DSMS Telecommunications Link
Design Handbook

203
Sequential Ranging

Effective November 30, 2000

Document Owner:

12/11/00
C.J. Ruggier — Date
Tracking System Engineer

Approved by:

12/13/00
A. Kwok — Date
Tracking and Navigation Service
Systems Development Engineer

Prepared by:

12/11/00
R. W. Sniffin — Date

Released by:

[Signature on file at TMOD Library]
TMOD Document Release — Date

Change Log

Rev	Issue Date	Affected Paragraphs	Change Summary
Initial	1/15/2001	All	All

Note to Readers

There are two sets of document histories in the 810-005 document, and these histories are reflected in the header at the top of the page. First, the entire document is periodically released as a revision when major changes affect a majority of the modules. For example, this module is part of 810-005, Revision E. Second, the individual modules also change, starting as an initial issue that has no revision letter. When a module is changed, a change letter is appended to the module number on the second line of the header and a summary of the changes is entered in the module's change log.

Module 203 supersedes module TRK-30, Rev. E, dated January 15, 1998, in 810-005.

Contents

Paragraph **Page**

1 Introduction 6
1.1 Purpose 6
1.2 Scope 6
2 General Information 6
2.1 Network Simplification Project Ranging 7
2.2 System Description 7
2.3 Parameters Specified for Ranging Operations 9
2.3.1 Transmit Time and Receive Time 9
2.3.2 Clocks and Components 9
2.3.3 Square-Wave and Sine-Wave Ranging 11
2.3.4 Integration Times 12
2.3.4.1 T_1 12
2.3.4.2 T_2 14
2.3.4.3 T_3 17
2.3.4.3 Cycle Time 17
2.3.5 Modulation Index 18
2.3.6 Frequency Chopping 19
2.3.7 Other Parameters 20
2.3.7.1 Tolerance 20
2.3.7.2 Servo 20
2.3.7.3 Pipe 21
2.4 Range Measurement Process 22
2.4.1 Range Measurement Technique 22
2.4.2 P_r/N_0 24
2.4.2 Figure of Merit 25
2.4.3 Differenced Range Versus Integrated Doppler 28
2.5 Ratio of Downlink Ranging Power to Total Power 28
2.6 Range Corrections 30
2.6.1 DSS Delay 31
2.6.2 Z-Correction 32
2.6.3 Antenna Correction 32
2.7 Error Contributions 35
Appendix A, The Current DSN Ranging System 36
A1.0 System Description Using the Sequential Ranging Assembly 36

A2.0 Range Measurement Process Using the SRA 37
A3.0 Performance Differences 38
A3.1 Integration Times 38
A3.1.1 T_1 38
A3.1.2 T_2 40
A3.1.3 T_3 40
A3.2 Other SRA Ranging Parameters 40
A3.3 SRA Calculations 40
A3.3.1 Cycle Time 40
A3.3.2 P_r/N_o 40
A4.0 Range Corrections Using the SRA 44
A4.1 DSS Delay 44
A4.2 Antenna Calibration 44
A5.0 Error Contributions for Ranging Using the SRA 45

Illustrations

Figure **Page**

1. The NSP Era DSN Ranging System Architecture 8
2. Integration Time T_1 Versus P_r/N_o, Clock Frequency F_c = 1 MHz, for Sine-Wave Ranging 14
3. Integration Time T_1 Versus P_r/N_o, Clock Frequency F_c = 500 kHz, for Square-Wave Ranging 15
4. Code Component Integration Time T_1 Versus P_r/N_o for Various Probabilities of Error and $n = 5$ 16
5. Code Component Integration Time T_1 Versus P_r/N_o for Various Probabilities of Error and $n = 10$ 16
6. Code Component Integration Time T_1 Versus P_r/N_o for Various Probabilities of Error and $n = 20$ 17
7. Chopping of C5, C6, and C7 (by C4) 21
8. Component Acquisition Process 23
9. Figure of Merit, with T_2 = 5 sec for Various Frequency Components. 26
10. Figure of Merit, with T_2 = 50 sec for Various Frequency Components 27

11. Figure of Merit, with T_2 = 500 s for Various Frequency Components 27

12. P_r/P_t as a Function of $\Gamma_{RNG/DN}$ for Selected Values of Modulation Index θ_{DN} 30

13. DSN Range Measurement 31

14. Typical DSS Delay Calibration 33

15. Measuring the Z-Component 34

A-1. Current DSN Ranging System 37

A-2. Integration Time T_1 Versus P_r/N_o, Clock Frequency F_c = 1 MHz, for Sine-Wave Ranging Using the SRA 41

A-3. Integration Time T_1 Versus P_r/N_o, Clock Frequency F_c = 500 kHz, for Square-Wave Ranging Using the SRA 42

A-4. Code Component Integration Time T_1 Versus P_r/N_o for Various Probabilities of Error and $n = 5$ 42

A-5. Code Component Integration Time T_1 Versus P_r/N_o for Various Probabilities of Error and $n = 10$ 43

A-6. Code Component Integration Time T_1 Versus P_r/N_o for Various Probabilities of Error and $n = 20$ 43

A-7. Typical Range Calibration Signal Path for DSS Using SRA and MDA Ranging Equipment 45

Tables

Table **Page**

1. Range Code Resolving Capability 11

2. One-Sigma Range Error for NSP Era Ranging System 35

A-1. One Sigma Range Error for SRA/MDA-Equipped Ranging System 46

1 *Introduction*

1.1 *Purpose*

This module describes the Ranging capabilities of the Network Simplification Project (NSP) and provides the performance parameters of the Deep Space Network (DSN) Sequential Ranging equipment for the 70-m, the 34-m High Efficiency (HEF), and the 34-m Beam Waveguide (BWG) subnets. Appendix A gives a description of the ranging architecture and performance for the 26-m subnet and the 34-m High-speed Beam Waveguide (HSB) antenna that are not included in the NSP implementation scheme, and for the 70-m, 34-m HEF, and 34-m BWG subnets prior to the NSP implementation.

1.2 *Scope*

The material contained in this module covers the sequential ranging system that is utilized by both near-Earth and deep space missions. This document describes those parameters and operational considerations that are independent of the particular antenna being used to provide the telecommunications link. For antenna-dependent parameters, refer to the appropriate telecommunications interface module, modules 101, 102, 103, and 104 of this handbook. Other ranging schemes employed by the DSN include the tone ranging system, described in module 204 and the pseudo random noise (PN) and regenerative ranging, described in module 214.

2 *General Information*

The DSN ranging system provides a sequentially binary-coded ranging scheme to measure the round-trip light time (RTLT) between a Deep Space Station (DSS) and a spacecraft. An uplink signal is transmitted to a spacecraft where it is received by the on-board transponder, then demodulated, filtered, and remodulated onto the downlink carrier. The downlink signal received at the DSS is correlated with a Doppler-modified replica of the transmitted codes that were sent to the spacecraft approximately one RTLT earlier. Using Doppler rate-aiding, the RTLT is determined by measuring the phase difference between the received code and the transmitted code.

The three basic tracking modes are one-way, two-way, and three-way. In the one-way tracking mode, the spacecraft generates a downlink signal that is received by the Earth-based station without a transmission being made to the spacecraft. Two-way tracking consists of transmitting an uplink to a spacecraft where it is received and coherently transmitted as a downlink to the same Earth station. For the three-way tracking mode, two-way tracking is performed by an Earth station, while another station tracks the downlink signal using a different antenna and possibly a different frequency standard.

The parameters to be specified for ranging operations are explained in Paragraph 2.3. Paragraph 2.4 presents the process of range measurement that includes the evaluation of RTLT, ranging-power-to-noise ratio (P_r/N_0), figure of merit (FOM), and differenced range versus integrated Doppler (DRVID). The relationship of downlink ranging power over total power is given in Paragraph 2.5. Paragraph 2.6 provides the corrections required to determine the actual range to a spacecraft. Error contributions of the ground system are discussed in Paragraph 2.7.

2.1 Network Simplification Project Ranging

The Deep Space Network is undergoing a redesign of the uplink and downlink architecture to achieve simplified operations and increased performance. A major feature of the modification is the splitting of the ranging and Doppler uplink and downlink functions, allowing recovery from anomalies on one without affecting the other.

In contrast to the previous design that employed a separate piece of equipment called the sequential ranging assembly (SRA), the new ranging system does not require a real-time interface between the uplink and downlink elements. There is a connection between the uplink and downlink in the sense that both elements must send data to a common node. However, the digital time-tagged data can be passed to the common node in non-real time, without loss of range measurement accuracy. The lack of a hardware connection to between the uplink and downlink elements of single antenna to the ranging equipment makes it possible to perform range measurements in the three-way tracking mode.

NSP ranging replaces the SRA with separate uplink and downlink ranging processors. Local code models are generated that match the SRA sequential tone ranging. The Tracking Data Delivery Subsystem (TDDS) replaces the Metric Data Assembly (MDA) and the Radio Metric Data Conditioning (RMDC) function of preparing the data for delivery to the user.

Ranging code components cover 1 MHz to 1 Hz in steps of powers of 2 provided by software local code models. Correlation of the ranging signal to determine clock phase and range ambiguity is handled using software algorithms.

2.2 System Description

The NSP architecture for the DSN ranging system is shown in Figure 1. It consists of a front end portion, an uplink portion, and a downlink portion. The front-end portion consists of the microwave components, including a Low-noise Amplifier (LNA) and the antenna. The uplink portion includes the Uplink Ranging Assembly (URA), an exciter, the transmitter, and the controller, referred to as the Uplink Processor Assembly (UPA). The downlink portion includes the RF-to-IF Downconverter (RID), the IF-to-Digital Converter (IDC), the Receiver and Ranging Processor (RRP) and the Downlink Channel Controller (DCC). The Downlink Telemetry and Tracking Subsystem (DTT) and the Uplink Subsystem (UPL) provide the essential functional capability for NSP ranging.

