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Station Delay Calibration for Ranging Measurements

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Ranging measurements in the Deep Space Network (DSN) have been contributing to spacecraft navigation and radio science investigations for 40 years. Performance over the past two decades has remained at the 1-m level limited by systematic effects. The goal of 10-cm ranging has long been sought. A task is underway to investigate possible improvements in the technique used to calibrate range measurements for delay through station microwave and electronic components. A new measurement technique is described here and the results of the first tests are presented. A comparison is given for Cassini range measurements obtained with the operational DSN system and with the new technique.

I. Introduction

Determination of the round-trip distance measured as the time in seconds (round-trip light time, RTLT) that is required for a radio signal to travel from an Earth antenna (a Deep Space Station, DSS) to a spacecraft and then back to the DSS has been used to support navigation and radio science investigations since early in the space age. These measurements, commonly referred to as ranging, are made by modulating coded waveforms onto a radio carrier signal and transmitting them to a distant spacecraft. The NASA Deep Space Network (DSN) has implemented several generations of ranging systems, each offering improved performance. The current system provides accuracy on the order of 1 m for line-of-sight distance. While the random error due to thermal noise can be much less than 1 m for some cases, there is still a systematic error of this order that varies for different spacecraft and different stations, and over time. Based on general considerations, ranging performance might be expected to be at least an order of magnitude better. The DSN has improved both line-of-sight Doppler and interferometric measurement systems to levels of performance approaching known limiting factors, but ranging systems have not yet been improved to such a level.

At current accuracy levels, ranging to spacecraft that are tied to other planetary systems has significantly contributed to studies of planetary dynamics, and to tests of general relativity. An order-of-magnitude improvement in measurement capability would benefit these fields as well as other radio science investigations. Some factors limiting ranging system perfor-

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mance are understood and proposals have been made to modify future flight and ground network components to address these issues. Processing techniques to address other limiting factors concerning system calibrations are now being studied. The first tests of an improved technique for ranging in the DSN have been completed using the Cassini spacecraft in orbit around Saturn. The new approach, based on an open-loop recording of concurrent spacecraft and calibration ranging codes, is described herein and experimental data are presented. Comparisons between measurements using the new/experimental approach and the operational DSN system are presented. An error budget is shown for ranging system performance that could be expected if the new observational technique were combined with other proposed improvements to measurement system components.

II. Range Measurement in the DSN

In ranging from a spacecraft to an Earth ground station, the sources of nongeometric delay in range measurements are the media, the spacecraft radio system, station clock drift, and the DSN ranging system. The DSN ranging system consists of the antenna (DSS) and microwave subsystem, and assemblies in the Signal Processing Center (SPC). The antenna is connected to the SPC by fiber-optic cables of up to several kilometers in length. The range measurement delay that is caused by the DSN ranging system is called the station delay. It results from the extended range due to the path from the uplink ranging assembly (URA) to the diplexer during the uplink path; and from the diplexer to the receiver and ranging processor (RRP) during the downlink path. This station delay is measured during pre-track calibration (pre-cal) or post-track calibration (post-cal) activities. The pre-cal is automatically performed at the beginning of a pass, and is used as a station delay calibration in general. The post-cal is done only in cases where the pre-cal is not performed due to lack of time, or if the configuration of equipment is changed during the track. The pre-cal path for two-way coherent ranging, in which the uplink and downlink are at the same DSS, is as shown by the red arrows in Figure 1. The equipment identified in this diagram consists of the URA, the exciter, the transmitter, the diplexer, the test translator, a low-noise amplifier (LNA), the RF-to-IF downconverter (RID), and the RRP. Either the downlink telemetry and tracking (DTT) subsystem or the radio science receiver (RSR) may function as the RRP.

The signal path measured by the station delay calibration does not exactly correspond to the signal path followed by the spacecraft radio signal. Correction terms are applied to account for the differences. First, the extra path to/from the test translator is included in the pre-cal procedure and must be removed by a correction term. Second, the round-trip delay between the range calibration coupler and the DSS reference location[1] must be removed by a correction term. These two corrections are determined by laboratory measurements and geometric calculations and are believed to be nearly fixed. By convention, the combination of these two terms is referred to as the station Z-correction. Finally, the delay caused by the spacecraft radio system is also removed by a correction term.

[1] The antenna reference location used in modeling of range observables is the intersection of axes and not the phase center.

