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Telemetry Ranging: Concepts

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Telemetry ranging is a proposed alternative to conventional two-way ranging for determining the two-way time delay between a Deep Space Station (DSS) and a spacecraft. The advantage of telemetry ranging is that the ranging signal on the uplink is not echoed to the downlink, so that telemetry alone modulates the downlink carrier. The timing information needed on the downlink, in order to determine the two-way time delay, is obtained from telemetry frames.

This article describes the phase and timing estimates required for telemetry ranging, and how two-way range is calculated from these estimates. It explains why the telemetry ranging architecture does not require the spacecraft transponder to have a high-frequency or high-quality oscillator, and it describes how a telemetry ranging system can be infused in the Deep Space Network.

I. Introduction

Ranging is a process to determine accurately the two-way time delay for a signal in traveling from a Deep Space Station (DSS) to a spacecraft and back again. This is accomplished, at present, with the phase measurement of a periodic ranging signal. In order to convert this phase measurement to a two-way time delay that represents only the geometric delay between a reference point on the DSS antenna and a reference point on the spacecraft antenna, it is necessary to account for delays in the signal processing both on the ground and in the spacecraft. In general, each range measurement is associated with a time tag in order to capture the time-varying nature of the spacecraft range.

Telemetry ranging was first described as an alternative to conventional two-way ranging in

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[1]. A modification of that technique was proposed in [2]. The modified technique is now preferred and is the subject of the present article.

In this introductory section, we give a brief overview of a generic two-range ranging system, then a brief elaboration of the basic principles of telemetry ranging, and finally a generalized definition of signal "phase" measurements from which ranging information can be derived. In Section II we lay out the fundamental measurements and calibrations necessary for two-way ranging, comparing those needed for telemetry ranging to the corresponding measurements and calibrations needed for conventional two-way ranging. Finally, Section III describes the changes needed within the Deep Space Network (DSN) to accommodate telemetry ranging.

A. Two-Way Ranging

Figure 1 shows a generic two-way ranging system. In the two-way ranging approach currently used by the DSN, a signal modulates the phase of an uplink carrier signal, it is demodulated on the spacecraft, and it is used to modulate the phase of a downlink carrier. The ranging design can either be *transparent* (turn-around) [3], in which case the imperfectly demodulated range signal on the spacecraft is simply filtered, amplified, and fed to the phase modulator for the downlink signal; or, it is *regenerative* [4], in which case the spacecraft acquires the uplink ranging signal and generates a clean local copy in-phase with the noisy received version and feeds it into the downlink phase modulator. In either case, the job of the spacecraft is to echo the uplink ranging signal, as shown in Figure 1.

Most NASA missions have used a *sequential ranging* signal, which is a carefully crafted sequence of sinusoidal tones [3]. Since any periodic signal delayed by one or more periods is indistinguishable from the original, an *ambiguity* arises in the delay measurement. In sequential ranging, the delay ambiguity is equal to the period of the lowest-frequency transmitted tone, which must be sufficiently long to enable the ambiguity to be resolved with the available prior knowledge of the approximate range. Conversely, the *precision* of a ranging system is

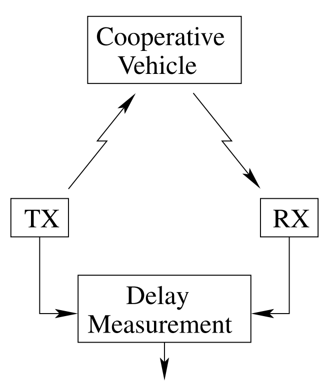
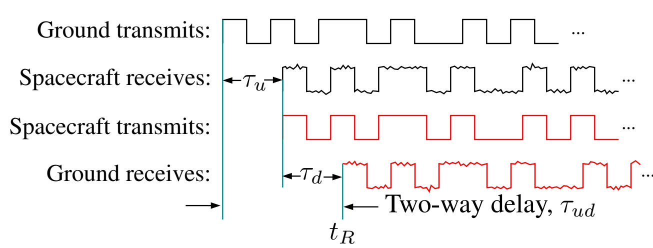


Figure 1. Two-way ranging.

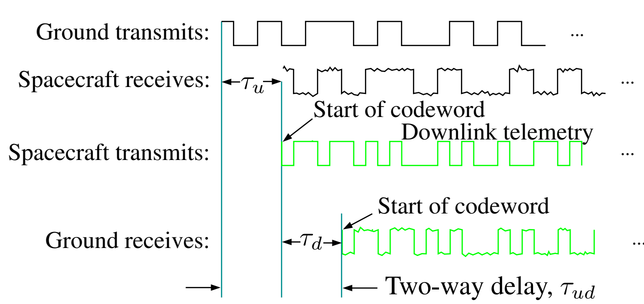
the minimum range difference it can resolve. In sequential ranging, the precision is generally determined by the ability of the receiver to resolve the phase of the highest frequency tone.

The DSN now also supports *Pseudo-random Noise (PN) ranging* [5, 6]. A PN ranging signal is formed by modulating a PN range code, or sequence, using binary phase-shift keying with a half-sine or square pulse shape, and a residual carrier. The New Horizons mission was the first to use PN ranging in the DSN [7]. While the telemetry ranging concept is in principle compatible with both sequential ranging and PN ranging systems, in the remainder of this article we discuss only PN ranging. This makes the presentation simpler and reflects our expectation that the advantages of PN ranging will make it a more widely used ranging method in the near future.

Figure 2(a) illustrates the notional timing relationship between the uplink and downlink signals of conventional two-way ranging. Since the format of the transmitted and received waveforms on the ground are identical, a correlator may be used to estimate the delay between them. (A previous article presented the maximum likelihood joint estimation of navigation parameters [8].) This measured delay is the round-trip light-time τ_{ud}, equal to the sum of the one-way uplink and downlink light-times, i.e., $\tau_{ud} \triangleq \tau_u + \tau_d$.



(a) Conventional two-way ranging.



(b) Telemetry ranging.

Figure 2. Timing of ranging signals.

B. Telemetry Ranging

This article presents a telemetry ranging architecture that eliminates the downlink ranging signal (shown in red in Figure 2(a)). Instead, the range measurement is accomplished by utilizing temporal properties of the downlink *telemetry* signal (Figure 2(b)). The telemetry signal normally has no temporal relationship to the uplink ranging signal—it is asynchronous to the uplink ranging signal. Telemetry-based ranging introduces such a relationship.

As shown in Figure 2(b), the spacecraft measures the phase of the arriving uplink ranging signal at the moment a telemetry codeword begins being radiated. (In the next subsection, we describe more about what we mean by the "phase" in this context.) The range code phase measurement is inserted into the downlink telemetry. During this process, the timing of the telemetry transmission is not altered in any way by the ranging system, i.e., in general it remains asynchronous with respect to the ranging signal arriving at the spacecraft. On the ground, the codeword timing is acquired, as shown in Figure 2(b), and together with the recorded range code phase from the spacecraft, the round trip light time $\tau_u + \tau_d$ can be made. This article explains the details of this computation, and the ranging performance that results.