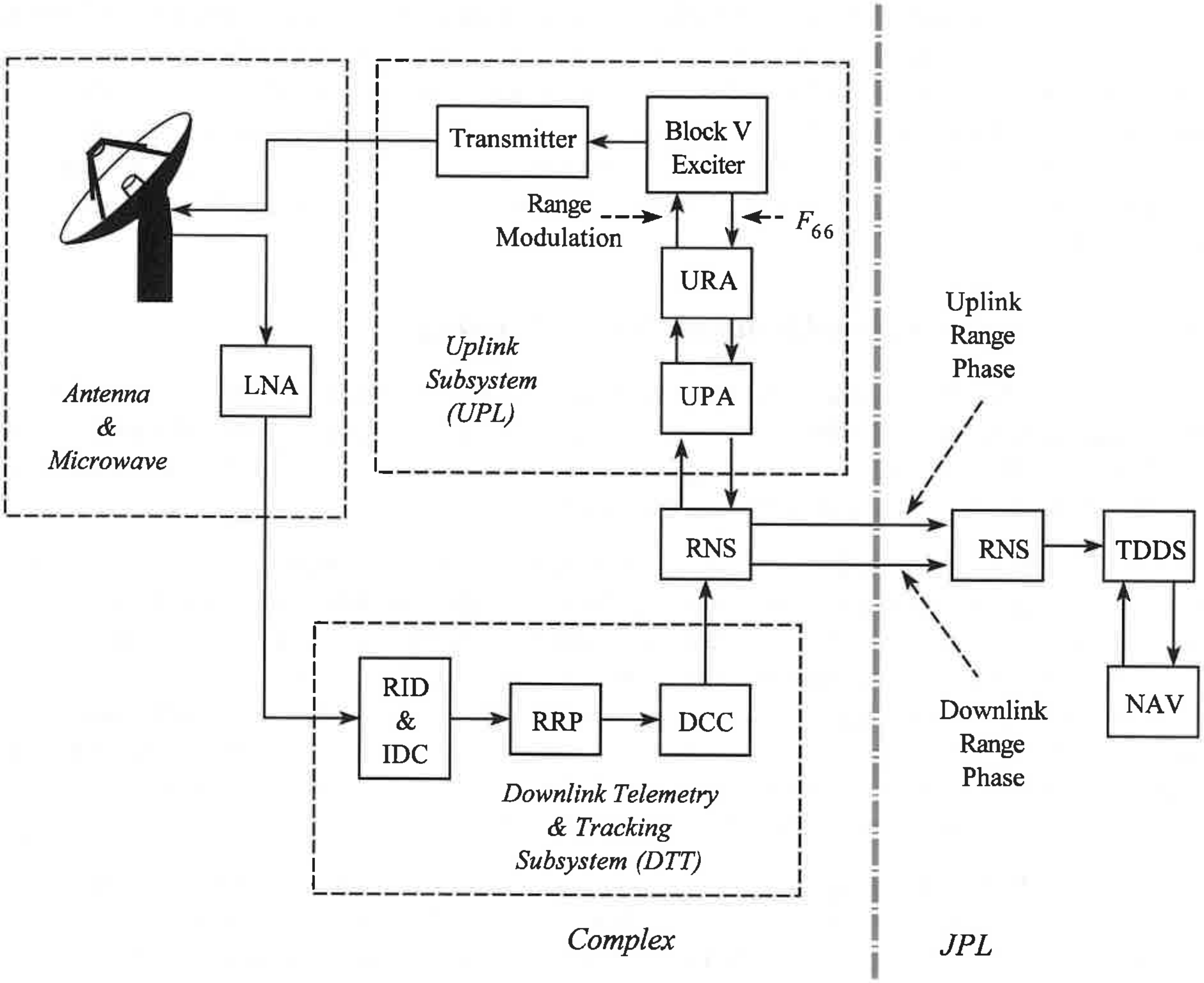

Figure 1. The NSP Era DSN Ranging System Architecture

Control of the ranging function is within the DTT. Control signals from the DTT are coupled to the URA in the UPL via the Reliable Network Service (RNS) and the UPA. The URA generates the sequential ranging codes for two-way and three-way ranging and forwards them to the exciter where they are modulated onto the uplink. It also monitors the uplink ranging phase and forwards this data to the TDDS.

The amplified downlink signal from the microwave is downconverted by the RID (located on the antenna) and fed to the IDC where it is sampled at 160 Msamples/s into an 8-bit digital signal at the RRP. After processing, the downlink range phase data are delivered to the TDDS by the Downlink Channel Controller (DCC), via the station RNS and a similar function at JPL. The TDDS formats the ranging data and passes the uplink and downlink phase information to the Navigation subsystem (NAV). Subsequently, the NAV provides the ranging data to projects.

Each DTT Controller Processing Cabinet (DCPC) is equipped with a single channel, which includes a single RRP. For spacecraft with multiple channels (for example, S-band and X-band), or for multiple spacecraft within a single antenna beamwidth, multiple DCPCs will be assigned to that antenna.

In addition to producing downlink phase information, the RRP generates a 66-MHz ranging reference analog signal with a Numerically Controlled Oscillator (NCO). The ranging reference frequency F_{RNG} (ref), is computed from the received frequency, f_r,, as follows:

$$F_{RNG}(\text{ref}) = \frac{F_r}{32 \cdot K} \tag{1}$$

where:

F_r = received carrier frequency

K = normalization factor (independent of uplink frequency)

240/221 (S-down)

880/221 (X-down)

3344/221 (Ka-down).

2.3 *Parameters Specified for Ranging Operations*

The following paragraphs present the parameters that are required in ranging operations.

2.3.1 *Transmit Time and Receive Time*

The rabging system needs a transmit time (XMIT) and an a-priori estimate of the RTLT, truncated to the nearest second, in order that the code sequence sent by the UPL can be correlated for measuring the phase shift through the round-trip-time delay. When a XMIT and an approximate RTLT are specified, the DTT automatically calculates the receive time T_O by adding the two quantities, T_O = XMIT + RTLT. This T_O is also called the start time of the correlation process for the code sequence. The two time quantities must be specified to the nearest second.

2.3.2 *Clocks and Components*

A range measurement begins with the highest frequency code followed by subsequent codes each having a frequency exactly half of the previous one. The first code in the sequence is called the clock component and determines the resolution of the measurement. The lower frequency codes that follow are used to resolve the ambiguity (uncertainty) of the a-priori range estimate.

Table 1 shows the clocks and components used in ranging operations. A total of 21 code components are available. They are referred to as component numbers 4 through 24 as shown in the Table. The first 7 components (numbered 4 through 10) are called the clock components or simply clocks. The approximate ambiguity resolving capability of a component is listed for reference. The approximate frequencies and periods of the codes are also shown.

The exact clock frequency (F_c) to replace the approximate frequency in the second column is computed by the relationship:

$$F_C = \frac{F_{66}}{2^{2+n}} \tag{2}$$

where n is an integer from 4 to 24 that represents a code component or a component number and F_{66} is the exciter reference frequency.

The value of F_{66} used to produce Table 1 was exactly 66.000 MHz. In ranging operations, this frequency varies depending upon the transmitting (uplink) carrier frequency. F_{66} is denoted by F_{66S} or F_{66X} depending on whether it was derived from an S-band or X-band uplink frequency and can be expressed in terms of the uplink frequency as follows:

S-band uplink:

$$F_{66S} = \frac{F_{ts}}{32} \tag{3}$$

X-band Uplink

$$F_{66X} = \frac{221}{749} \times \frac{F_{tx}}{32} \tag{4}$$

where, F_{ts} and F_{tx} are the S- and X-band transmitting (uplink) frequencies.

The third column (approximate period) shows the periods of the corresponding frequencies in the second column. The fourth column (ambiguity resolving capability) lists the products of the periods and the speed of light (299,792.5 km/s), divided by a factor of 2 to determine the one-way distance.

Depending on the uncertainty of the range estimate, a flight project determines the number of components needed for ranging operations. An example in choosing the clock and components is given as follows:

Example: Suppose the spacecraft is known to be at a 10-minute RTLT from Earth to within ±100,000 km. If it is desired to resolve the ambiguity to about 40,000 km, and if the distance is desired to be resolved to within 150 m, then components 4 through 22 should be defined for ranging. That is, clock 4 (about 1 MHz) is used with the subsequent 18 components (5 through 22).

Table 1. Range Code Resolving Capability

Component Number	Approximate Frequency (Hz)	Approximate Period (s)	Approximate Ambiguity Resolving Capability (km)
4*	1,030,000.000	9.700E-07	0.1450
5*	516,000.000	1.940E-06	0.2910
6*	258,000.000	3.880E-06	0.5810
7*	129,000.000	7.760E-06	1.160
8*	64,500.000	1.550E-05	2.330
9*	32,200.000	3.100E-05	4.650
10*	16,100.000	6.210E-05	9.30
11	8,060.000	1.240E-04	18.60
12	4,030.000	2.480E-04	37.20
13	2,010.000	4.960E-04	74.40
14	1,010.000	9.930E-04	149.0
15	504.000	1.990E-03	298.0
16	252.000	3.970E-03	595.0
17	126.000	7.940E-03	1,190.0
18	62.900	1.590E-02	2,380.0
19	31.500	3.180E-02	4,760.0
20	15.700	6.360E-02	9,530.0
21	7.870	1.270E-01	19,100.0
22	3.930	2.540E-01	38,100.0
23	1.970	5.080E-01	76,200.0
24	0.983	1.020E+00	152,000.0
* available clocks			

2.3.3 Square-Wave and Sine-Wave Ranging

The DTT may process the received codes in two ranging modes. They are referred to as square-wave and sine-wave operation. For square-wave operation, the DTT processes all harmonics of the received codes. For sine-wave operation, only the fundamental (the first harmonic) is processed. Square-wave operation is the default because, with the exception of the higher frequency clock components, the codes are received as square waves. However, sine-wave operation may be desirable if non-linearities or other processes exist that may delay the range code fundamental and its harmonics differently. The two modes can be summarized by:

Square-wave operation:	*transmit*	**square waves**
	correlate as	**square waves**
Sine-wave operation:	*transmit*	**square waves**
	correlate as	**sine waves**

Ranging with the 500-kHz and 1-MHz clocks are special cases due to the limited ranging bandwidths of most spacecraft and an intentional 1.2 MHz bandwidth limit in the DSN ranging modulators. This limit has been installed to prevent interference with services adjacent to the DSN uplink allocations . The ranging equipment presently requires the 1 MHz clock to be processed using sine-wave correlation. If square-wave correlation is specified, the 500 kHz code will be processed using the square-wave correlation algorithm although only its fundamental will have been transmitted to the spacecraft.

2.3.4 Integration Times

Three integration times must be specified for ranging operations. They are: T_1 for clock integration, T_2 for each lower-frequency component integration, and T_3 for DRVID measurement(s).