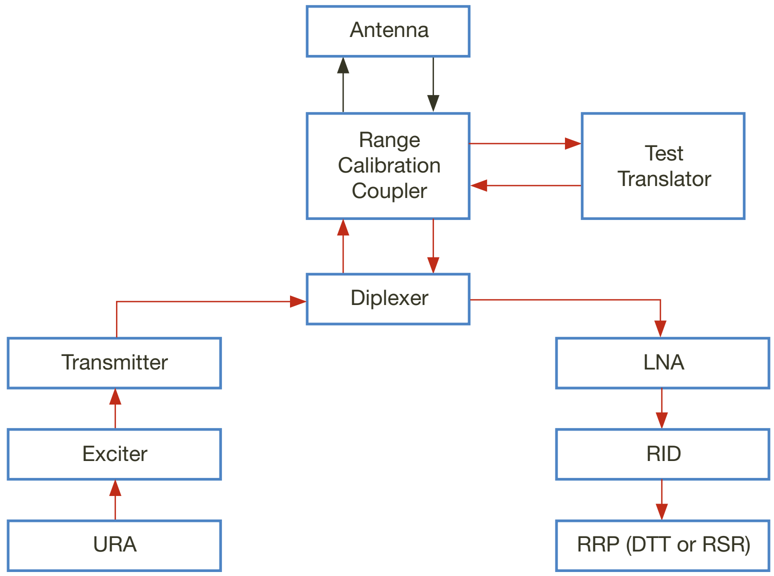

Figure 1. Typical station delay calibration path.

Because the pre-cal and post-cal procedures are not performed concurrently with the real signals, they cannot account exactly for the delay that occurs at the time of each ranging measurement. Also, they do not account for the time variation or changes during a pass. We might expect changes of path delay of 10 cm or larger in cables and other analog components due to temperature variations over a pass. A more precise measurement of the station delay is therefore needed — one that can detect the time variation over a pass — as well as measure the station delay at the same time as the signal reception. In order to satisfy such a requirement, this article investigates a new observational approach to making range measurements. The configuration of experiments, modeling of range measurements, procedure for range observable generation, and the feasibility of more precise calibrations of station delay are demonstrated.

III. Expected System Performance

Overall performance of the DSN ranging system has changed little over the past two decades. Even though improvements have occurred in instrumentation and in media calibration techniques, the dominant components of the error budget are affected by design parameters that are unchanged. The most accurate measurements today are made in the two-way coherent mode using an 8.4-GHz (X-band) uplink and downlink. A range code with a high-frequency component of approximately 1 MHz is uplinked from the ground station, transponded in a transparent[2] way at the spacecraft, and received back at the ground station. The measurement is essentially the difference in delay between the received spacecraft ranging signal and the station ranging signal that would be transmitted at the time of reception.

[2] The term *transparent* means that the spacecraft does not detect or regenerate the range code. The spacecraft transponder locks to the uplink carrier, demodulates a noise channel containing the range code, and remodulates the noise channel on the downlink carrier.

Suggestions for improvements in ranging system design have been made previously. J. Layland et al. noted in 1978 that a wider bandwidth ranging code would be needed to improve performance [1]. L. Young [2] proposed a system in 1989, based on technology available at that time, that would be capable of 6 cm accuracy. But most of these recommended system upgrades have not yet been implemented, perhaps due to a lack of driving requirements. The improvements proposed in this article are broadly consistent with [1,2].

Ranging system performance depends on several factors. Three potential ranging systems are contrasted in this section to offer suggestions for improved performance and to evaluate the benefits. Errors are expressed in this section as one-way distance at the 1-sigma level. The three systems are described as follows:

- *Current System*: This is the current DSN ranging system with station delay measured during pre-calibration period, X-band uplink, transparent turnaround at the spacecraft, X-band downlink, and 1-MHz range code.
- *Experiment Goal*: This system assumes use of current DSN and spacecraft capabilities, except that the observational technique described in this article is used for calibrating station delay and generating observables.
- *Further Improvements*: This system assumes enhancements to DSN and spacecraft components that are necessary to provide significantly better ranging performance. Multiple frequency links, such as an X-band uplink with coherent downlinks at both X-band and 32 GHz (Ka-band) and a Ka-band uplink with a coherent Ka-band downlink, would be used for calibration of charged particle delays. The ranging signal would be a pseudonoise (PN) code with a high frequency component of at least 4 MHz, and the spacecraft would regenerate the code on board.

The expected performance of the three ranging systems is shown in Figure 2. The figure is not meant to be a definitive error budget but rather it illustrates the relative significance of major error components and contrasts the three systems. The components that may limit performance are solar plasma, thermal noise, station delay, and spacecraft transponder. Errors due to ionosphere, troposphere, Earth orientation, station location, and station clock are generally at the few-cm level and are not significant for most ranging applications.

For single-band data, solar plasma is usually the dominant error for smaller Sun–Earth–probe (SEP) angles. The magnitude of this error is over 2 m for X-band signals at 30 deg SEP. With current spacecraft operating only at X-band, this error term cannot be reduced except by making observations at larger SEP angles. However, since delay due to charged particles scales with inverse frequency squared, the use of signal links in multiple-frequency bands can be used to nearly eliminate this source of error. Missions that require higher ranging accuracy will need to implement dual frequency uplinks and downlinks.