There are several potential advantages of telemetry ranging. First, simultaneous ranging and high rate telemetry is possible throughout the duration of a pass, even when a suppressed carrier and/or higher order modulation is used. Second, no power is used for a dedicated downlink ranging signal, making more power available for telemetry. Third, for low data rates the ranging resolution is as good as that of conventional ranging, and for data rates more than about 1 Mbps, it can be orders of magnitude better. Fourth, the method enables a more accurate calibration of the spacecraft clock.

This contrasts with conventional ranging, which requires a dedicated downlink ranging signal separate from the telemetry [3, 5], and typically, a residual carrier [9, section 2.2.8]. Simultaneous ranging and telemetry usually precludes use of higher order modulations, as well. Because of these and other practical constraints of dedicating power and bandwidth to separate carrier, ranging, and telemetry signals, missions typically use lower data rates when simultaneously conducting ranging. As a result, mission planners balance the need for ranging and telemetry data return. For example, Mars Reconnaissance Orbiter (MRO) typically conducts ranging during about one quarter of each pass, and during that period, the maximum data rate is 0.48 Mbps. During the remaining three quarters of the pass, there is no ranging data and the data rate can be up to 5.2 Mbps. A telemetry ranging approach would enable simultaneous ranging and 5.2 Mbps telemetry throughout the entire pass.

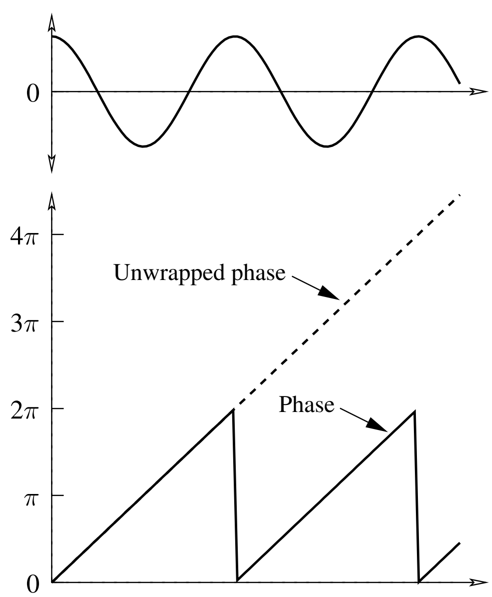
C. The Generalized Meaning of "Phase"

Before we get into the details of telemetry ranging signaling, we caution the reader that in this article we use the term "phase" in a way that may seem unusual. In textbook usage, a signal of the form $A\cos(\omega t + \theta(t))$ has amplitude A, frequency ω radians/s, and phase $\theta(t)$ radians. Similarly, a complex signal of the form $A\exp[j\omega t + \theta(t)]$ has phase $\theta(t)$. These types of signals are common in communications engineering, and we typically think about a receiver being able to track such a phase in the presence of noise.

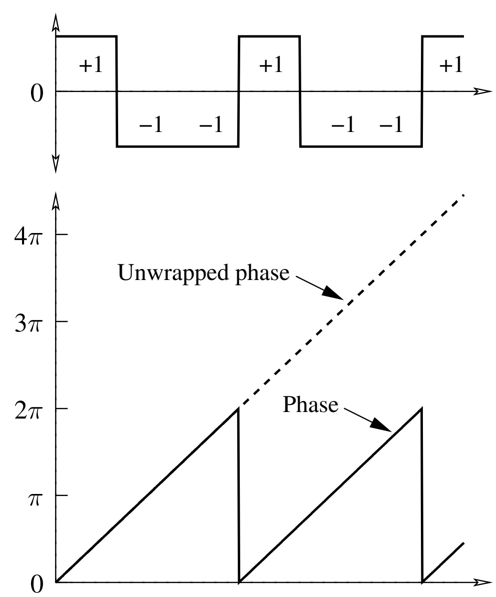
In other textbook contexts, it is convenient to refer to the entire angle argument $\omega t+\theta(t)$ as the phase. In this case, for constant ω and $\theta(t)$, the phase increases linearly with time, as shown in Figure 3(a). Since the underlying signal is sinusoidal, a phase $\omega t + \theta(t)$ is indistinguishable from a phase of the form $\omega t + \theta(t) + 2\pi n$, for any integer n.

Implicit in these textbook usages is the presumption that the underlying signal is sinusoidal. Since an arbitrary periodic signal can be expanded in a Fourier series as a sum of sinusoids, there is a natural generalization of the definition of "phase": the phase of any periodic signal is the argument of the first complex coefficient of its Fourier series expansion. This implies that there is a time t_0 for which the phase is zero, and that the phase of the signal at time t is $2\pi(t - t_0)/T \mod 2\pi$, where T is the period. In this way, the phase begins at zero at $t = t_0$ and increases linearly in time until it reaches 2π at the end of a full period. This is shown in Figure 3(b) for a waveform of the periodic sequence $+1, -1, -1$.

A coherent receiver typically tracks the phase modulo 2π, so that the phase is always in $[0, 2\pi)$. However, as the phase varies it could also track an "unwrapped phase" in which the phase is allowed to increase without bound, as shown by the dashed lines in Figure 3(a) and Figure 3(b). Ranging measurements are derived from observations of *unwrapped* phases.



(a) Sinusoid.



(b) PN sequence.

Figure 3. Phases of periodic waveforms.

II. Phase Measurements and Two-Way Time Delay

A two-way ranging system infers the range to a distant spacecraft by calculating a two-way time delay for a signal making a round trip between a DSS and a spacecraft. The accuracy with which the DSN can presently determine this range is about 1 m. This corresponds to an error in the determination of the two-way time delay of about $2 \cdot (1 \text{ m})/c \approx 7$ ns, where c is the speed of an electromagnetic wave in vacuum, and the factor of two accounts for converting a *two*-way time delay into a *one*-way distance (the range).

The main advantage of a two-way ranging system is that an accurate determination of the two-way time delay can be accomplished without any need to synchronize clocks between the DSS and the spacecraft. Instead, the two-way *time* delay is calculated from the two-way *phase* delay for a signal making a round trip between a DSS and a spacecraft [10]. The use of phase measurements to substitute for direct measurements of time delays is complicated by two issues. First, there is ambiguity when inferring a time delay from the phase delay of a periodic signal. Second, the points along the signal path at which the phases are measured do not coincide exactly with the end points of the geometric path between the the DSS and the spacecraft.