2.3.4.1 T_1

T_1 is the total time used to integrate the correlation samples for the clock component. It is a function of the clock frequency, the desired variance of RTLT measurements, and the ranging signal to noise spectral density and can be calculated by the following expressions:

Sine-wave operation:

$$T_1 = \frac{1}{64} \times \frac{1}{F_c^2} \times \frac{1}{\sigma^2(t)} \times \frac{1}{P_r / N_o}, \text{ s} \tag{5}$$

where

F_c = the clock frequency, Hz

$\sigma^2(t)$ = the desired variance of the RTLT measurements, s^2

P_r/N_o = the ranging signal to noise spectral density, Hz

The factor 1/64 has been derived empirically from the most probable variance of a range point when using sine-wave correlation.

Square-wave operation:

$$T_1 = \frac{1}{49} \times \frac{1}{F_c^2} \times \frac{1}{\sigma^2(t)} \times \frac{1}{P_r / N_o}, \text{ s} \tag{6}$$

where

F_c, $\sigma^2(t)$, and P_r/N_o are as above and the factor 1/49 has been derived empirically from the upper bound variance of the 1 MHz sine-wave ranging when using square-wave correlation.

The above equations can be rewritten in terms of the uncertainty $\sigma(r)$ in meters, by multiplying the uncertainty $\sigma(t)$ in seconds by the speed of light and dividing by a factor of 2. This provides:

Sine-wave operation:

$$\sigma(r) = \sqrt{\frac{352}{F_c^2(\mathrm{MHz}) \times T_1 \times P_r/N_o}}, \ \mathrm{m} \tag{7}$$

Square-wave operation:

$$\sigma(r) = \sqrt{\frac{458}{F_c^2(\mathrm{MHz}) \times T_1 \times P_r/N_o}}, \ \mathrm{m} \tag{8}$$

where:

F_c = the clock frequency, MHz

T_1 = the clock component integration time, s

P_r/N_o = the ranging signal to noise spectral density, Hz.

Note: The uncertainty, σ, here is only due to thermal noise. Other errors must be added to this to get the total uncertainty (see Paragraph 2.7).

Figure 2 plots integration time (T_1) as a function of P_r/N_o for sine-wave operation using a 1 MHz clock component with $\sigma(r)$ as a parameter. For a desired $\sigma(r)$, the user may find the proper integration time, T_1, for an estimated P_r/N_o (in dB-Hz). Figure 3 is a similar graph for square-wave operation using a 500-kHz clock component. This figure may also be used for lower frequency square-wave clocks by recognizing that dividing F_c by 2 will result in T_1, being multiplied by 2^2, etc.

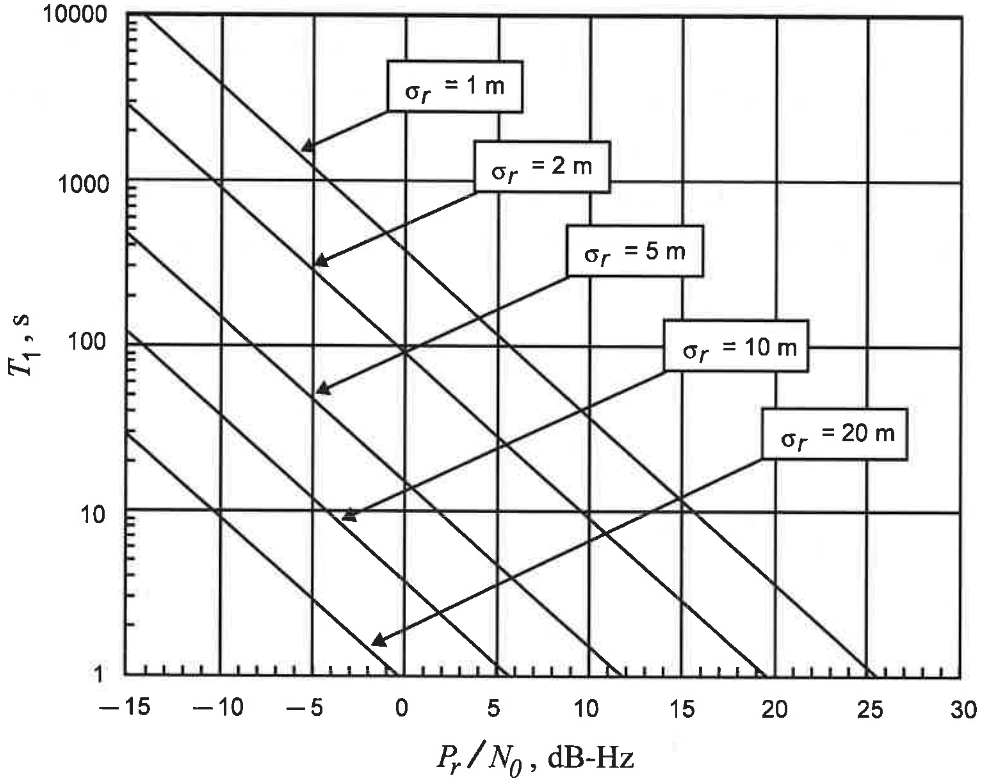

Figure 2. Integration Time T_1 Versus P_r/N_0, Clock Frequency F_c = 1 MHz, for Sine-Wave Ranging

Ranging is possible as long as the receiver remains in lock over the measurement time. However, there is a practical lower limit for P_r/N_0 (usually about −10 dB-Hz) determined by the combination of integration times (cycle time) and the minimum number of range points needed by the project. See Cycle Time in Paragraph 2.3.4.4 for further details.

2.3.4.2 T_2

T_2 is the integration time for each of the lower-frequency components. It is a function of P_r/N_0 and the probability of error in acquiring all components (excluding the clock). In general, T_2 is given by the following equation

$$T_2 = \frac{1}{P_r/N_0} \times \left\{ \text{InvErf}\left[2(1 - P_e)^{\frac{1}{n-1}} - 1 \right] \right\}^2 \text{, s} \tag{9}$$

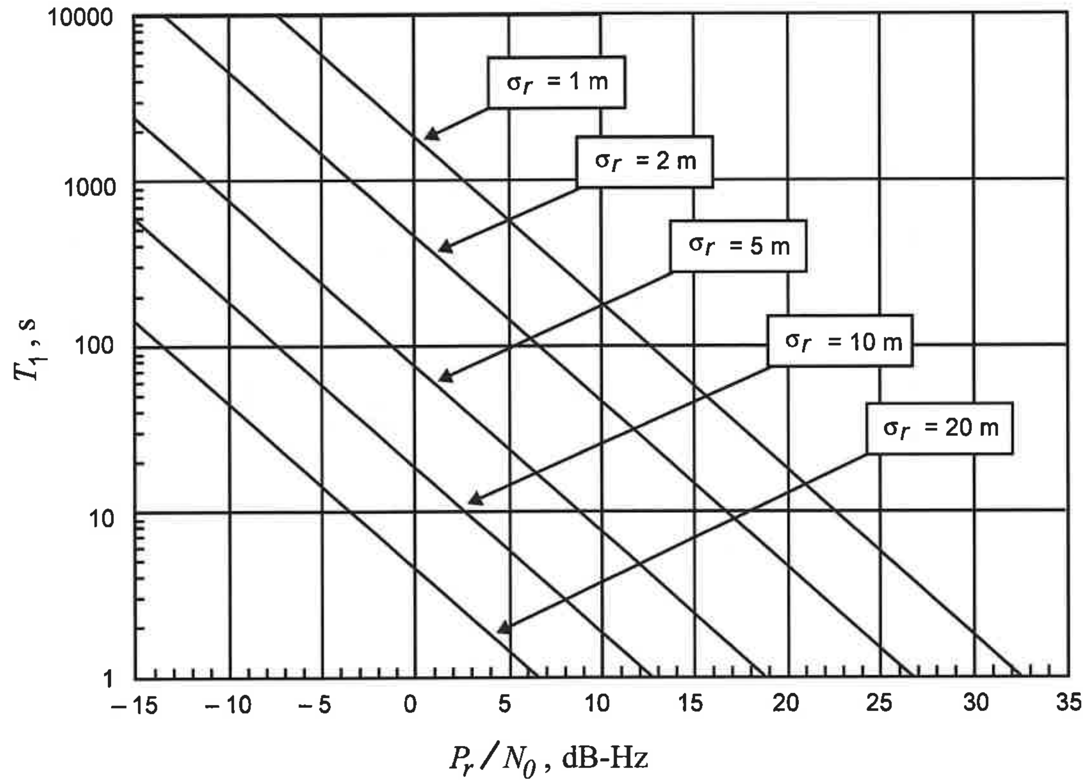

Figure 3. Integration Time T_1 Versus P_r/N_0, Clock Frequency $F_c = 500$ kHz, for Square-Wave Ranging

where

P_r/N_0 = the ranging signal to noise spectral density, Hz

InvErf[∗] = the inverse error function of the ∗ quantity.

P_e = the probability of error in acquiring all (n-1) components.

n = the total number of components including the clock being acquired.

Figures 4 through 6 show T_2 versus P_r/N_0 for various P_e and n. An appropriate T_2 for ranging operations can be determined from these curves by choosing the desired n, the desired, P_e, and the estimated P_r/N_0.