The error due to thermal noise may dominate for a weak signal or a distant spacecraft. But thermal noise is less significant for a stronger signal such as that available from a Mars telecommunications orbiter. Also, the thermal noise component will average down with observation time, so that its effect is usually small when considering the accuracy of range

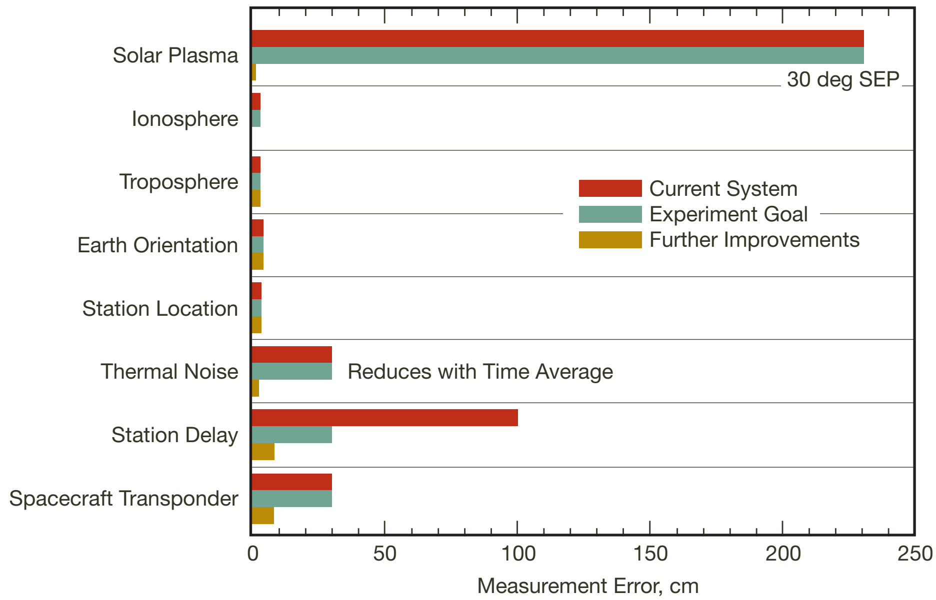

Figure 2. Expected ranging system performance (one-way distance, 1-sigma).

determination over a full tracking pass. For the *Further Improvements* system, the use of regenerative PN ranging reduces this term to an insignificant level over even short averaging times.

Uncertainty in station delay calibration is also a significant source of error. Over the past decade, high-quality ranging measurements have been acquired from three orbiters at Mars. Analyses of these data provide the best current assessment of ranging system accuracy. The data shown in Figure 3 are typical of residuals after best solutions have been obtained for spacecraft orbits and the Mars ephemeris. The variation in residuals from one pass to another at the same station, and the variation between stations, both appear to be larger than the variation within a single pass. The variation is believed to be due to inaccuracy in the station delay calibration, but the exact source of the problem is not yet understood.

It will do little good overall to redesign other components of the ranging system unless calibration techniques are improved. The main hypothesis of the work reported in this article is that calibration accuracy can be improved if (i) the calibration is made at the time of the measurement, and (ii) the calibration is made at a frequency close to the frequency of the spacecraft signal. But calibration accuracy is still limited by the restricted bandwidth of the ranging code. A phase error of only 1 deg for a 1-MHz code, for example, corresponds to a delay error of 42 cm. For the *Further Improvements* system, it is assumed that the higher frequency of the ranging code will allow more accurate delay calibration.[3] It should be noted that there are parts of the signal path that are not directly measured by the calibration signal. While it is difficult to specify the absolute accuracy of these other delays, it can

[3] Experience with delta differential one-way range (ΔDOR) instrumental effects indicates that differential delay errors — that is, the difference between a spacecraft signal and a calibration signal — are reduced when the spanned bandwidth of the measurement is increased.