This article assumes that the ranging signal, or range code, is one of the range codes described in [5] or [11]. These range codes are constructed from PN codes.[2] The PN-based range code is periodic, so its (generalized) phase may be defined as described in Section I-C and depicted in Figure 3(b). In practice, it is more convenient to measure this phase in units of chips (rather than radians), including both a fractional part as well as an integer number of chips.[3] The period of the composite range-code phase is 1,009,470 chips. A clock, called the *range clock*, in the DSN controls the timing of the chips on the uplink. Each zero crossing of the range clock initiates a chip. Therefore, two chips correspond to one cycle of the range clock, and the chip rate (chips/s) is numerically equal to twice the range-clock frequency (Hz). Therefore, for a typical range-clock frequency of 1 MHz, the chip rate is 2 Mchips/s, and the range-code period is approximately 0.5 s. Since a priori knowledge of the two-way time delay has an error that is usually smaller than 0.5 s, ambiguity arising from the periodicity of the range code can be resolved in post-processing, and therefore the range-code phase is modeled as if it were unwrapped, i.e., with discontinuities of size 1,009,470 chips removed, as depicted by the dashed line in Figure 3(b).

The two-way *phase* delay is measured between points located within the Signal Processing Center (SPC): a point $\mathcal{P}_{\mathrm{T}}$ in the uplink signal processing and a point $\mathcal{P}_{\mathrm{R}}$ in the receiver. The two-way *time* delay of interest for a spacecraft range measurement refers to the round trip

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[2] Two-way ranging can also be done with sequential sine waves [3], and the measurement in that case is similar.

[3] The conversion from radians to chips corresponds to a simple linear rescaling of the vertical axis in Figure 3(b). In practice, a unit of phase measurement called the Range Unit is used [5]; but for the purpose of the present discussion, it is more convenient to quantify the range-code phase in chips.

delay between a reference point $\mathcal{A}_{\text{DSS}}$ in the DSS antenna and a reference point $\mathcal{A}_{\text{SC}}$ in the spacecraft antenna. In the DSS antenna, the reference point is the intersection of the azimuth and elevation axes. Figure 4 illustrates the situation.

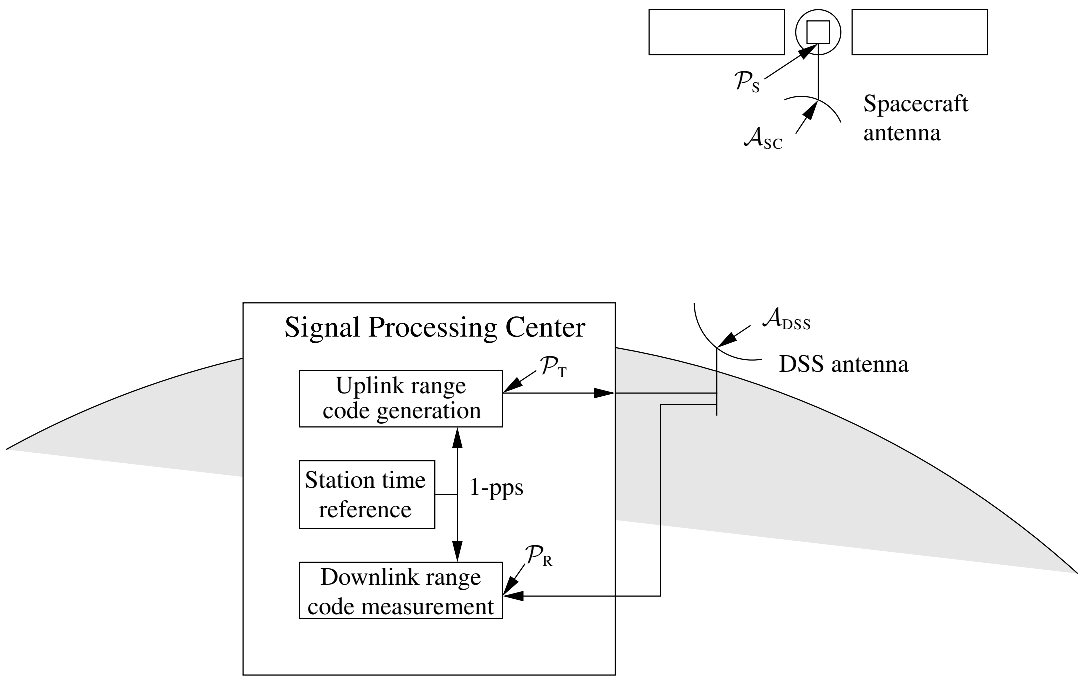

Figure 4. Reference locations for two-way ranging.

A. The Two-Way Geometric Time Delay

Figure 5 is a timeline showing the range-code phase at each of several points and the time delay between each pair of points. The antenna reference points $\mathcal{A}_{\text{DSS}}$ and $\mathcal{A}_{\text{SC}}$ are shown in this figure. Also shown are the points $\mathcal{P}_{\text{T}}$ and $\mathcal{P}_{\text{R}}$ in the SPC associated with phase measurement. A point $\mathcal{P}_{\text{S}}$ in the spacecraft transponder is significant for telemetry ranging. The range-code phases at $\mathcal{P}_{\text{T}}$, $\mathcal{P}_{\text{S}}$ and $\mathcal{P}_{\text{R}}$ are denoted ψ_T, ψ_S, and ψ_R, respectively. The geometric delays τ_u and τ_d represent the signal delay through space on the uplink ($\mathcal{A}_{\text{DSS}}$ to $\mathcal{A}_{\text{SC}}$) and on the downlink ($\mathcal{A}_{\text{SC}}$ to $\mathcal{A}_{\text{DSS}}$), respectively. Time delays that are part of the phase delay measurement but which are excluded from τ_u and τ_d are also shown: τ_u^{DSS} ($\mathcal{P}_{\text{T}}$ to $\mathcal{A}_{\text{DSS}}$), τ_u^{SC} ($\mathcal{A}_{\text{SC}}$ to $\mathcal{P}_{\text{S}}$), τ_d^{SC} ($\mathcal{P}_{\text{S}}$ to $\mathcal{A}_{\text{SC}}$) and τ_d^{DSS} ($\mathcal{A}_{\text{DSS}}$ to $\mathcal{P}_{\text{R}}$). These last four delays are collectively called instrumentation delays; and, ultimately, they must be calibrated.

The notation in Figure 5 suppresses the time dependence of the range-code phases and of the time delays τ_u and τ_d . The instrumentation delays τ_u^{DSS}, τ_u^{SC}, τ_d^{SC}, and τ_d^{DSS} are approximately constant, at least over a given tracking pass. The uplink and downlink geometric time delays τ_u and τ_d vary with time, as the range between the DSS and the spacecraft changes. When

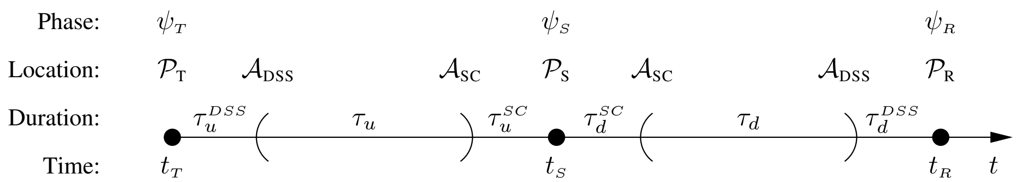

Figure 5. Timeline with range-code phase values and time delays.

the time dependence of a time delay is denoted explicitly, the time argument t represents the time the signal arrives at $\mathcal{P}_R$.