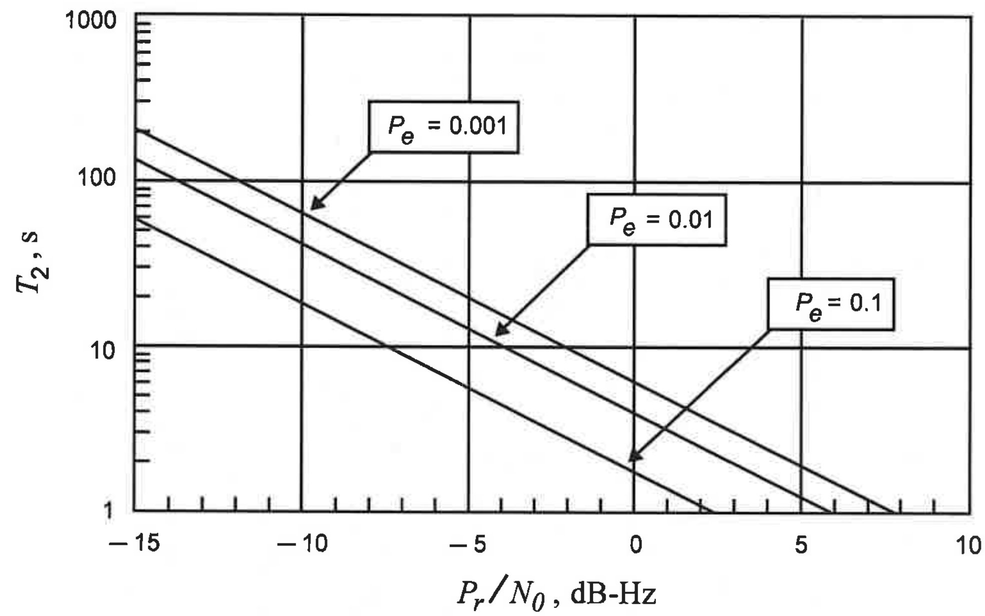

Figure 4. Code Component Integration Time T_1 Versus P_r/N_0 for Various Probabilities of Error and $n = 5$

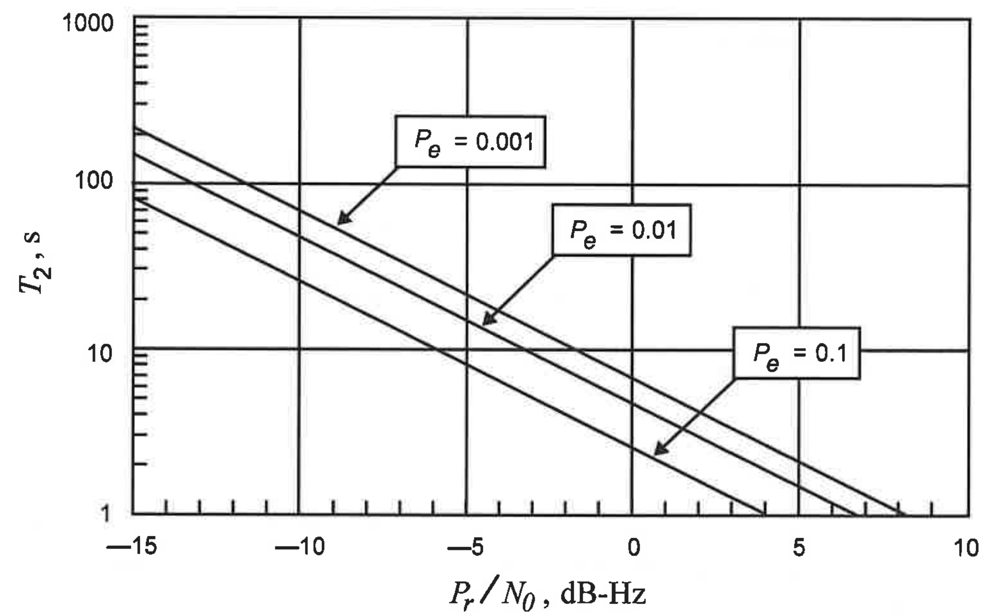

Figure 5. Code Component Integration Time T_1 Versus P_r/N_0 for Various Probabilities of Error and $n = 10$

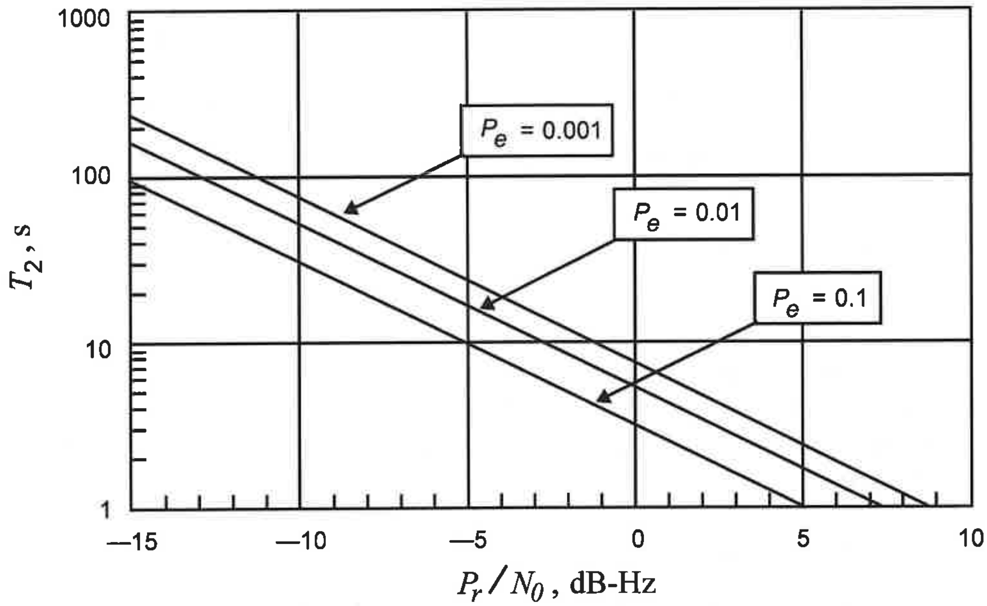

Figure 6. Code Component Integration Time T_1 Versus P_r/N_o for Various Probabilities of Error and $n = 20$

2.3.4.3 T_3

T_3 is the integration time for differenced range versus integrated Doppler (DRVID) measurements (see Paragraph 2.4.3 for a further discussion of DRVID). Since the phase information is already available from the clock acquisition, T_3 can be less than T_1 (typically 7/8 T_1).

2.3.4.3 *Cycle Time*

Cycle time is the total time that the DTT spends to perform measurements for the clock, the (n-1) components, and the DRVIDs. It also includes some dead time between component integrations to accomodate the 1-second inaccuracy permitted in specifying the estimated RTLT. In other words, it is the time required to complete one range acquisition. The cycle time (CYC) is automatically calculated by the DTT, and it is given by the following formula:

$$CYC = (2 + T_1) + (1 + T_2)(n - 1) + DRVN(2 + T_3) + 1, \text{ s} \tag{10}$$

where:

T_1 = clock integration time

T_2 = component integration times

T_3 = DRVID integration time

n = the total number of components including the clock

DRVN = the number of DRVIDs specified for the acquisition.

For a typical 8-hour tracking pass, it is recommended that *CYC* be less than the following limits:

Soft limit: CYC $\leq$ 30 minutes

Hard limit: CYC $\leq$ 55 minutes.

The chance of getting a desired number of good range points decreases substantially as the cycle time approaches the 55-minute limit. Any glitch occurring in the system during the time of measurement will cause a range point to become invalid. It is better to stay closer to, or within the soft limit.

2.3.5 Modulation Index

In ranging operations, square-wave codes are modulated on the uplink carrier by the exciter phase modulator. This results in an attenuation of carrier power and a corresponding increase of power spread into the sidebands. The phase displacement of the carrier due to modulation is referred to as the modulation index and may be specified as a peak-to-peak or root mean square (RMS) value. That is, if the modulation waveform is specified as peak-to-peak value, the modulation index will define the peak-to-peak phase modulation. If, on the other hand, the modulation waveform is specified as an RMS value, the modulation index will define the RMS phase modulation The expressions for carrier power and ranging power are given in terms of the modulation index as follows:

$$P_c = P_t\left(\cos^2\theta\right), \text{ numeric, units of power} \tag{11}$$

$$P_r = P_t\left(\sin^2\theta\right), \text{ numeric, units of power} \tag{12}$$

where:

P_c = the carrier power

P_r = the ranging power

P_t = the total power before ranging modulation (that is, $P_t = P_c + P_r$)

θ = the modulation index in radians (or degrees).

Therefore, the carrier suppression in dB is given by:

$$\frac{P_c}{P_t} = 10\log(\cos^2\theta)\ . \tag{13}$$

The modulators used in the DSN operate over the range of 0.1 to 1.5 radians, peak. It should be noted that equation 13 assumes ideal conditions, and variations between the calculated and that measured values of carrier suppression may occur depending on the amplitude, frequency, and phase responses of the modulator in use.

Example: An unmodulated signal is received by a spacecraft with $P_t = -100$ dBm. When this signal is modulated by square waves of a 30-deg modulation index, the carrier power (P_c) becomes –101.25 dBm (suppressed by 1.25 dB) and the ranging (sidebands) power (P_r) is –106.0 dBm ($P_r = -100 \text{ dBm} + 10\log(\sin(30)^2)$).

2.3.6 Frequency Chopping

Separation between the ranging modulation products and the carrier frequency decreases as a ranging acquisition steps through the code components of the lower frequencies. If this were allowed to continue, 1) the receiver tracking loop would follow the waveform and track out the code(s); or 2) interference occurs to the telemetry or command modulation. A frequency chopping modulation function can be enabled to prevent these problems. The function is defined by:

$$C = C_m \oplus C_c \tag{14}$$

where:

C = modulation

C_m = the square-wave modulation of the component, m, being chopped

C_c = the square-wave modulation of the clock component

$\oplus$ = modulo 2 addition.

The chopping process results in a power spectrum for a sideband pair relative to the ranging power as follows:

$$\frac{P_k}{P_r} = 10\log\left\{8 \times \left[\frac{\tan\left(\frac{k\pi}{2^{m-n+1}}\right)}{k\pi}\right]^2\right\}, \text{dB} \tag{15}$$

where:

P_k = the power of the k-th odd sideband pair (a perfect square wave will not have any even harmonics)

P_r = the total ranging power (all sidebands)

m = the component number being chopped

n	=	the number of the clock (2 to 10)
k	=	the odd sideband-pair number of the component being chopped.

The physical meaning of chopping can best be illustrated by Figure 7, which shows components C5, C6, and C7 being chopped by the 1-MHz clock, C4. The dotted lines indicate where the edges of the components would be without chopping. Note that C4⊕C5 is the same as C5 shifted 1/4 cycle to the left. This occurs when a component is chopped by another component at twice its frequency.

In the chopping-disabled mode, no components are chopped until 1 kHz (C14) and the remaining lower frequency components (C15 to C24) are reached. The chopping component must be of the same or lower frequency than the clock component, and it should be no lower than 16 kHz (C10). The chopping function is handled by the ranging default software and can be overridden by directive if necessary.

2.3.7 Other Parameters

There are four other parameters that must also be specified for ranging operations. Their meaning and usage are briefly summarized below.

2.3.7.1 Tolerance

Tolerance is used to set the acceptable limit of the FOM — an estimate of the goodness of an acquisition, based on the P_r/N_0 measurement (see Paragraph 2.4.3 for additional discussion).