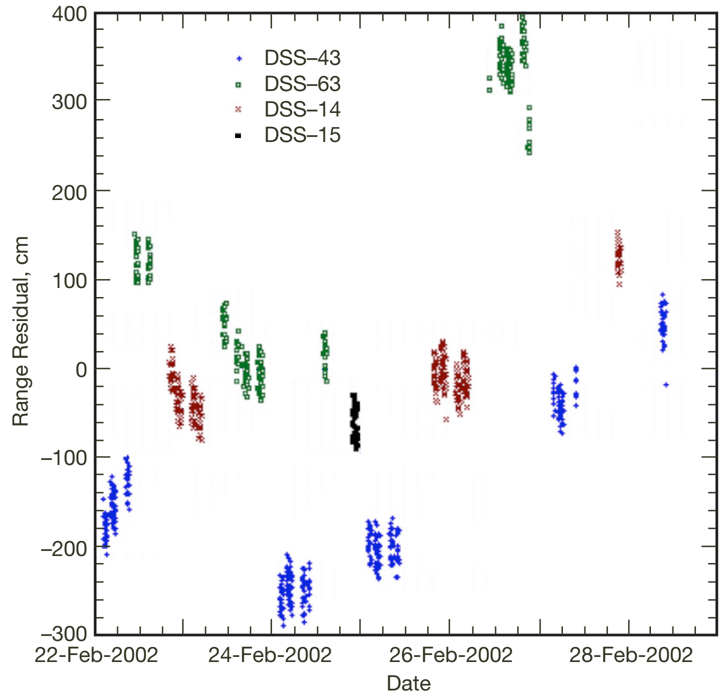

Figure 3. Range residuals (one-way distance) over a 7-day interval from Odyssey spacecraft in orbit at Mars.

be said that they are expected to remain nearly constant over long periods of time for any given station. Absolute range is expected to be difficult to know to the cm level. At cm-level accuracy, it may be necessary to include a parameter for a constant range bias (over a long arc) during data analyses to account for an unknown path delay.

Delay through the spacecraft radio system must be calibrated before launch. Curves of delay versus frequency and temperature are normally made to support high-accuracy ranging. Even then, component aging after launch may change the actual delay. Narrowband analog components generally are the worst actors for delay stability. For the *Further Improvements* system, it is assumed that the wider bandwidth of the ranging signal and the use of digital components will improve delay stability through the spacecraft radio system.

As shown in Figure 2, the station delay calibration technique under development is expected to improve ranging system performance by a factor of 2, at least for large SEP angles where the solar plasma error is small. For large SEP angles, the current system has accuracy of about 1 m and the goal for improved calibrations is to obtain accuracy of 50 cm. To achieve accuracy at the 10-cm level, the further improvements described above are required.

IV. Experiment Configuration

In the experiment described below, only coherent two-way ranging using an X-band uplink is conducted.

The microwave subsystem of the DSN ranging system accepts the received signals and directs them, via polarizer plates and microwave mirrors, to amplifying devices. The amplified signals are then directed to the receivers. Two types of receivers can be used: closed-loop and open-loop. The closed-loop (tracking) receiver, known as the downlink telemetry and tracking (DTT), is the primary DSN receiver for telemetry and tracking data. It locks onto the carrier signal and demodulates the telemetry data as well as the ranging signal transmitted by the spacecraft. The tracking subsystem produces Doppler shift and ranging information based on the closed-loop receiver output. The open-loop receiver, called the radio science receiver (RSR), downconverts and digitizes a selected bandwidth of the frequency spectrum, centered on the carrier signal. The RSR relies on downlink frequency predicts, which take into account the relative motion between the spacecraft and DSN station, for tuning in the incoming signal (instead of locking onto the carrier signal to track the downlink signal). The RSR has the capability to capture multiple signals at offset frequencies, and this makes the new ranging approach feasible. For the ranging experiment described herein, the signal is distributed to a DTT for normal range data acquisition and to an RSR for the new ranging experiment.

Since normal DTT range data acquisition is well described by J. Berner et al. [3], only the new ranging experiment using the RSR is described herein. For the RSR, multiple signals are received through six channels. Three of these channels are assigned to receive the same two-way spacecraft downlink signal as the DTT. This signal measures the range of the spacecraft, and is available one RTLT after the signal is transmitted. The other three RSR channels are assigned to receive signals that are routed from the URA, through the test translator, and then on to the RRP following the red arrows in Figure 1. Functionally, both the DTT and RSR are inside the RRP. To avoid interference, the test translator is configured so that the translated signal is offset in frequency from the spacecraft signal. This test signal is recorded for the entire duration of the experiment in order to measure changes in station delay over the full pass length.

A ranging signal is transmitted to a spacecraft by modulating a coded waveform onto the uplink carrier. Thus, a ranging signal is a sequence of periodic signals, of which the first component is called the clock and defines the range measurement resolution. The other components are used to resolve range measurement ambiguity, which is caused by using a periodic signal to measure signal delay. Several notations from [3] have been adopted to explain the details. For X-band uplink, the nth component of a transmitting sequence is

$$f_n = \beta \cdot f_T, \qquad \beta = \frac{221}{749} \cdot 2^{-7-n}$$

where f_T is the uplink frequency and n is an integer. The current DSN instrumentation has a limit of $n \geq 4$, so that the available maximum frequency is approximately 1 MHz for the range clock. Each RSR channel is assigned to a specific frequency based on the downlink predicts for a selected pass. The three RSR channels are assigned for two-way spacecraft downlink as

