Terminology of Ranging Measurements and DSS Calibrations

T. Komarek
Telecommunications Systems Section

T. Otoshi
Radio Frequency and Microwave Subsystems Section

This article presents a proposed set of basic terminology related to deep space ranging measurements. Calibration equations are derived for the "dish-mounted zero delay device" method for 26-m antenna systems and the "translator" method for 64-m antenna systems.

I. Introduction

Data produced by the ranging system can be used in many ways: spacecraft orbit determination, space plasma measurements, earthquake detection, etc. Whatever the objective is, the basic element is always the measurement of the time elapsed between transmission and reception of a ranging code by an Earth-bound Deep Space Station (DSS). The ranging code is modulated on a RF carrier transmitted from a DSS to a distant spacecraft (S/C), where it is demodulated and retransmitted back to Earth. The time delay measured, therefore, necessarily includes the DSS and spacecraft hardware delays, as well as medium effects due to tropospheric refraction and "deceleration" in the ionosphere and space plasma.

This article addresses terminology of ranging measurements with obvious emphasis on DSS delay calibrations since this is the most complicated part of the ranging telecommunication link. To make the semantics meaningful, it is useful to recognize the following "axioms:"

(1) Range is always one-way; it is measured in units of length.

(2) Delay is measured in time units (whatever they are).*

(3) "Light time" corresponds to propagation with the velocity of light in vacuum.

This article was originally a response to the immediate needs of the Viking Radio Science Team. It is suggested, however, that the terminology presented would be con-

*The "range unit" is a time unit since it is an integer fraction of the time period of the DSS master oscillator.

sidered for acceptance by the Ranging Accuracy Team and, through this body, acceptance by other organizations involved, i.e., DSN, Spacecraft Telecommunications, Navigation, and Mission Control.

II. Definitions and Explanations

The following definitions apply to the general case ranging system geometry shown in Fig. 1:

Topocentric range ρ, in meters, is the distance between the DSS and spacecraft reference locations.

Reference locations are the spacecraft antenna aperture plane, DSS antenna axis crossing for the azimuth-elevation (az-el) mount, and the intersection of the polar axis with the hour angle (HA) plane for the hour angle-declination (HA-Dec) mount.

Round trip light time, in seconds, is

$$RTLT = 2\,\rho/c$$

where c is the velocity of light in vacuum.

Round trip propagation time is the time for the ranging modulation to propagate from the *DSS reference location* through the propagation media (planetary atmosphere, space plasma, . . .) to the *S/C reference location* and back, as measured by a correlation-type ranging machine.

$$RTPT = RTLT + BIAS_{MEDIA}$$

Delay to spacecraft, $D_{S/C}$, in seconds, is the total delay measured by a ranging machine when ranging to a spacecraft. It is related to *RTPT* by

$$RTPT = D_{S/C} - BIAS_{S/C} - BIAS_{DSS} + Z_{CORRECTION} \qquad (1)$$

where all entries are in seconds, and

$BIAS_{S/C}$ = spacecraft turnaround delay

$BIAS_{DSS}$ = 2-way DSS delay pre- and post-track measured from the ranging machine to a DSS turnaround device (either ZDD or translator) and back.

$Z_{CORRECTION}$ = 2-way ground station delay correction which must be made to account for the

(a) difference in the DSS turnaround device path and the ranging-to-spacecraft path up to the DSS aperture plane.

(b) difference between the DSS antenna aperture plane and the DSS reference location.

III. DSS Calibrations

A. Dish-Mounted Zero-Delay-Device Method

Station delay calibrations by means of a dish-mounted zero delay device (ZDD) are presently used by the 26-m DSS subnets. This technique (Fig. 2) uses the geometric optics principle in which, for a large antenna with a parabolic geometry (including Cassegrain S/X reflex feed systems), the distance for any ray path from the primary feed phase center to the paraboloid aperture plane via the microwave optics airpath is a constant. Under this assumption, the time delay for any ray propagating along the microwave optics path from the feed horn phase center to the aperture plane is the same as that for any other ray path between these two points (going from the feed horn phase center to the aperture plane or from the aperture plane to the feed horn phase center via the microwave optics ray paths).

Assuming that the internal delay of the ZDD is negligible, it can be seen from Fig. 2 that when ranging to a spacecraft

$$D_{S/C} = D_{ZDD} + \tau_X + \tau_{R,up} + BIAS_{S/C} + \tau_{R,\,down} + \tau_X \qquad (2)$$

where D_{ZDD} is the round trip delay from the ranging machine to the ZDD located on the dish surface and back to the ranging machine. It includes transmitter and receiver delays as well as round trip airpath delays within the antenna structure.