Tolerance may be selected over the range of 0.0% to 100.0%. As an example, if the tolerance is set to 0.0%, all range acquisitions will be declared valid. Alternately, if the tolerance is set to 100.0%, all range acquisitions will be declared invalid. A typical value set for tolerance is 99.9%. This value will flag acquisitions that have a 99.9% or better chance of being good as valid, and the rest as invalid.

An acquisition is declared valid or invalid depending upon the following criteria:

FOM ≥ Tolerance	*results in*	Acquisition declared valid
FOM < Tolerance	*results in*	Acquisition delcared invalid.

2.3.7.2 Servo

Servo is used to correct distortions of the data due to charged particle effect using DRVID information (See Paragraph 2.4.3 for a discussion of DRVID). When Servo is enabled, the local Doppler-corrected components will be shifted back into phase with the received components. The correction is made by setting a proper Servo value.

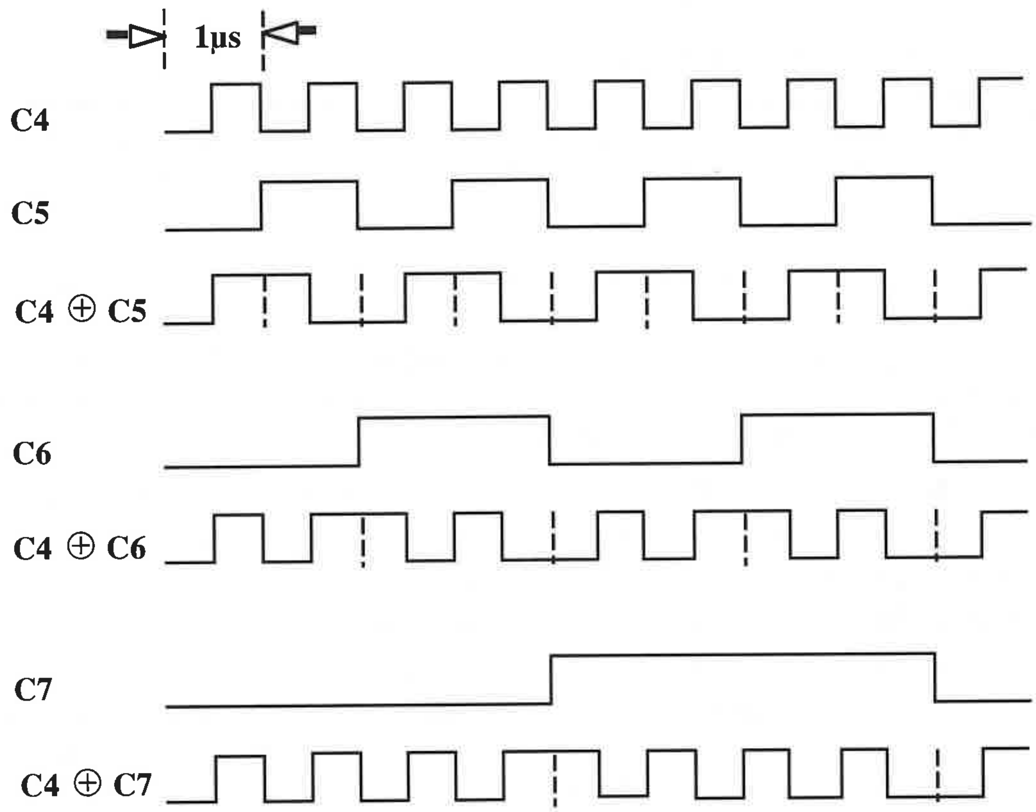

Figure 7. Chopping of C5, C6, and C7 (by C4)

Servo has a value between 0 and 1.0. It should be set to 1.0 with a noiseless signal, but if the noise level is too high, no DRVID refinement is possible and Servo should be set to 0. Note that if Servo is 1.0, the correction is made immediately; however, if Servo is set to a fractional value between 0 and 1.0, that fraction of the correction will be done on any one DRVID measurement.

2.3.7.3 *Pipe*

The *Pipe* parameter (for pipelining) specifies the number of range acquisitions to be made. This parameter enables multiple measurements to be initiated before the first measurement is completed. Only one acquisition is made if Pipe is disabled. If it is enabled, range measurements will be made until the total number of acquisitions reaches $(2^{15} - 1)$ or until the specified number of acquisitions. In other words, the number of range acquisitions that can be performed is between 1 and $(2^{15} - 1)$.

2.4 Range Measurement Process

The URA uses a reference frequency (denoted by F_{66} in this document) from the exciter to generate a sequence of square waves (or binary codes). This code sequence is phase-modulated onto the uplink carrier beginning at the transmit time. The measurement process begins at T_0 which is between 0 and 1 second before this signal is received by the RRP, one RTLT later.

The RRP contains an identical coder that is driven by a reference frequency (denoted by F_{RNG} in this document) that is derived from the received carrier frequency but scaled to the corresponding uplink frequency as discussed in paragraph 2.2. Thus, the receiver coder is able to provide a code sequence that includes compensation for the frequency shift introduced by Earth-spacecraft relative Doppler.

At T_0, the first (clock) component from the reciever coder is correlated against the received signal to produce the correlation values V_I and V_Q. The V_I s and V_Q s are used to compute the angle and amplitude of the received code; hence, the phase and signal strength are determined. The following paragraphs provide further detail.

The measurement of the phase (angle) displacement of the clock provides the resolving capability of the range measurement (See Table 1). Once the phase displacement is determined, the receiver coder is shifted by this displacement amount to produce a zero-phase shift in the in-phase channel. Since the remaining components are phase-coherent with the clock component, it is only necessary to determine if each component is in or out of phase with the previous component. This is done by integrating the V_I s and V_Q s for the time T_2 specified during initialization. If each component is in phase, no action is necessary; if one is out of phase, that component and the remaining components are shifted by half its period. This process is repeated for each component. The sum of the required shifts (plus the clock-phase shift) is the phase delay between the transmitted and received signals, and the range is determined. The process is illustrated in Figure 8.

2.4.1 Range Measurement Technique

The RRP measures two-way range, that is, the RTLT, by determining the phase difference between the transmitted and received modulation. This phase displacement (τ) is computed by the following expressions:

Sine-wave ranging:

$$\tau = \text{atan2}\left(\sum V_Q, \sum V_I\right), \text{ radians} \tag{16}$$

Square-wave ranging:

$$\tau = \text{SGN}\left(\sum V_Q\right) \times \frac{1}{4} \times \left(1 - \frac{\sum V_I}{\left|\sum V_Q\right| + \sum V_I}\right), \text{ cycles.} \tag{17}$$

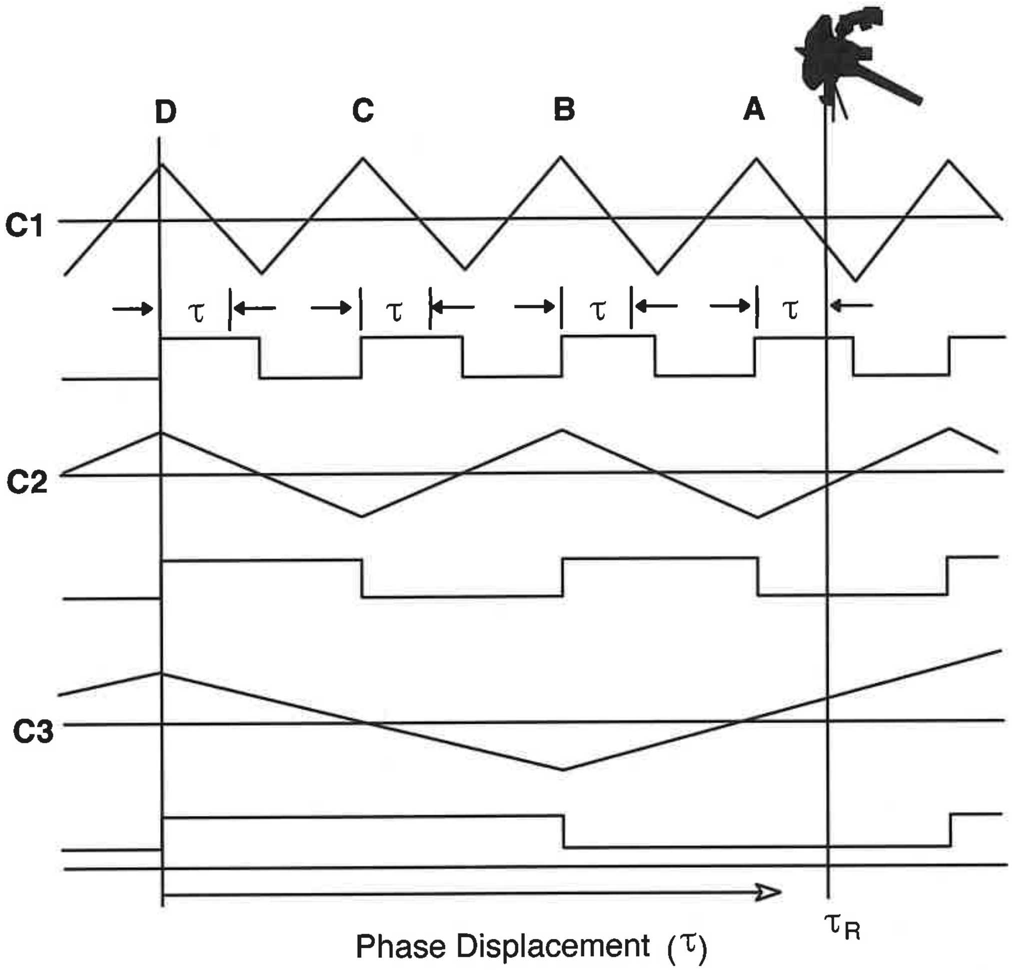

Figure 8. Component Acquisition Process

Notes:

1. Assume that the range to the spacecraft results in $\tau = \tau_R$ and that the range uncertainty is in the interval defined by C2 and C3.
2. Measurement of the phase offset of C1 indicates that the correlation amplitude is not at a peak value. The receiver coder is shifted (delayed) to bring the correlation value to a positive peak, A.
3. At A, the correlation function for C2 is at a negative peak; thus C2 is out of phase. The reference code is shifted by half the period of C2 (to bring it into phase), arriving at B.
4. At B, C3 is out of phase with C2. The reference code is shifted by half the period of C3, arriving at D.
5. The sum of the phase shifts required to bring all components into phase is τ_R, the range measurement.

where

V_I and V_Q = the in-phase and quadrature correlation values

atan2(y,x)= the arctangent function that produces an angle in the proper quadrant

$$\mathrm{SGN}(*) = \begin{vmatrix} +1, & * \geq 0 \\ -1, & * < 0. \end{vmatrix}$$

For ranging operations, the above τ of different dimensions are converted to a measurement unit called the range units (RU). RUs have the dimension of seconds and are defined as 1/16 of the period of the reference frequency, that is

$$\mathrm{RU} = \frac{1}{16} \times \frac{1}{F_{66}}, \mathrm{s} \qquad (18)$$

where F_{66} is the reference frequency, F_{66S} or F_{66X} as discussed earlier.