The time-dependent two-way geometric delay $\tau(t)$ is defined as

$$\tau(t) = \tau_u(t) + \tau_d(t). \tag{1}$$

In (1), $\tau_u(t)$ denotes the time delay experienced by a signal on the path segment $\mathcal{A}_{DSS}$ to $\mathcal{A}_{SC}$ for an arrival time t of the signal at $\mathcal{P}_R$, and $\tau_d(t)$ is the time delay experienced by a signal on the path segment $\mathcal{A}_{SC}$ to $\mathcal{A}_{DSS}$, for an arrival time t of the signal at $\mathcal{P}_R$. The time-dependent two-way geometric time delay $\tau(t)$ is the sum of these two components, and its argument t is the time tag marking the arrival time of the downlink signal at $\mathcal{P}_R$.

The ranging system measures the two-way geometric delay $\tau(t)$ when the signal arrives at $\mathcal{P}_R$ at a specific sample time $t = t_R$. The phase of the signal observed at time t_R will have been present at $\mathcal{P}_T$ at the earlier time t_T. Referring to Figure 5, this sampled delay can be expressed as

$$\tau(t_R) = (t_R - t_T) - \left(\tau_u^{SC} + \tau_d^{SC} + \tau_u^{DSS} + \tau_d^{DSS}\right). \tag{2}$$

The round-trip time difference $(t_R - t_T)$ in (2) is calculated from phase measurements. Then, once the instrumentation delays are calibrated and removed, $\tau(t_R)$ is determined.

Note that the interpretation of some of the quantities in Figure 5 and (2) is slightly different for telemetry ranging and conventional two-way ranging. However, the above development can serve as a valid outline of the calculation of $\tau(t_R)$ for both conventional two-way ranging and telemetry ranging, as discussed in more detail in the next two subsections.

B. Calculating Time Delay from Phase Measurements

The range-code phases ψ_T, ψ_S, ψ_R, shown in Figure 5, also have a time dependence. This time dependence is a fast variation, with time derivative equal to the range-clock frequency in units of chips/s. When the time argument t of the range-code phase functions is shown explicitly, it refers to a fixed frame of reference at the DSS, even though this time reference may not be known at all of the measurement points.

The range-clock phase $\psi_T(t)$ may be calculated to excellent accuracy for any given time t, as $\psi_T(t)$ is generated in the uplink signal processing (at $\mathcal{P}_T$ in the SPC). The range clock is coherently related to the uplink carrier. A characterization of the uplink carrier frequency as a function of time is archived, and so the derivative $\dot{\psi}_T(t) = d\psi_T(t)/dt$ is available to the analyst in post-processing. The derivative $\dot{\psi}_T(t)$ is, in general, a function of time, as the uplink carrier frequency is often varied to pre-compensate for the time-varying uplink Doppler effect. In every case, $\psi_T(t)$ increases monotonically, as it is assumed that the range-code phase has been unwrapped.

The mathematical problem of converting a phase-delay measurement to a time-delay measurement may be formulated as follows. In post-processing, the analyst has available a phase sample $\psi_T(t_R)$, calculated in the uplink signal processing at $\mathcal{P}_\mathrm{T}$ for a known sample time t_R, and a record of $\dot{\psi}_T(t)$. A second phase value $\psi_T(t_T)$ is also needed for the calculation; this is the phase at $\mathcal{P}_\mathrm{T}$ at time t_T, the departure time for a signal traveling from $\mathcal{P}_\mathrm{T}$ to $\mathcal{P}_\mathrm{R}$ and arriving at time t_R. This departure time t_T is the unknown quantity in (2) that will be determined by the phase measurement. Both conventional two-way ranging and telemetry ranging identify the phase value $\psi_T(t_T)$ with the range-code phase measured somewhere else along the timeline depicted in Figure 5. The measured phase value will have appeared at the point $\mathcal{P}_\mathrm{T}$ at the departure time t_T. The location where the phase value $\psi_T(t_T)$ is measured is different for telemetry ranging and for conventional two-way ranging. The time t_T is *not* the time at which the phase value $\psi_T(t_T)$ is measured, but rather the (earlier) time at which this phase value was present at $\mathcal{P}_\mathrm{T}$.

The difference between the known phase value $\psi_T(t_R)$ at the known sample time t_R, and the remotely measured phase inferred to equal the phase $\psi_T(t_T)$ at the unknown time t_T when this phase value was present at $\mathcal{P}_\mathrm{T}$, is just the integral of the known time derivative $\dot{\psi}_T(t)$ between t_T and t_R:

$$\int_{t_T}^{t_R} \dot{\psi}_T(t)dt = \psi_T(t_R) - \psi_T(t_T). \tag{3}$$

(3) is valid even when $\dot{\psi}_T(t)$ is a function of time, as it will be when the uplink carrier is tuned (for the sake of uplink Doppler compensation).

Since $\psi_T(t)$ is known for all t, the only unknown in (3) is the lower limit t_T of the integral on the left-hand side. A numerical technique can be used to solve for t_T with excellent accuracy. At this point then, (2) for the two-way geometric time delay is solved, provided that the instrumentation delays have been calibrated. Before discussing calibration methods, we conclude this subsection by describing the different methods used by conventional two-way ranging and telemetry ranging to infer the phase value $\psi_T(t_T)$ by observing it remotely at different locations.

1. Conventional Two-Way Ranging

In conventional two-way PN ranging (as presently practiced by the DSN), the signal path of the range code can be described as follows [5]. The range code is phase-modulated onto the uplink carrier. At the spacecraft transponder, the uplink carrier is demodulated, and the baseband range code is then passed to a ranging channel. This channel can be regenerative or not. A regenerative channel includes a code-tracking loop that produces a replica of the uplink range code that is in approximate phase-alignment with the original and that is nearly free from noise. At $\mathcal{P}_{\mathrm{S}}$ this replica range code is then phase-modulated onto the downlink carrier. At the DSS receiver, open-loop correlations measure the phase of the range code. The local model of the range clock, which is required by the correlations, is generated using Doppler-rate aiding from the carrier loop. This is possible because the range clock and downlink carrier are coherently related.