It can also be seen from Fig. 2 that

$$RTPT = \tau_b + \tau_h + \tau_X + \tau_{R,up} + \tau_{R,down} + \tau_X + \tau_h + \tau_b \qquad (3)$$

Solving for $(\tau_{R,up} + \tau_{R,down})$ from (2) and substitution into (3) gives

$$RTPT = D_{S/C} - BIAS_{S/C} - D_{ZDD} + 2\tau_h + 2\tau_b \qquad (4)$$

Comparison of (4) with (1) gives

$$BIAS_{DSS} = D_{ZDD} \qquad (5)$$

$$Z_{CORRECTION} = 2\tau_h + 2\tau_b \qquad (6)$$

where, from the geometry of Fig. 2, the one-way airpath delays τ_h and τ_b (in seconds) are

$$\tau_h = \frac{h}{c} \qquad (7)$$

$$\tau_b = \frac{b}{c}\cos\delta \qquad (8)$$

and where

h = distance in meters between two planes parallel to the aperture plane. The first plane intersects the ZDD and the second plane contains the declination (secondary) axis.

b = perpendicular distance in meters between the hour-angle (primary) and declination (secondary) axes. This distance in JPL antenna drawings is shown to be 6.7056 meters (22.0 ft).

c = speed of electromagnetic wave in vacuum (2.997925×10^8 m s^{-1})

δ = spacecraft declination angle

The values of D_{ZDD} given by (5) are reported for pre- and post-track on the "DSS Post-Track Report." The $Z_{CORRECTION}$ given by (6) depends not only on the physical location of the ZDD on the dish surface but also on the spacecraft declination angle δ. Values of h and b are obtained at each 26-m DSS from physical measurements and are the constants supplied by the DSN. These constants together with the declination angle information should be used by the Orbit Determination Software to determine the $Z_{CORRECTION}$ from (6) for the appropriate tracking pass.

B. Translator Method

The DSS calibration method using the dish-mounted ZDD suffers by multipath errors due to multiple reflections from the antenna structure. For 64-m stations, where the multipath error can be several meters, another calibration method was developed using the Block IV translator (Fig. 3). In this method, only a portion of the DSS hardware delays is pre- and post-track measured. The rest of the hardware delays (including antenna and cabling) is calculated from geometrical dimensions (in the case of waveguide and airpath) and precalibrated (in the case of complex components such as diplexers and filters).

When ranging to a spacecraft, the ranging machine measures $D_{S/C}$, the total two-way delay-to-spacecraft. $D_{S/C}$ contains the propagation delays and both DSS and S/C biases. From Fig. 3, using τ to denote one-way delay, it can be seen that

$$D_{S/C} = \tau_1 + \tau_3 + \tau_{C,up} + \tau_{R,up} + BIAS_{S/C} + \tau_{R,down} + \tau_{C,down} + \tau_4 + \tau_2 \qquad (9)$$

where

all entries are in time units

$\tau_1, \tau_2, \tau_3, \tau_4$ = DSS hardware delays shown in Fig. 3.

τ_R = propagation delay (including medium effects) from the DSS antenna aperture plane to the S/C reference location.

τ_C = one-way delay from feedhorn phase center to aperture plane of the DSS antenna via the microwave optics airpath. The S-band airpath includes points on the ellipsoidal reflector, dichroic plate, hyperboloidal subreflector, and the main paraboloidal reflector surface.

τ_D = one-way delay between the aperture plane and DSS reference location

Both τ_C and τ_D are constants for a given DSS, independent of the point on the dish surface where reflection takes place, due to the parabolic geometry of DSS antenna dishes and Cassegrain design.

Also from Fig. 3, it can be seen that the round trip propagation time is

$$RTPT = \tau_D + \tau_{R,up} + \tau_{R,down} + \tau_D \qquad (10)$$

But from (9)

$$\tau_{R,up} + \tau_{R,down} = D_{S/C} - \sum_{i=1}^{4} \tau_i - \tau_{C,up} - \tau_{C,down} - BIAS_{S/C} \qquad (11)$$

Substituting (11) into (10) gives

$$RTPT = 2\tau_D + D_{S/C} - \sum_{i=1}^{4} \tau_i - \tau_{C,up} - \tau_{C,down} - BIAS_{S/C} \qquad (12)$$

Defining one-way delays τ_5 and τ_6 as

$$\tau_5 \stackrel{\Delta}{=} \tau_{C,up} - \tau_D$$

$$\tau_6 \stackrel{\Delta}{=} \tau_{C,down} - \tau_D,$$

then substituting into (12) leads to the RTPT expression when ranging to spacecraft of

$$RTPT = D_{S/C} - BIAS_{S/C} - \sum_{i=1}^{6} \tau_i \qquad (13)$$

When ranging to translator, the ranging machine measures D_{XLATOR}, the two-way delay-to-translator.