Using the above RU equation, one may convert the measurement obtained in RUs to physical quantities such as time (nanoseconds) and distance (meters). For example, if the F_{66} used in a range measurement is 66.000 MHz and suppose the measurement obtained is 6,500,000 RU, then the equivalent RTLT delay is 6.155 ms, and the one-way distance is about 923,295 m.

2.4.2 P_r/N_0

The actual ranging power-to-noise spectral density (P_r/N_0) is evaluated at the end of the integration of all in-phase and quadrature correlation values for the clock. It combines ranging system performance with receiver noise. This ratio is given by:

$$P_r/N_0 = 10\log\left(\frac{\text{Ranging Signal Power } (P_s)}{\text{Noise Power} (P_n)} \times \text{Bandwidth} (\text{BW})\right), \text{dB} \qquad (19)$$

where, depending on a ranging operation, P_s is evaluated by two different expressions.

Sine-wave operation:

$$P_s = \frac{\left(\sum_1^N V_I\right)^2 + \left(\sum_1^N V_Q\right)^2}{N^2}, \qquad (20)$$

Square-wave operation:

$$P_s = \frac{\left(\left|\sum_1^N V_I\right| + \left|\sum_1^N V_Q\right|\right)^2}{N^2} \tag{21}$$

where:

V_I and V_Q are the correlation values.

N is the total number of samples collected during the clock acquisition.

Noise power is estimated by adding the variances of the in-phase and quadrature correlation samples:

$$P_n = \mathrm{Var}_I + \mathrm{Var}_Q \,, \tag{22}$$

where:

$\mathrm{Var_x}$ is the variance function:

$$\mathrm{Var_x} = \frac{\sum_1^N \left(x^2\right)}{N} - \frac{\left(\sum_1^N (x)\right)^2}{N^2} \tag{23}$$

where:

x represents the correlation sample V_I s and V_Q s

N is the number of samples.

Finally, because $P_n = N_0 \times$ the process bandwith of the RRP, it is necessary to multiply P_s/P_n by the process bandwidth (1 Hz) to put it in the form of P_r/N_0.

2.4.2 Figure of Merit

The FOM is a probability measure which estimates the chance of successful acquisition of all lower frequency codes. The probability of making at least one error in acquiring these codes is:

$$P_e = 1 - \left[\frac{1}{2} + \frac{1}{2}\mathrm{Erf}\left(\sqrt{\frac{P_r}{N_0} \times T_2}\right)\right]^{n-1} \tag{24}$$

where:

n = the number of components including the clock.

Erf(∗) = the error function.

P_r/N_0 = the ranging power-to-noise ratio.

T_2 = the integration time for each of the lower frequency components, s.

Therefore, the probability P_c of getting all correct measurements is:

$$P_c = 1 - P_e \tag{25}$$

$$\text{FOM} = 100 \times P_c, \text{ percent.} \tag{26}$$

The FOM is calculated following the clock phase measurement using the measured P_r/N_0, the integration time T_2, and the number of lower-frequency components. The FOM is a valid estimate only if conditions do not change. It provides a reference by which a user may judge the validity of a range measurement. Figures 9 to 11 show P_c versus P_r/N_0 for various values of T_2 and n.

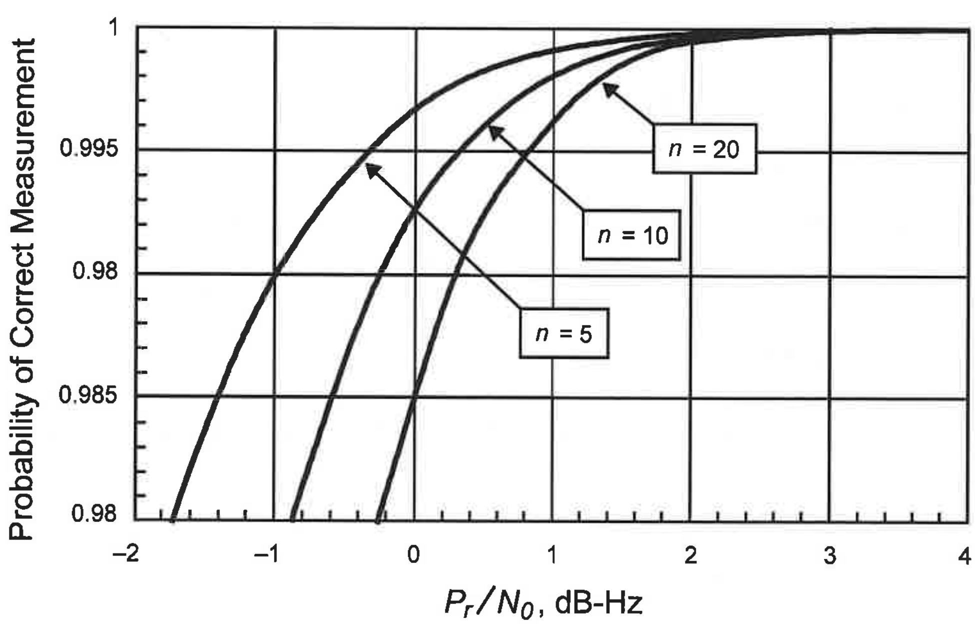

Figure 9. Figure of Merit, with T_2 = 5 sec for Various Frequency Components.

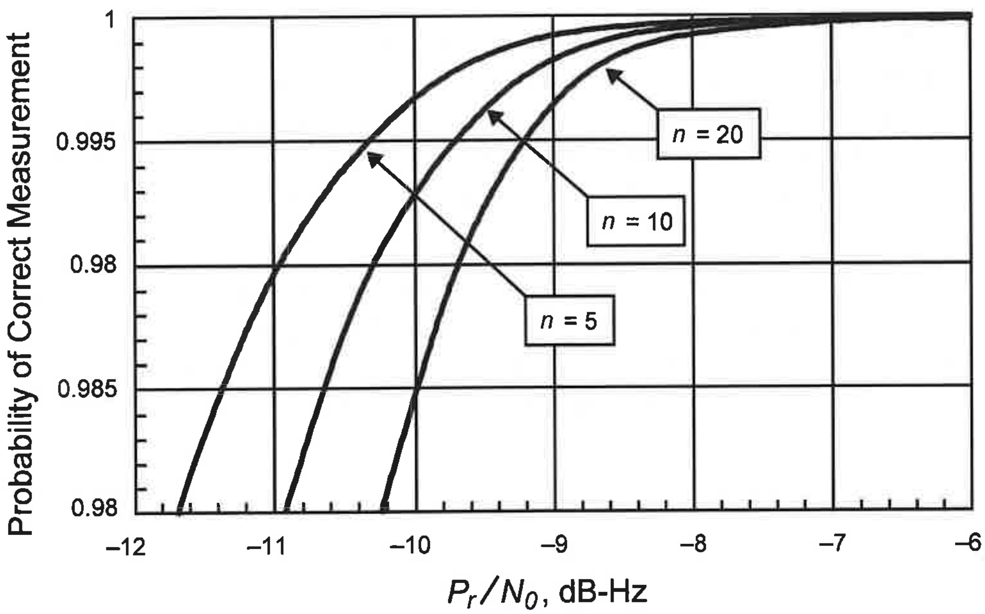

Figure 10. Figure of Merit, with T_2 = 50 sec for Various Frequency Components.

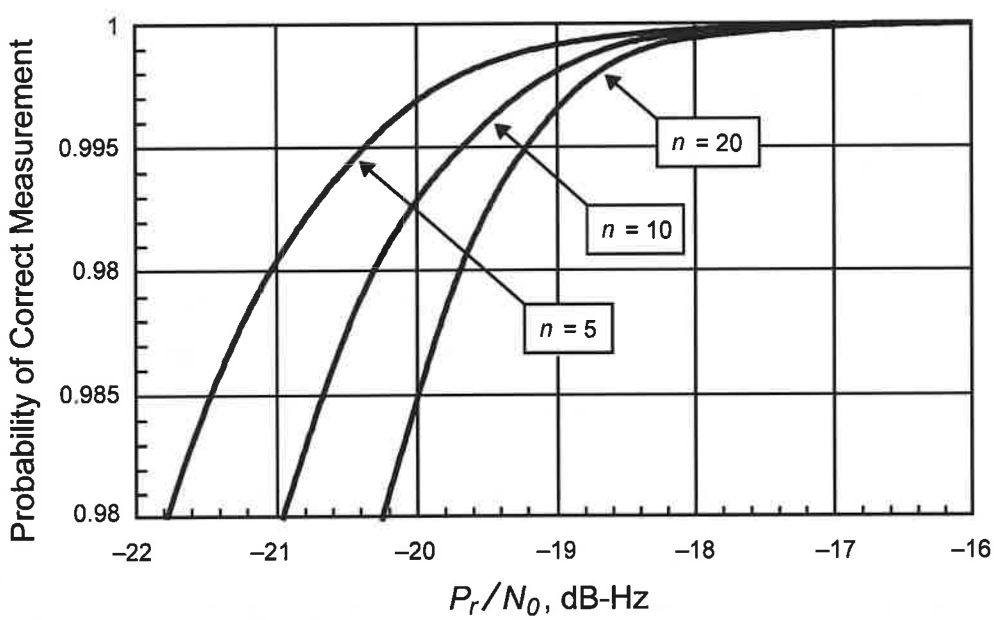

Figure 11. Figure of Merit, with T_2 = 500 s for Various Frequency Components.

2.4.3 *Differenced Range Versus Integrated Doppler*

Differenced range versus integrated Doppler (DRVID) may be used to calibrate the range observable and to study the electron content in the transmission medium. For a given range observable, charged particles have the effect of making the spacecraft appear further than its actual distance. As the signal propagates through the charged-particle medium, the phase velocity of the carrier increases by a certain quantity, while the group velocity of the range code decreases by exactly the same quantity.