For conventional ranging, the phase $\psi_R(t)$ is measured at $\mathcal{P}_{\mathrm{R}}$ (the location of the open-loop correlations) within the DSS receiver at time $t = t_R$, yielding $\psi_R(t_R)$. This time is selected as an epoch of the DSS 1-pps (1 pulse per second) clock. On the same 1-pps epoch, $\psi_T(t)$ is sampled at $\mathcal{P}_{\mathrm{T}}$ within the DSS uplink signal processing, yielding $\psi_T(t_R)$. No range-code phase measurement is made at $\mathcal{P}_{\mathrm{S}}$ because the phase measurement at $\mathcal{P}_{\mathrm{R}}$ obviates any need to observe the range-code phase at the spacecraft in order to determine the two-way range.

The phase $\psi_R(t_R)$ measured at $\mathcal{P}_{\mathrm{R}}$ was present at $\mathcal{P}_{\mathrm{T}}$ at the earlier time t_T, that is,

$$\psi_R(t_R) = \psi_T(t_T). \tag{4}$$

In other words, the two phase measurements recorded at two different places at the same time ($t = t_R$) are equivalent to having sampled the single phase function $\psi_T(t)$ at two different times ($t = t_R$ and $t = t_T$). Thus, the value of t_T can be deduced by solving for the lower limit of the integral in (3), given knowledge of $\dot{\psi}_T(t)$. The two-way geometric delay $\tau(t_R)$ is then calculated from (2).

Figure 6 illustrates how $\tau(t_R)$ is calculated from the phase samples $\psi_T(t_R)$ and $\psi_R(t_R)$ in the simplest case where the transmitted range clock has a constant frequency ω and the instrumentation delays are zero. The sloped line on the left is a plot of $\psi_T(t)$. The slope is ω, the rate of advance of the range-code phase in units of chips/s. The sloped line on the right is a plot of $\psi_R(t)$. The horizontal spacing between these two lines is $\tau(t_R)$. Both sloped lines are sampled at the common time t_R. With $\Delta\psi = \psi_T(t_R) - \psi_R(t_R)$, $\tau(t_R)$ is easily calculated as $\Delta\psi/\omega$.

2. Telemetry Ranging

Telemetry ranging also relies on two values of the range-code phase. As with conventional ranging, one of these phase values is from the phase function $\psi_T(t)$, sampled within the DSS uplink signal processing at $\mathcal{P}_{\mathrm{T}}$ at time t_R. The second phase value is from the phase function $\psi_S(t)$ at $\mathcal{P}_{\mathrm{S}}$ in the spacecraft transponder. There is no phase measurement $\psi_R(t)$ at $\mathcal{P}_{\mathrm{R}}$ in the DSS receiver because the range-code signal is not transmitted from the spacecraft to the DSS in this case.

Onboard the spacecraft, the range-code phase $\psi_S(t)$ at $\mathcal{P}_{\mathrm{S}}$ is tracked by a code-tracking loop [2].

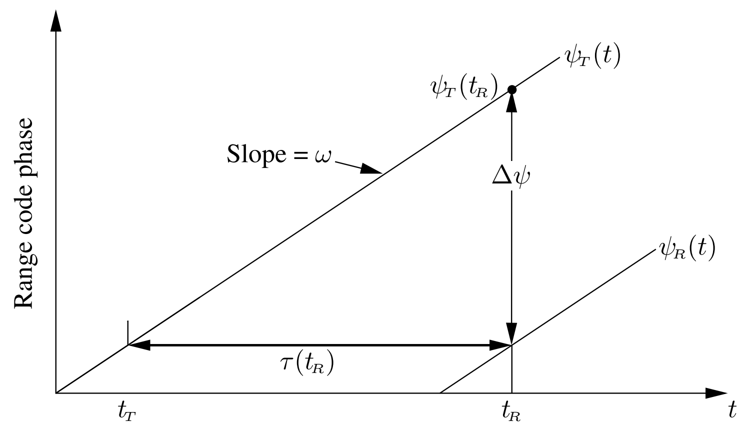

Figure 6. Timing relationships for conventional two-way ranging.

This loop produces a measure of range-code phase that is accurate, at any instant in time, to within a small fraction of a chip period. Samples of the range-code phase from the code-tracking loop are taken, with each sample coincident with the start of a telemetry frame. The range-code phase samples are initially known modulo 1,009,470 chips. In post-processing these phase samples are unwrapped by removing discontinuities of size 1,009,470 chips. It is convenient to denote the time of a phase sample by t_S, even though no time tag is applied to the phase sample onboard the spacecraft and knowledge of t_S is *not* needed to determine the two-way range.

Each range-code phase sample $\psi_S(t_S)$ from the spacecraft transponder's code-tracking loop is inserted into a telemetry frame for transmission to the DSS. The telemetry frame that conveys a phase sample is not the telemetry frame whose start triggered the phase sample; rather, a subsequent telemetry frame is used. A master frame count that identifies the triggering frame accompanies the phase sample, so the triggering frame can be unambiguously associated with its range-code phase sample.

In conventional two-way ranging, the signal arrival time t_R at the DSS receiver (as depicted in Figure 5) is always an epoch of the DSS 1-pps clock. For telemetry ranging, this ground station arrival time t_R instead denotes the Earth-received time of the start of the same telemetry frame that triggered the phase sample $\psi_S(t_S)$. The ground station time tag t_R is determined in the DSS receiver with a combination of a symbol synchronization loop and a frame synchronization loop.

A phase value on the transmitter side of the DSS is calculated for the DSS receiver time tag t_R corresponding to (the start of) the same telemetry frame that triggered the phase sample $\psi_S(t_S)$ onboard the spacecraft. We denote this transmitter-side phase value $\psi_T(t_R)$. This calculation can be done with excellent accuracy, even though the time tag t_R has a fractional part relative to the DSS 1-pps clock. The phase value $\psi_S(t_S)$ measured at the spacecraft will have appeared earlier at time t_T at $\mathcal{P}_\mathrm{T}$ in the uplink signal processing, i.e.,

$$\psi_S(t_S) = \psi_T(t_T). \tag{5}$$

As with conventional ranging, the two phase values recorded at two different places are equivalent to having sampled the single phase function $\psi_T(t)$ at two different times ($t = t_R$ and $t = t_T$), even though in this case the two original phase samples were recorded at two different times as well ($t = t_R$ and $t = t_S$).

As with conventional ranging, the value of t_T can then be deduced by solving for the lower limit of the integral in (3), given knowledge of the two phase values $\psi_T(t_T)$, $\psi_T(t_R)$, and the time derivative $\dot{\psi}_T(t)$. Finally, the two-way geometric time delay $\tau(t_R)$ is calculated from (2) assuming that the instrumentation delays have been calibrated.