Channel 1: spacecraft two-way downlink carrier signal, $F_2 = G \cdot f_T$
Channel 2: spacecraft ranging signal, $F_2 + f_{SR}$
Channel 3: spacecraft ranging signal, $F_2 - f_{SR}$

Here, G is the transponder ratio used by Cassini (880/749) for X-band up/X-band down. The uplink frequency f_T (approximately 7175 MHz) is time-varying to compensate for the Doppler shift on the uplink. The downlink carrier signal (represented by F_2) is about 8429 MHz. The range clock (approximately 1 MHz) is modeled by

$$f_{SR} = \beta \cdot f_T = \frac{221}{749} \cdot 2^{-11} \cdot f_T$$

Another three channels are assigned for signals turned around by the test translator:

Channel 4: station delay calibration carrier signal, f_{CT}
Channel 5: station delay calibration ranging signal, $f_{CT} + f_{SR}$
Channel 6: station delay calibration ranging signal, $f_{CT} - f_{SR}$

The carrier frequency for station delay calibration is modeled by

$$f_{CT} = \frac{839}{714} \cdot f_T$$

and is about 8431 MHz. For the test translator, a factor of 839/714 is used for the ratio to offset the test signal from the spacecraft downlink.

All of the station delay calibration signal frequencies vary due to changes resulting from ramping of the uplink frequency. The time-varying frequency translation $(839/714)f_T - f_T$ is applied to the full bandwidth of the uplink signal.

One IF feed is used for all input signals to the RSR, so that only one analog path and only one analog to digital converter are used. For all channels, the same downconversion frequency, 331 MHz, is applied to the IF signal to generate baseband channels for further digital processing. The baseband channels are downconverted using the tuning predicts described above, filtered, and sampled. The downconverter mixing phase is recorded so that the phase of the input signal can be restored to the RF level.

Four experiments using the above configuration have been conducted during Cassini ranging tracks: day of year (DOY) 188 and DOY 215 in 2007, and DOY 125 and DOY 128 in 2008. The Goldstone 70-m antenna (DSS-14) was used for all experiments. Table 1 provides information about each of the data sessions. Since the SEP angle is not approaching 180 deg (opposition) for any of these experiments, we expect solar plasma to be the dominant error source in the data set.

During the experiment, the range code sequentially cycles between its clock component and lower-frequency components for the purpose of ambiguity resolution. Only the upper and lower first harmonics of the clock component are processed in the RSR data.

V. Data Processing

By processing the ranging signals, the following four measurements will be obtained at reception time t_3:

Table 1. Cassini improved ranging experiments.

Date	Experiment Duration	Sun–Earth Probe Angle
2007–188	3.1 hr	38 deg
2007–215	2.9 hr	16 deg
2008–125	3.7 hr	108 deg
2008–128	3.7 hr	105 deg

$\varphi_{SU}(t_3)$ = Measured phase of spacecraft upper range tone harmonic
$\varphi_{SL}(t_3)$ = Measured phase of spacecraft lower range tone harmonic
$\varphi_{CU}(t_3)$ = Measured phase of station delay calibration upper range tone harmonic
$\varphi_{CL}(t_3)$ = Measured phase of station delay calibration lower range tone harmonic

Since the phase of a propagating signal at the time and place of reception is the same as the phase at the time and place of transmission, these measurements can be represented as follows:

$$\varphi_{SU}(t_3) = \int_{t_0}^{t_3-\rho-\tau_s} F_2 + f_{SR}\,dt$$
$$\varphi_{SL}(t_3) = \int_{t_0}^{t_3-\rho-\tau_s} F_2 - f_{SR}\,dt$$
$$\varphi_{CU}(t_3) = \int_{t_0}^{t_3-\tau_s} f_{CT} + f_{SR}\,dt$$
$$\varphi_{CL}(t_3) = \int_{t_0}^{t_3-\tau_s} f_{CT} - f_{SR}\,dt$$

In these equations, t_0 is a reference time at the beginning of transmission when the transmitter phase is zero, ρ is the round-trip range to the spacecraft (*s*), and τ_s is the station delay (*s*). Phase is measured in units of cycles.