In the NSP era, DRVID is calculated from tracking data containing the observed differences between the range measurements affected by the range-code group velocity, and the delta range measurements derived from the Doppler measurements influenced by the carrier-phase velocity. A more proper term for this quantity is pseudo-DRVID (PDRVID); however, the traditional name will be used in this article.

$$\begin{aligned}\mathrm{DRVID}(t) = {} & \{[\Phi_u(t) - \Phi_d(t)] - [\Phi_u(t - T_{cycle}) - \Phi_d(t - T_{cycle})]\} \\ & -16 * \{r1 * [\Theta_u(t) - \Theta_u(t - T_{cycle})] \\ & \quad - r2 * [\Theta_d(t) - \Theta_d(t - T_{cycle})]\} \bmod \textit{range ambiguity}\end{aligned} \tag{27}$$

where

$\Phi_u(t)$ = uplink range phase, s

$\Phi_d(t)$ = downlink range phase, s

$\Theta_u(t)$ = uplink carrier phase, RU

$\Theta_d(t)$ = downlink carrier phase, RU

T_{cycle} = anging cycle time, s

r_1 = exciter reference frequency/carrier frequency ratio (either 1/32 or 221/(749 × 32) — see Paragraph 2.3)

r_2 = transponder turnaround ratio.

2.5 *Ratio of Downlink Ranging Power to Total Power*

For the type of currently used turn-around ranging channel, the ratio of power in the fundamental ranging sidebands to the total signal power in the downlink is a function of the uplink ranging signal-to-noise ratio. The P_r/P_t ratio for two-way ranging is given as:

$$\left[\frac{P_r}{P_t}\right]_{DN} = 2J_1^2\left[\sqrt{2}\cdot\theta_{DN}\sqrt{\frac{\Gamma_{RNG/UP}}{1+\Gamma_{RNG/UP}}}\right]\cdot\exp\left[-\frac{\theta_{DN}^2}{1+\Gamma_{RNG/UP}}\right] \tag{28}$$

where:

$\left[\frac{P_r}{P_t}\right]_{DN}$ = the ratio of power in fundamental ranging sidebands to total signal power for downlink

$J_1^2[*]$ = the Bessel function of the first kind of order one

θ_{DN} = the downlink ranging modulation index, radians rms

$\Gamma_{RNG/UP}$ = the uplink ranging signal-to-noise ratio at the output of the transponder's ranging channel filter, given by:

$$\Gamma_{RNG/UP} = \frac{8}{\pi^2}\left[\frac{P_r}{N_0}\right]_{UP} \cdot \frac{1}{B_{RNG}} \tag{29}$$

where:

$\left[\frac{P_r}{N_0}\right]_{UP}$ = the ranging power to noise spectral density ratio at input to the transponder's ranging channel filter, Hz

B_{RNG} = the transponder's ranging channel filter bandwidth, Hz. A typical value for B_{RNG} is 1.5 MHz.

Figure 12 is a plot of equation 28, with $\left[\frac{P_r}{P_t}\right]_{DN}$ versus $\Gamma_{RNG/UP}$ for selected values of θ_{DN}. For deep space missions, the uplink ranging signal-to-noise ratio is usually quite small, and the operating point lies on the steep curve on the left side of Figure 12. In this case, equation 28 may be approximated as follows:

$$\left[\frac{P_r}{P_t}\right]_{DN} \approx \Gamma_{RNG/UP}\, \theta_{DN}^2 \exp(-\theta_{DN}^2),\ \Gamma_{RNG/UP} << 1. \tag{30}$$

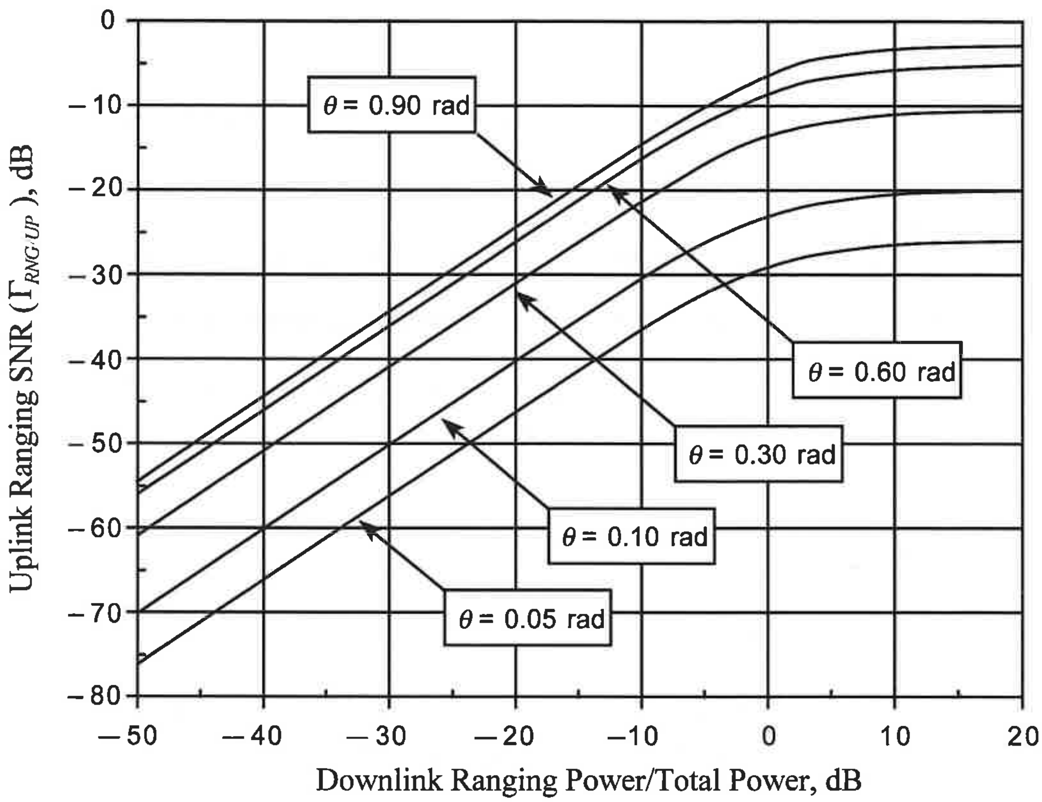

Figure 12. P_r/P_t as a Function of $\Gamma_{RNG/DN}$ for Selected Values of Modulation Index θ_{DN}

The presence of uplink noise feeding through onto the downlink has two effects on ranging performance: loss of ranging power and interference. Noise affects the ranging performance by dissipating valuable downlink power from the fundamental ranging signal sidebands. This is characterized by the above expressions for $[P_r/P_t]_{DN}$. Alternately, the potential exists for noise to interfere with the fundamental ranging sidebands, causing degradation to the ranging signal by raising its noise floor. For most deep space missions, the latter effect is not considered to cause significant degradation for two-way ranging measurements.

2.6 Range Corrections

The DTT range measurements include delays of equipment within the DSS as well as those of the spacecraft. These delays must be removed in order to determine the actual range referenced to some designated location at the antenna. Figure 13 illustrates the end-to-end range measurement and identifies the delays that must be removed before an accurate topocentric range can be established. The DSN is responsible for providing three measurements to the project. They are the DSS delay, the Z-correction, and the antenna correction.

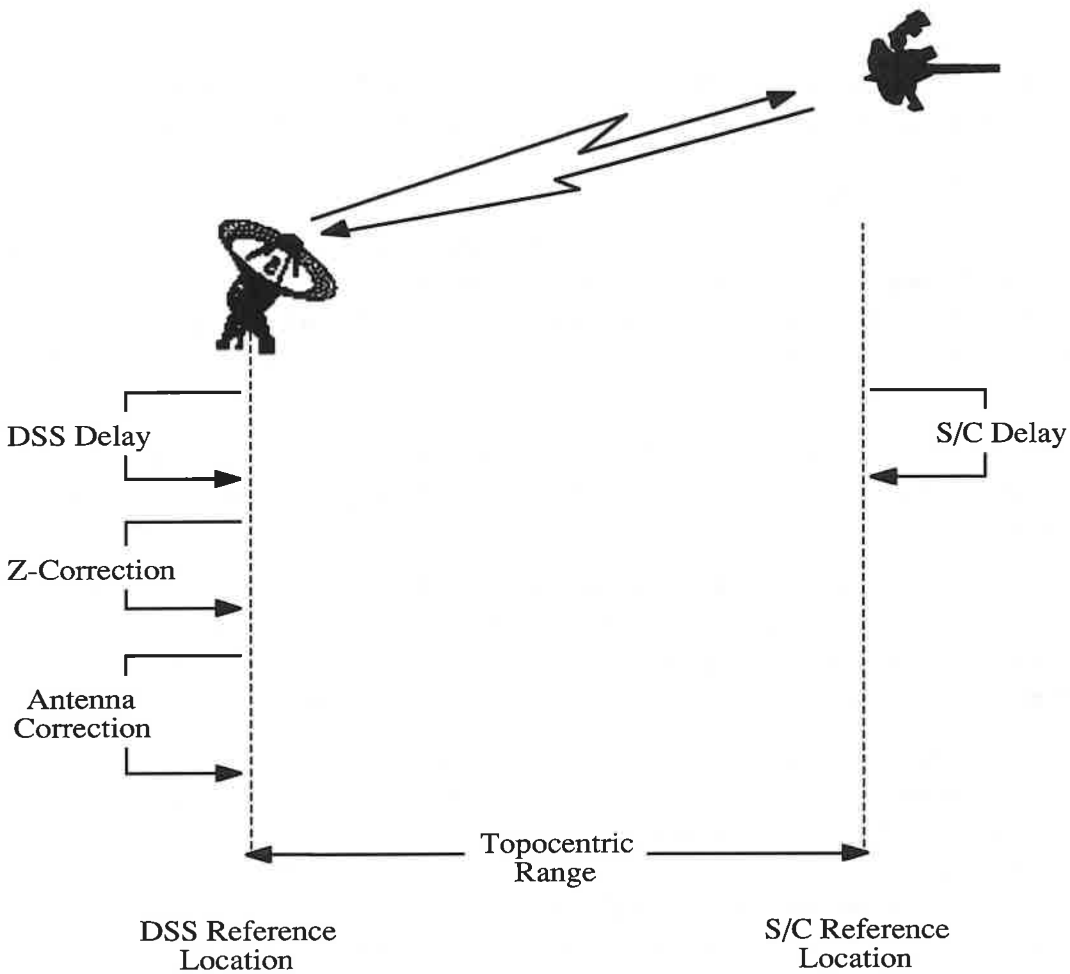

Figure 13. DSN Range Measurement

2.6.1 DSS Delay

The DSS delay is station and configuration dependent. It should be measured for every ranging pass. This measurement is called precal for pre-track calibration and postcal for post-track calibration. The former is done at the beginning of a ranging pass; the latter is only needed when there is a change in equipment configuration during the track or precal was not performed due to a lack of time.