Figure 7 illustrates how $\tau(t_R)$ is calculated from the phase samples $\psi_T(t_R)$ and $\psi_S(t_S)$ in the simplest case where the transmitted range clock has a constant frequency ω and all instrumentation delays are zero. The telemetry frame (codeword) that triggered the phase sample $\psi_S(t_S)$ arrives at the DSS receiver at time t_R. The DSS transmitter phase $\psi_T(t)$ is calculated for this exact time. The sloped line on the left is a plot of $\psi_T(t)$. The slope is ω, the rate of advance of the range-code phase in units of chips/s. The sloped line on the right is a plot of $\psi_S(t)$. The horizontal spacing between these two lines is $\tau_u(t_R)$. Considering that $\Delta\psi = \psi_T(t_R) - \psi_S(t_S)$, $\tau(t_R)$ is easily calculated as $\Delta\psi/\omega$.

C. Removing the Instrumentation Delays

The instrumentation delays in (2) must be removed. The error in calibrating an instrumentation delay becomes an error of the same magnitude in the determination of τ. Hence, we require calibrations with an accuracy on the order of a nanosecond.

In addition, the time tag of the two-way geometric time delay should, in general, be adjusted in order to mark the signal arrival at $\mathcal{A}_\mathrm{DSS}$, rather than at $\mathcal{P}_\mathrm{R}$. An error in the time tag has only a secondary effect on the accuracy of the range measurement. It is a question of how much the range changes over a duration equal to the error in the reported time tag. A time tag that is accurate to within a few microseconds should be adequate.

1. Calibration for Conventional Two-Way Ranging

For conventional ranging, it is common to combine the uplink and downlink components of the instrumentation delays. The two-way spacecraft instrumentation delay $\tau^{SC} \triangleq \tau_u^{SC} + \tau_d^{SC}$ is approximately constant, and is calibrated before flight. Even if this delay is not measured accurately before flight, range data from multiple passes can be used within the orbit determination program to solve for τ^{SC}.

The two-way DSS instrumentation delay $\tau^{DSS} \triangleq \tau_u^{DSS} + \tau_d^{DSS}$ is approximately constant over

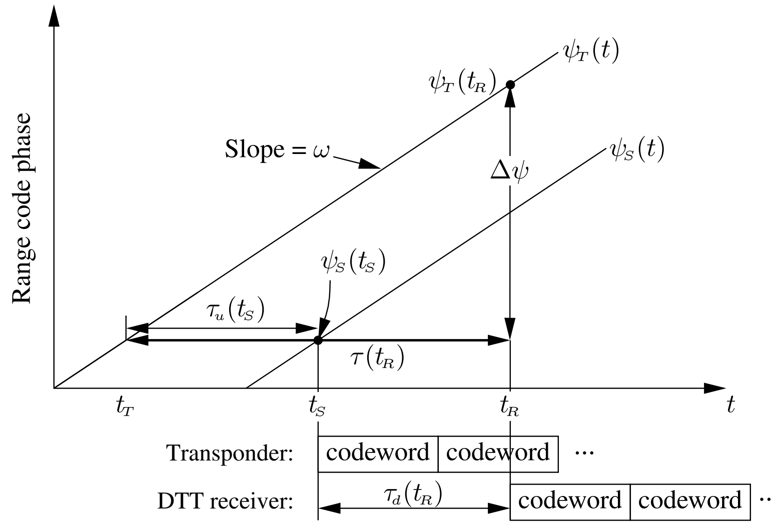

Figure 7. Timing relationship for telemetry ranging.

a tracking pass. This delay is calibrated before most tracking passes in which range measurements are scheduled. This is a summary of how a station delay calibration is done:

Algorithm 1 Two-way station delay calibration

1: Record the range-code phase at $\mathcal{P}_{\mathrm{T}}$ while transmitting an uplink carrier with ranging modulation.
2: Intercept the uplink carrier with a range calibration coupler located near $\mathcal{A}_{\mathrm{DSS}}$.
3: Translate the intercepted uplink carrier frequency to the downlink band (by means of a test translator).
4: Insert this "downlink" carrier with modulation into the downlink path near $\mathcal{A}_{\mathrm{DSS}}$.
5: Measure the range-code phase at $\mathcal{P}_{\mathrm{R}}$.

The time tag of the two-way geometric delay $\tau(t_R)$ should be reduced from t_R to $t_R - \tau_d^{DSS}$. In the conventional ranging system, there is no direct measurement of the one-way delay τ_d^{DSS} needed to adjust this time tag. However, it is generally adequate for this purpose to estimate τ_d^{DSS} as one-half of the calibrated two-way instrumentation delay τ^{DSS}.

2. Calibration for Telemetry Ranging

For telemetry ranging, the total instrumentation delay through the spacecraft $\tau_u^{SC} + \tau_d^{SC}$ will not generally equal the total instrumentation delay τ^{SC} for a conventional two-way ranging signal through the spacecraft. This is because τ_d^{SC} follows the telemetry path within the transponder rather than the downlink ranging signal path. It should still be possible to calibrate $\tau_u^{SC} + \tau_d^{SC}$ before flight, but it will be a more elaborate procedure than that required to calibrate τ^{SC} for conventional ranging.

Likewise, the sum $\tau_u^{DSS} + \tau_d^{DSS}$, representing the instrumentation delay through the DSS, will generally not equal the DSS instrumentation delay τ^{DSS} of a conventional two-way ranging signal, since τ_d^{DSS} follows the telemetry path within the DSS rather than the downlink ranging signal path. However, the telemetry path and the downlink ranging signal path are mostly the same. The difference between these paths, if constant, can be estimated. For telemetry ranging, a calibration of τ^{DSS} should be performed before each tracking pass in the usual way (see Algorithm 1), and then a small correction can be applied to account for the difference between $\tau_u^{DSS} + \tau_d^{DSS}$ (the DSS delay for telemetry ranging) and τ^{DSS} (the DSS delay for two-way ranging).

As with conventional ranging, the time tag of τ should be reduced from t_R to $t_R - \tau_d^{DSS}$. This adjustment of the time tag can be done with an accuracy of a few microseconds.

D. Discussion of How and Why Telemetry Ranging Works

This subsection briefly recapitulates how two-way time delay is determined by the telemetry ranging technique. As with conventional two-way ranging, the uplink has a ranging signal which is constructed from PN codes. The range code is generated at the DSS transmitter in digital signal processing, so for any given time the range-code phase may be calculated and archived. For telemetry ranging, unlike the case of conventional two-way ranging, the range-code phase in the transponder is sampled at the beginning of a telemetry frame [2]. This recorded phase is conveyed to the DSS as part of the telemetry stream. On the ground, the Earth-received time of (the start of) the telemetry frame is measured. The two-way time delay is calculated from the following quantities: the range-code phase $\psi_S(t_S)$ at the start of the telemetry frame as recorded in the spacecraft transponder; the measured Earth-received time t_R of the telemetry frame at the DSS; the calculated phase $\psi_T(t_R)$ of the range code at the DSS transmitter for the Earth-received time of the telemetry frame; and various instrumentation delays which are removed by calibration.