Using the above equations, the spacecraft range observables can be derived as follows:

$$\varphi_S(t_3) = \tfrac{1}{2}[\varphi_{SU}(t_3) - \varphi_{SL}(t_3)] = \int_{t_0}^{t_3-\rho-\tau_s} f_{SR}\,dt$$

And, the calibration observables for the station delay are computed as

$$\varphi_C(t_3) = \tfrac{1}{2}[\varphi_{CU}(t_3) - \varphi_{CL}(t_3)] = \int_{t_0}^{t_3-\tau_s} f_{SR}\,dt$$

The range observable, in DSN range units (RU), is obtained by:

$$R_{OBS} = 1024 \cdot [\varphi_C(t_3) - \varphi_S(t_3)] = 1024 \cdot \int_{t_3-\rho-\tau_s}^{t_3-\tau_s} f_{SR}\,dt \qquad (1)$$

Here, 1024 is the conversion from cycles to RU.[4] This formulation for RSR range observables calibrates the station delay concurrently with the range measurement. The calibration procedure for DTT data is to subtract the (constant) station delay measured during the pre-cal period from the measured spacecraft range before the range observables are provided

[4] One RU corresponds to approximately 0.94 ns in round-trip range for a 1-MHz range code, or 14 cm in one-way distance.

to the project for use in the navigation software. The orbit-determination program (ODP) software package has been used for data analysis in this demonstration.

Next, the procedure for obtaining the ranging phase measurements from the RSR will be explained in detail. The first thing to note is that the measured phase derives from three quantities:

$$\phi(t) = \phi_{predict}(t) + \phi_{LM}(t) + \phi_{R}(t)$$

The first quantity, $\phi_{predict}(t)$, is the predicted phase used to downconvert the signal to baseband for sampling. Each RSR Standard Formatted Data Unit (SFDU) record includes coefficients for the predicted phase polynomial, for each 1-s interval, so that the value of the predicted phase for each time is calculated from the polynomial on the current SFDU. It should also be noted that the coefficients in the RSR SFDU have, by convention, the opposite signs as those in the DSN phase predicts.

Since the predict values might be imperfect, there could be pseudo-residual frequencies between the predicted and actual received frequencies:

$$\phi_{pseudo-resid}(t) = \phi(t) - \phi_{predict}(t)$$

By convention, this is called pseudo because it is the difference between the actual signal and a predicted model used at the time of data recording rather than a model that is based on an updated orbit solution. The raw RSR SFDU data comprise the in-phase (I) sample and quadrature (Q) sample of the pseudo-residual signal, with a sample rate of *N* measurements per second. The sample rate is the same as the bandwidth of the RSR channel, and 2 kHz was selected for these experiments. The pseudo-residual frequency was computed from the raw RSR data using Fourier transforms. The second quantity, $\phi_{LM}(t)$, is a local model based on the pseudo-residual frequencies. A linear polynomial fit to the pseudo-residual frequencies for each 1-s interval is integrated over time, which then corresponds to a local model of the phase of the pseudo-residual signal over the time interval.

The third quantity, $\phi_{R}(t)$, is the remainder after the phase of the local model is removed from the phase of the pseudo-residual signal. It is computed by averaging the *N* leftover phases of the mixing product as described here. The signal in the RSR baseband channel can be represented by the equation $I_n + iQ_n = V(t_n)\exp i(\phi_{pseudo-resid}(t_n)) + noise$, where $V(t_n)$ is the input signal voltage at sample time t_n. There are *N* samples in each 1-s interval. When mixing with the local model, in order to avoid loss of coherence, the leftover phases must not wander by more than about 0.1 cycle over the averaging interval. Using the relation

$$\begin{aligned}\sum_{n=1}^{N}(I_n + iQ_n)(\cos(\phi_{LM}(t_n)) - i\sin(\phi_{LM}(t_n))) &\approx \sum_{n=1}^{N} V(t_n)\exp i(\phi_{pseudo-resid}(t_n)) \cdot \exp i(-\phi_{LM}(t_n)) \\ &= \sum_{n=1}^{N} V(t_n)\exp i(\phi_{pseudo-resid}(t_n) - \phi_{LM}(t_n)) \\ &= N \cdot \overline{V}\exp i\phi_R(t) = I + iQ\end{aligned}$$

the residual phase value is computed at the interval midtime *t* by setting $\phi_R(t) = \arctan(Q/I)$.

VI. Results

To compare the RSR range observable (R_{OBS}) to that from the DTT, the spacecraft radio system delay and the station Z-correction are factored into the range observables (R_{OBS}) by applying the same formulation as for DTT data — i.e., RSR measurement – spacecraft delay + Z-correction. The observables cannot be directly compared since data-compression algorithms used by the two different techniques have resulted in slightly different data timetags. Instead, residuals are compared. A reference trajectory fit to a long arc of data and identical measurements models are used for both data sets. Both DTT observables and corrected RSR observables are run through the ODP to get the residuals — the difference between the measured observable and the computed observable — which are calculated in program REGRES. Figure 4 shows the comparisons of residuals between DTT and RSR in four experiments that used the Cassini spacecraft. The difference in residuals between the two techniques is also shown. The reference trajectory fit is dominated by Doppler data, hence range data are expected to exhibit residuals due to spacecraft position error and uncalibrated solar plasma delay.