From Fig. 3

$$D_{XLATOR} = \tau_1 + \tau_{XLATOR} + \tau_2 \qquad (14)$$

where

τ_{XLATOR} = one-way delay from the uplink sample point through the translator to the downlink sample point. This delay is calibrated by a portable ZDD.

From (13) and (14)

$$RTPT = D_{S/C} - BIAS_{S/C} - D_{XLATOR} - \sum_{i=3}^{6} \tau_i + \tau_{XLATOR} \qquad (15)$$

Comparing (15) with (1) we get the DSS calibrations for the translator method:

$$BIAS_{DSS} = D_{XLATOR} \qquad (16)$$

$$Z_{CORRECTION} = \tau_{XLATOR} - \sum_{i=3}^{6} \tau_i \qquad (17)$$

or from substitutions of τ_5 and τ_6

$$Z_{CORRECTION} = \tau_{XLATOR} + 2\tau_D - \tau_3 - \tau_4 - \tau_{C,up} - \tau_{C,down} \qquad (17a)$$

where all terms are defined in Fig. 3.

The $Z_{CORRECTION}$ does not require knowledge of τ_h as in the case of a dish-mounted ZDD. Except for τ_{XLATOR}, which is a calibrated value obtained through measurement, most of the terms in $Z_{CORRECTION}$ are calculated quantities, which is a major drawback of this calibration method. The station bias (D_{XLATOR}) is a measured delay, reported by a station pre- and post-track. Values of τ_D,($\tau_{C,up}$) and ($\tau_{C,down}$) for the S/X reflex feed configuration for 64-m antenna systems have been determined by Batelaan and are reported in Ref. 1.

Reference

1. Otoshi, T. Y., ed., *A Collection of Articles on S/X-Band Experiment Zero Delay Ranging Tests*, Technical Memorandum 33-747, Vol. 1, Jet Propulsion Laboratory, Pasadena, Calif., Nov. 1975, p. 50.