Following is an intuitive explanation for how two-way delay may be extracted from telemetry ranging. The value $\psi_S(t_S)$ of the range-code phase recorded on the spacecraft at $\mathcal{P}_\mathrm{S}$ is identical to the value that would be observed at $\mathcal{P}_\mathrm{R}$ in the DSS receiver if the ranging signal were echoed to the downlink, and the time associated with that value of range-code phase at $\mathcal{P}_\mathrm{R}$ would be t_R. Hence, telemetry ranging provides the same information as conventional two-way ranging: uplink and downlink range-code phases plus a common time tag. With both conventional and telemetry ranging the transponder's range-code phase is sent to the ground and associated with a time tag. In the conventional method, the transponder phase is sent by regenerating a signal with that phase and modulating it onto the downlink carrier; in telemetry ranging, the transponder phase is sampled and placed into the telemetry. The new element in telemetry ranging is that the range-code phase measurement that conventionally has been made in the DSS receiver is now shifted to the spacecraft transponder. But it is not a one-way measurement, because the time delay on the downlink is incorporated into the measurement.

For telemetry ranging, two range-code phases, $\psi_T(t_R)$ and $\psi_S(t_S)$, along with the non-integer time tag t_R, are required for each determination of a two-way time delay. At present with conventional two-way ranging, the story is the same, except that the phases are $\psi_T(t_R)$ and $\psi_R(t_R)$, and the common time tag is an integer relative to the DSS 1-pps clock. The processing done by the orbit determination program will be the same, except that the time tag becomes a non-integer in the case of telemetry ranging. The calibration of instrumentation delay is more complicated for telemetry ranging, but if the instrumentation delays are approximately constant, a suitable calibration procedure will be available.

It is important to note that telemetry ranging is not sensitive to clock instabilities in the spacecraft transponder. The phase sample from the transponder, called $\psi_S(t_S)$ here, does not receive a time tag in the transponder. In fact, the time t_S is not needed for the calculation of the two-way time delay. The symbol t_S was introduced in this analysis just to facilitate the description of the measurement. Moreover, the measured value $\tau(t_R)$ is, to first order, independent of any drift in the spacecraft data clock.

III. DSN Infusion Plan

This section summarizes the changes needed within the DSN to accommodate telemetry ranging. The same uplink is produced in support of telemetry ranging. Changes are required for the downlink signal processing. The first subsection below describes the existing infrastructure within the DSN that handles conventional two-way ranging data. The second subsection considers how the DSN can, in the future, support telemetry ranging.

A. Existing Infrastructure for Two-Way Ranging Data

The present system for acquiring and delivering range data is shown in Figure 8. Abbreviations are listed in Table 1. This system supports both sequential ranging and PN ranging. The description that follows, however, is for PN ranging.

The phase $\psi_T(t)$ of the PN range code on the uplink is available in the Uplink Ranging Assembly (URA). One uplink phase sample $\psi_T(t_R)$ is needed for each range measurement; this sample has a time tag t_R that is an epoch of the 1-pps station clock. $\psi_T(t_R)$ is passed to the Uplink Processor Assembly (UPA), and from there it is sent, via Data Capture and Delivery (DCD), to the Tracking Data Delivery System (TDDS) at JPL [5].

The history of the uplink carrier frequency f_c is also provided by the UPA. Since the range clock is coherently related to the carrier, the history of f_c provides an accurate model for the derivative $\dot{\psi}_T(t)$ of $\psi_T(t)$.

In the downlink signal processing, a phase measurement $\psi_R(t_R)$ is extracted from the received ranging signal by open-loop correlations, made possible by Doppler rate-aiding. The time tag t_R for this measurement is set by the moment at which Doppler rate-aiding is applied; this is the same epoch of the 1-pps clock that is used to sample $\psi_T(t)$. $\psi_R(t_R)$ is sent from the Downlink Channel Controller (DCC) at the Deep Space Communications Complex (DSCC), via the DCD, to the TDDS [5].

The TDDS archives radiometric data, including range measurements. These data are used by mission navigation teams and others. The TDDS uses the format of a Standard Formatted Data Unit (SFDU)[4] For each two-way range measurement, there is one Tracking Data SFDU that conveys the difference $\Delta\psi$ of $\psi_T(t_R)$ and $\psi_R(t_R)$, as well as the time tag t_R. The user can calculate the two-way time delay from $\Delta\psi$, t_R, and $\dot{\psi}_T(t)$.

B. Accommodation of Telemetry Ranging

Figure 9 illustrates, at a high level, how telemetry ranging can be accommodated within the DSN. Details of the signal processing required for telemetry ranging are not described here.

On the uplink side, the UPA will provide, as at present, samples of $\psi_T(t)$ (taken at epochs of the 1-pps clock) and a model for $\dot{\psi}_T(t)$.

On the downlink side, the DCC will extract one phase sample $\psi_S(t_S)$ at a time from the telemetry stream and then report those samples to the TDDS via the DCD. In order to simplify the extraction of $\psi_S(t_S)$ from telemetry, a virtual channel might be used. It is not necessary to return $\psi_S(t_S)$ in the same frame whose starting edge triggered the sample. Rather, the sample can be returned in a later frame. This will work so long as the triggering frame can be uniquely identified. This might be accomplished, for example, by having a master frame count (for the triggering frame) accompany $\psi_S(t_S)$. Only one sample $\psi_S(t_S)$ is required from the transponder for each range measurement. However, a contiguous set of range measurements are normally made, as this has more value for navigation than an isolated measurement.

The time tag t_R to be reported with $\psi_S(t_S)$ is the Earth-received time of the telemetry frame that triggered the sampling of $\psi_S(t)$ within the transponder. (The time t_S on the spacecraft at which the sampling occurs is not recorded, as it is not needed, as explained in Section II.) t_R is measured in the Receiver, Ranging, and Telemetry (RRT) module and is available within the DCC. An 80-MHz reference is used to measure t_R. Quantization noise on the time tag has a maximum error of one-half the period of the reference clock; this is 6.25 ns. In order to get range measurement performance similar to that available from conventional two-way ranging, the 6.25 ns quantization error must be reduced. This can be accomplished with a smoothing algorithm. As an example, if the true Earth-received time increases linearly with frame number, a least-squares linear fit of the Earth-received times for 20 consecutive frames

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[4] *TRK-2-34, DSN Tracking System Data Archival Format*, DSN document 820-013 (internal document), Jet Propulsion Laboratory, Pasadena, California, 2014.