Two facts come out of the results of these experiments. The first is that the two ranging techniques are basically consistent because the DTT and RSR residuals are very close in signature and magnitude in all of these experiments. The second is that the time variation of station delay cannot be too large since the continual measurement of station delay in the RSR processing does not lead to a large difference in residual values. However, slowly varying systematic differences of order 20 cm between the two techniques are observed for each data set, implying that a correction of this order might be expected if the new technique is adopted.

We cannot determine if one technique or the other has provided a more accurate value of range during these experiments. Knowledge of the Cassini spacecraft position and knowledge of solar plasma delay cannot be independently determined to the 1-m level.

VII. Conclusions

A new method has been developed (and verified) to make precise range measurements from open-loop recordings and to enable the removal of the time variation in station delay measurements. It has been shown that the station calibration signal may be used during a tracking pass without negative impact to normal Doppler, ranging, or telemetry functions. The data sets that have been analyzed do not show a clear advantage for the new technique as compared to normal DTT ranging, but they do show that there are signatures in the data that need further study. The improved time resolution of the new technique should provide better data at least for geometries where thermal noise and solar plasma are not the dominant effects.

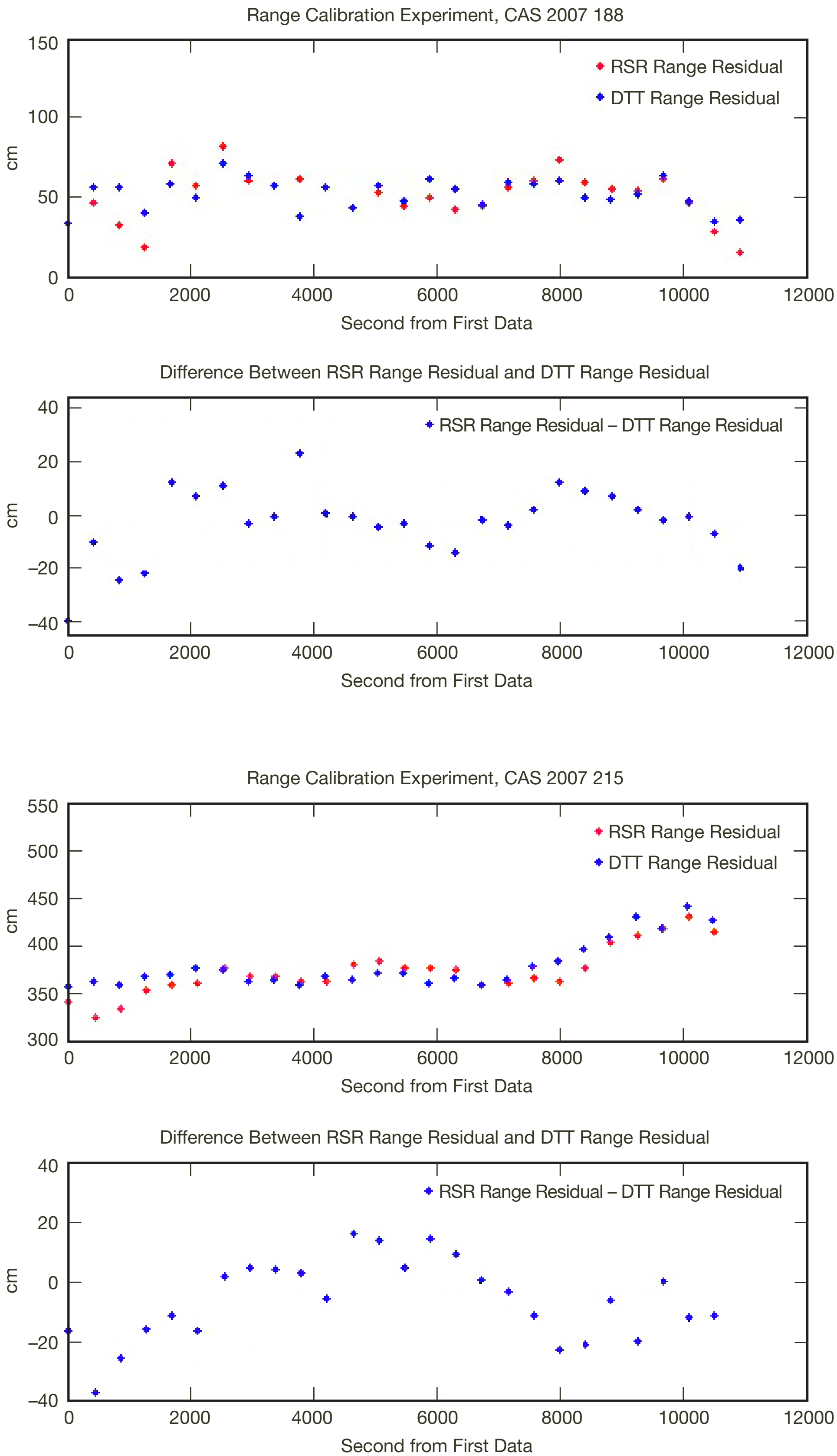

Figure 4. Cassini ranging residuals (one-way distance).