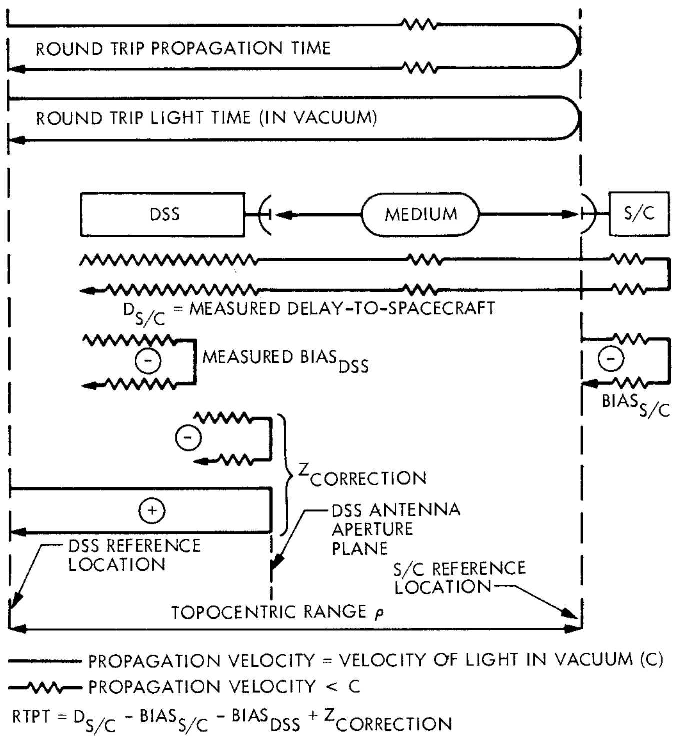

Fig. 1. Ranging measurement definitions

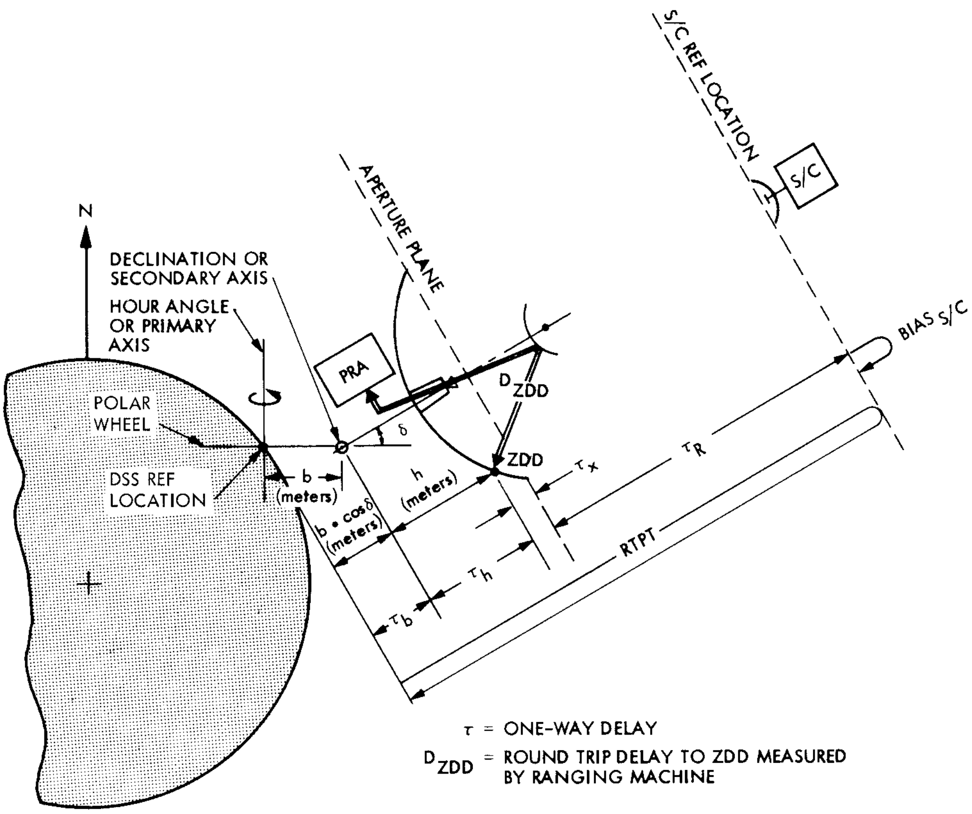

Fig. 2. DSS calibration — dish-mounted ZDD method

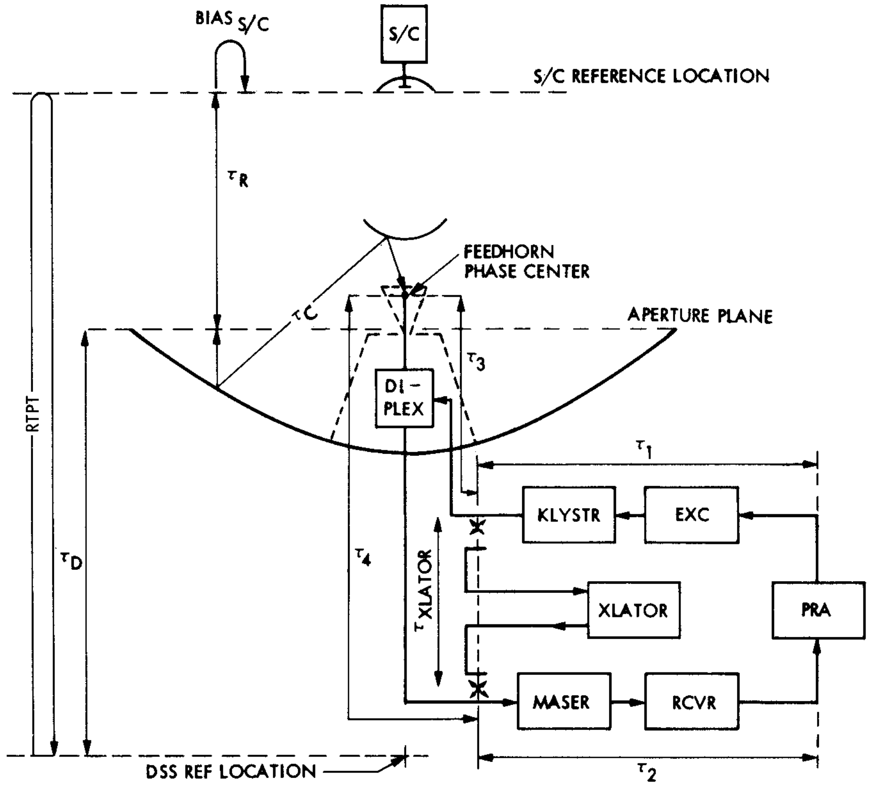

Fig. 3. DSS calibration — translator method