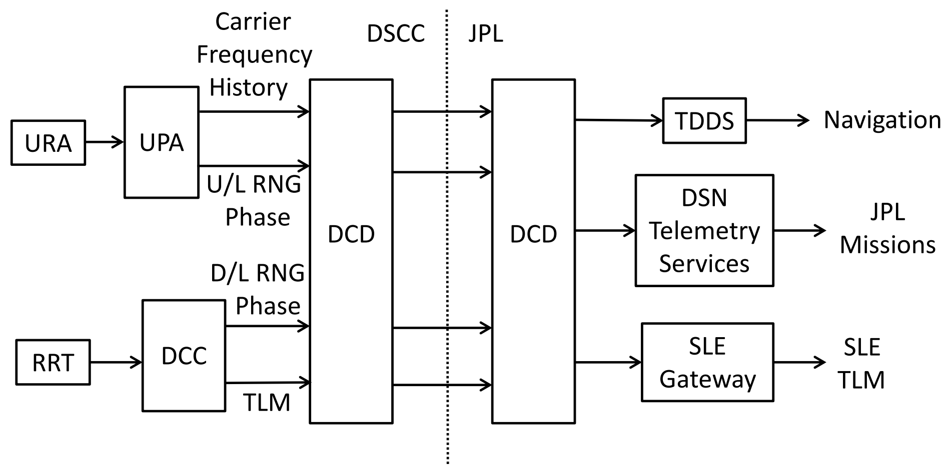

Figure 8. Existing infrastructure for two-way ranging.

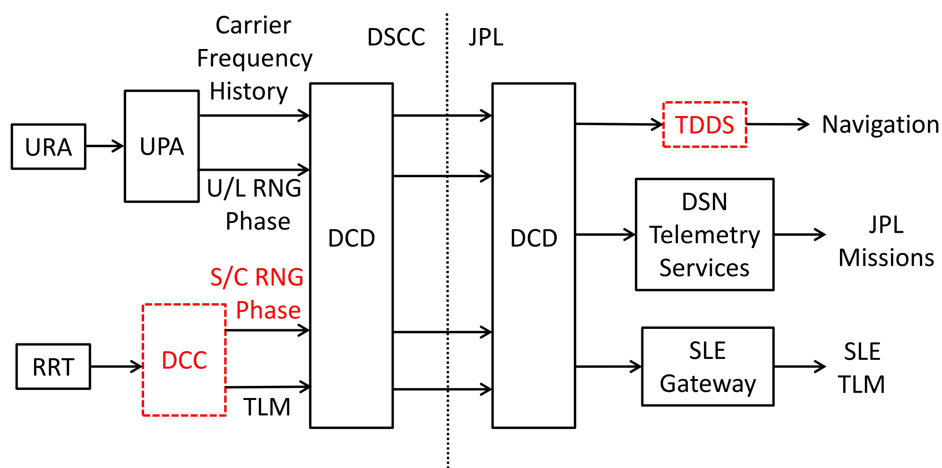

Figure 9. Modified infrastructure for the accommodation of telemetry ranging.

Table 1. Abbreviations

DCC	Downlink Channel Controller
DCD	Data Capture and Delivery
DSCC	Deep Space Communications Complex
RRT	Receiver, Ranging, and Telemetry
SLE	Space Link Extension
TDDS	Tracking Data Delivery Subsystem
UPA	Uplink Processor Assembly
URA	Uplink Ranging Assembly

will produce a standard deviation of the smoothed Earth-received time of about 1 ns.

t_R will have, in general, a non-integer value relative to the 1-pps clock. It is essential that $\psi_T(t)$ be evaluated for the time t_R. The TDDS has the following data from the UPA: a set of samples of $\psi_T(t)$ for the epochs of the 1-pps clock and a model for $\dot{\psi}_T(t)$. From this information, $\psi_T(t_R)$ may be calculated accurately for the non-integer time t_R. The TDDS can then calculate the difference $\Delta\psi$ of $\psi_T(t_R)$ and $\psi_S(t_S)$. From $\Delta\psi$, t_R, and $\dot{\psi}_T(t)$, the user may calculate the two-way time delay.

In order to accommodate telemetry ranging, software changes are required for the DCC and the TDDS. The DCC must extract each sample $\psi_S(t_S)$ from the arriving telemetry. The DCC must identify the triggering frame. Finally, the DCC will likely smooth the Earth-received times. The TDDS must calculate $\psi_T(t_R)$. This last modification is certainly not difficult because the TDDS already does a similar calculation for the case of three-way ranging.

With the modifications described above, the TRK-2-34 interface[5] that the TDDS presents to users is unchanged. As at present, $\Delta\psi$ is reported for a time tag t_R. With telemetry ranging, t_R is not an integer (relative to the 1-pps clock). Fortunately, the TRK-2-34 interface, even at present, conveys t_R as a floating-point number, so the new time tag can be delivered accurately to the user without modification of the interface.

There is already a precedent for non-integer time tags in the user's calculations with range data. At present, each t_R reported in the TRK-2-34 interface is an integer (but in a floating-point field); however, t_R must sometimes be adjusted by the user. This is because t_R applies to $\psi_R(t_R)$, which is measured in the receiver (at point $\mathcal{P}_{\mathrm{R}}$). However, the calculated two-way time delay, after correction for station delay, represents the delay experienced by a signal arriving at the DSN antenna reference point $\mathcal{A}_{\mathrm{DSS}}$. Therefore, for best accuracy, t_R must also be adjusted to refer to the point $\mathcal{A}_{\mathrm{DSS}}$. This is accomplished by accounting for the one-way time delay from $\mathcal{A}_{\mathrm{DSS}}$ to $\mathcal{P}_{\mathrm{R}}$. This adjustment is not always necessary, but when the one-way station delay is relatively large, as it is at Goldstone, and when the range is relatively fast changing, this adjustment can be essential.

The final issue, which is still unresolved, is calibration. Telemetry ranging will require some changes to the station delay calibration procedure. However, the best approach has not yet been identified.

IV. Conclusions

Telemetry ranging holds the promise of better performance than conventional two-way ranging for high-rate telemetry. With telemetry ranging, the uplink ranging signal is not echoed onto

[5] *TRK-2-34, DSN Tracking System Data Archival Format*, DSN document 820-013 (internal document), Jet Propulsion Laboratory, Pasadena, California, 2014.

the downlink: telemetry frames are employed instead. Telemetry, therefore, will abet the range measurement and not interfere with it.

Telemetry ranging shares some features of regenerative PN ranging. A PN range code modulates the uplink carrier. The transponder tracks the arriving range code. No ultra-stable oscillator is required on board the spacecraft to support the range measurement. The telemetry data clock may be asynchronous with the uplink range clock. The major receiver functions at the station, including the tracking loops, will remain unchanged with the advent of telemetry ranging.

Changes will be required both in the transponder and on the ground to support telemetry ranging. The transponder must sample the phase of the uplink range code, and the sampling must coincide with the start of a telemetry frame. Moreover, the transponder must insert range-code phase samples into the telemetry stream. On the ground, software changes will be required in the DCC (at the stations) and in the TDDS. With these changes, the same TRK-2-34 interface will be presented to users of ranging data (except that the time tag will not be an integer).

Acknowledgments

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