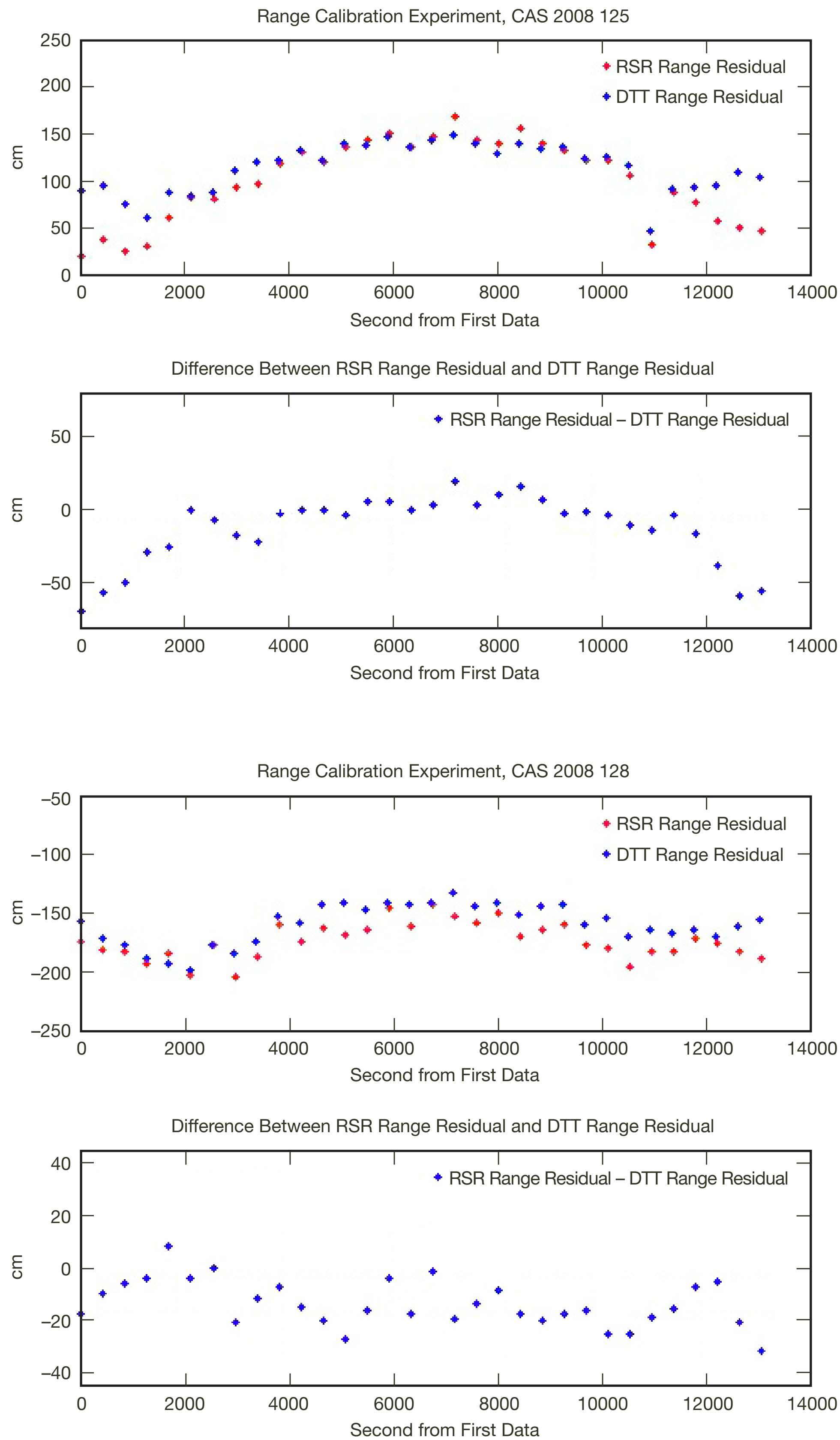

Figure 4 (continued). Cassini ranging residuals (one-way distance).

Additional station tests are needed to:

(1) Better characterize temporal variations in station delay.

(2) Better characterize dependence of station delay measurement on transmitter frequency.

(3) Better characterize stability of the test translator.

(4) Demonstrate improvement in ranging accuracy by using the new technique.

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