dawn	157	15	113	1	28
Juno	431	29	277	3	122
M01O	1452	277	763	318	94
MAVEN	92	0	40	3	49
Messenger	544	3	478	7	56
MRO	1283	112	754	180	236
Total	4355	454	2681	577	622
Distribution	N/A	10.5%	61.9%	13.3%	14.4%

ly, with the exception of MRO and M01O, which simultaneously utilize the same DSS and designated 75 min for the pre-cal time, regardless of tracking mode. With the new method, three-way tracks with 45 min pre-cal time require an additional 15 min.

Consequently, two-way and three-way Doppler data delivery will be reduced, and ranging and delta-DOR data will be increased. Tracking data delivery time reduction or addition for each mode is analyzed and listed in Table 4. Table 4 shows a 3.4 percent increase in total tracking time with the new method. However, additional tracking data would not necessarily benefit every mission.

NHPC track analysis was done separately because the S/C is in the state where three-way mode became necessary, since RTLT was about 7 hours in 2013 and increased to 11 hours in 2015. Two-way ranging is no longer feasible for NHPC. Table 5 illustrates the distribution of tracking time and track number for each tracking data type in 2013.

VII. DSN Operation Revision

This section addresses DSN operational changes with the new method.

Table 4. Data delivery impact.

Tracking Mode	Current Method	New Method	Loss/Gain	Percent Change
One-way Doppler	5012:03:50	5012:03:50	0	0
Two-way Doppler	13150:56:30	12839:56:30	–311:00:00	–2.4
Three-way Doppler	1609:10:30	1289:10:30	–320:00:00	–19.9
Two-way ranging	7919:20:22	7608:20:22	–311:00:00	–3.9
Three-way ranging	0	1289:10:30	1289:10:30	N/A
Delta-DOR	0	559:30:00	559:30:00	N/A
Total	27691:31:12	28638:11:42	946:40:30	+3.4

Table 5. NHPC track summary and distribution.

Track Time and Data Delivery Distribution					Number of Tracks				
One-Way Doppler	Two-Way Doppler	Three-Way Doppler	Two-Way Ranging	Three-Way Ranging	Total	Doppler Only	Two-Way Ranging	Three-Way Ranging	Two-/Three-Way Ranging
631:05:32	63:57:51	483:27:23	43:05:22	434:50:05	233	128	8	57	40
38.1%	3.9%	29.2%	2.6%	26.3%		54.9%	3.4%	24.5%	17.2%

A. DSN Schedule

A flight project submits schedule requests, and the DSN allocates its resources based on the service user's submitted schedule requests. A summary of the proposed DSN schedule is as follows:

- Ranging pre-cal time is currently designated for 60 min and does not need to be increased for two-way DSS. Three-way DSS pre-cal time is currently designated for 45 min and requires an additional 15 min.
- Schedule the quasar observation activity during station overlap. It requires 30 min at each DSS.
- New configuration (work category) code is not needed. Existing code contains all necessary equipment.

The track activity timeline for the uplink and downlink DSSs is illustrated in Figure 6.

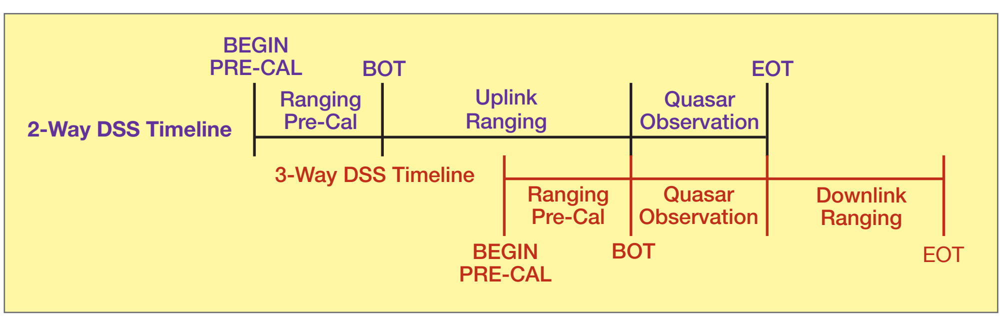

Figure 6. Track activity timeline.

B. DSN Keyword File

A flight project supplies the DSN keyword file (dkf) that describes the actual sequence of operation for each pass. An activity sequence of two-way or three-way ranging requires merging with the quasar observation activity sequence. Note that NHPC is the only S/C that utilizes three-way ranging support, and a dkf keyword "SPEC ADVISORY" is used to specify the ranging reception time for the reception DSS.

C. Post-Pass Analysis

Post-pass analysis must be done to determine a DSS delay. The VSR delay estimation is currently done with a clock-only correlation method. A new technique must be developed to fully utilize non-clock components to resolve phase ambiguity. This process also needs to be automated.

D. Data Output

A new DSS delay must replace existing values in the navigation data after the completion of post analysis.

VIII. Future Considerations

This demonstration shows that accurate three-way ranging can be done in the DSN using existing capabilities. Today, nonstandard data processing must be done with both closed-loop (RRP) and open-loop (VSR) data. A future architecture, where a common platform [6] is used for all downlink signal processing, should remove unknown timing offsets and path delays within a DSS. This would simplify the calibration method presented in Section IV.C. Further, the analog portion of the DSN instrument path could be more stable, implying that a quasar calibration would only need to be done infrequently to maintain synchronization between a DSS. With proper planning, it should be possible to make three-way ranging a routine service.

Three-way ranging is obviously necessary when the RTLT gets too large. Another application would occur for a tracking network architecture that had more downlink assets and fewer uplink assets. Navigation requirements might be met using short ranging uplink bursts from the uplink asset and three-way acquisition at the downlink asset.

IX. Summary

The rationale for use of three-way ranging has been presented. This data type will be used to support the New Horizons flyby of Pluto. A new calibration method, using a quasar observation to tie the instrumental ranging paths at two DSSs together, has been demonstrated. The new method gave less than 2 m systematic error in all five S/C tracks and provides three-way accuracy almost as good as two-way accuracy, and much better than the existing technique for three-way of averaging two-way station calibrations at the two DSSs. The new method can be used in the current DSN, though additional nonstandard data processing is required. It is anticipated that a future DSN architecture may enable three-way range as a standard service.

Acknowledgments

This task is a collaborative effort of the Deep Space Tracking Systems group of the JPL Tracking Systems and Applications Section under the DSN Advanced Technology Development Program. The author would like to thank the following: Faramaz Davarian for facilitating the task and providing the funding to make this work possible; K. J Lee of JPL and Bob Jenson of Applied Physics Laboratory (APL) for the residual analysis on three-way ranging data, making it as accurate as it can be; Gabor Lanyi for helping to analyze the open-loop data; and the ITT DSN Operation teams that coordinated, operated, and executed the tests that are not DSN standard operation.

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