The delay is measured by a test configuration, which approximates the actual ranging configuration. The signal is transmitted to the sky; however, before reaching the feedhorn, a sample is diverted to a test translator through a range calibration coupler. The test translator shifts the signal to the downlink frequency, which is fed into the coupler. The signal flows through the LNA to the DTT for calibration.

Figure 14 shows the signal path for a typical calibration of DSS delay when the uplink and downlink are in the same frequency band. The heavy lines identify the calibration path. When the uplink and downlink are in different bands, the downlink signal from the test translator is coupled into the receive path ahead of the LNA and as close to the feed as practical.

2.6.2 Z-Correction

The delay in the microwave components ahead of the coupler and the airpath (the distance from the horn aperture plane to the subreflector, to the antenna aperture plane, and finally to the antenna reference location) must be included in the calibration. Also, the translator delay must be removed. A measurement called "Z-correction" is made to obtain an adjusted DSS delay.

The Z-correction is given by the difference of two quantities: the translator delay and the microwave plus air path delay. Figure 15 relates these quantities to the physical structure of the antenna.

The test translator delay is measured by installing a zero delay device (ZDD) in place of the test translator. Since the ZDD delay is measured in the laboratory, the signal delay contributed by the test translator can be calculated to a known precision. This measurement is made approximately twice a year or when there are hardware changes in the signal path.

The microwave and air path delays are measured by physically calibrating the microwave hardware components prior to installing them on the antenna. The antenna aperture plane, the horn aperture plane, and an antenna reference location are used to determine the actual air path delay as shown in Figure 14. The antenna reference location is the perpendicular intersection of the primary antenna axis with the plane of the secondary axis. Geocentric and geodetic locations for the antenna reference location can be found in module 301.

2.6.3 Antenna Correction

An antenna correction is required when the antenna reference location is not at a fixed location with respect to the Earth. Because the NSP ranging equipment only is being installed at Azimuth-Elevation (Az-El) antennas that have a fixed reference location, no antenna correction is required. The antenna correction for the 26-m subnet antennas is described in Appendix A.

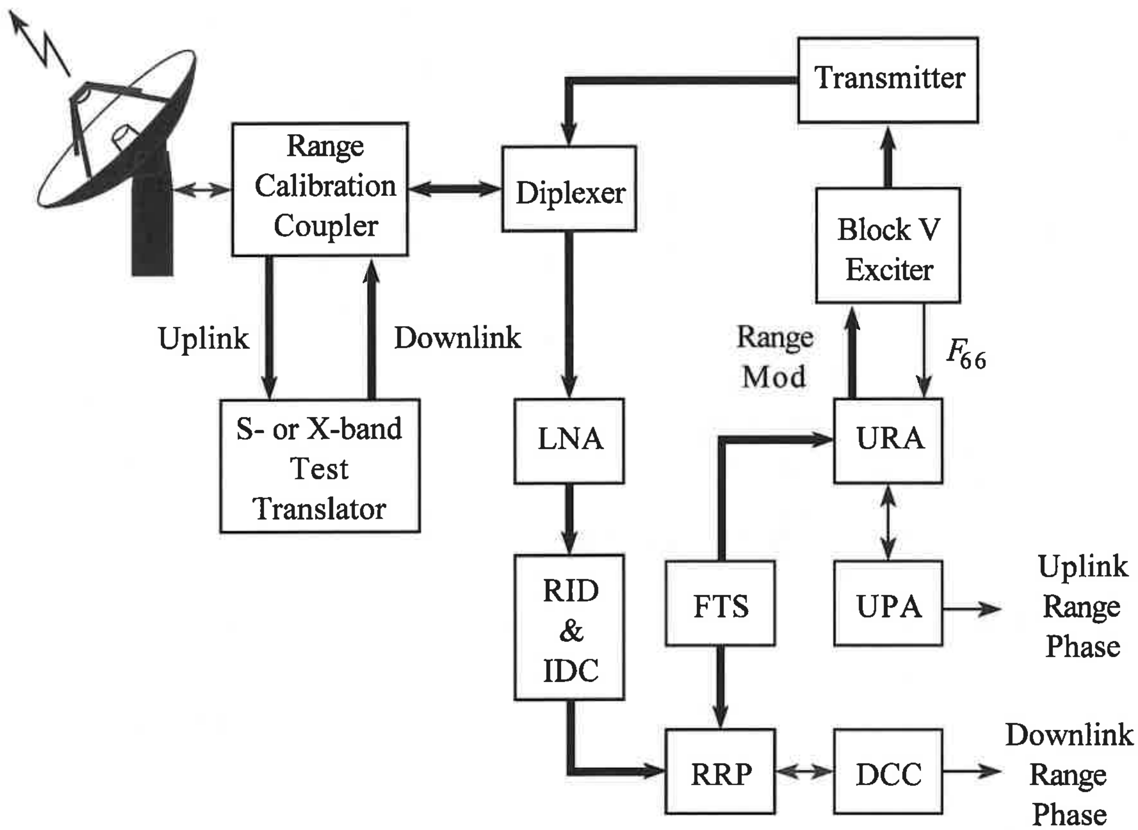

Figure 14. Typical DSS Delay Calibration

1. DSS Delay (measured pre-pass or post-pass) includes additional delay of Test Translator and cables between Test Translator and the Ranging Coupler.
2. Zero-Delay Device (ZDD) is precision test equipment used periodically to measure the delay at the Ranging Coupler and the aperture plane. However, the aperture plane is closer to a spacecraft by the delay from the reference height (T_A).
3. Z-height correction is the total round-trip delay from the Ranging Coupler to the aperture plane (heavy gray line) reduced by the calculated round-trip delay between the aperture plane and the reference height and the measured delay from the Ranging Coupler through the Test Translator.

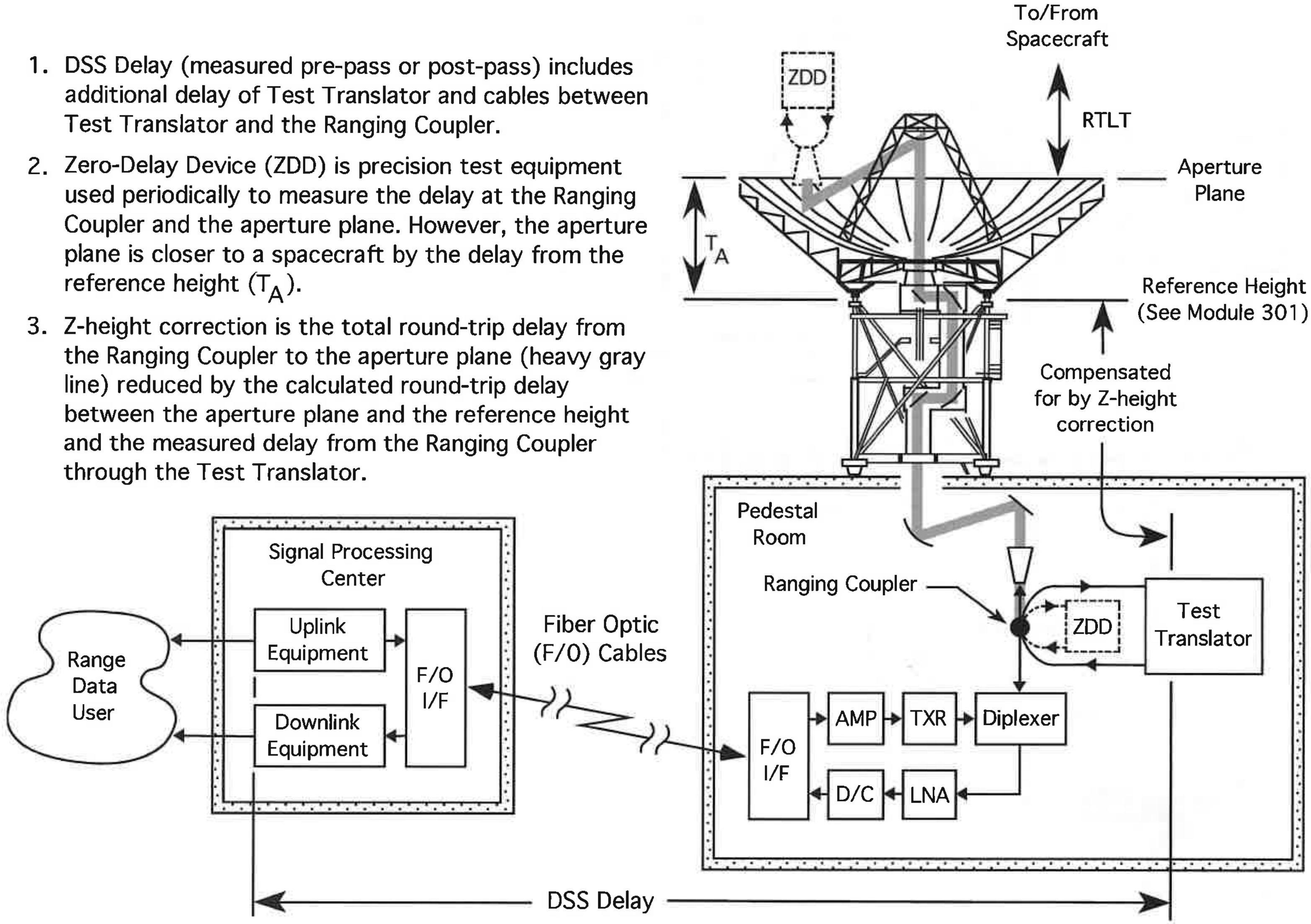

Figure 15. Measuring the Z-Correction

2.7 *Error Contributions*

The ground system, the media, and the spacecraft contribute errors to range measurements. The error contributions of the media and spacecraft are outside the scope of this document and have not been included.

The round-trip one-sigma delay error of the DSN ranging system over a ranging pass has been estimated for the X-band system as 6.3 nanoseconds (about 0.95 meter one-way). The S-band one-sigma delay error has been estimated as 12.5 nanoseconds (about 1.9 meters one-way).

Table 2 provides a breakdown of long-term error contributions due to calibration and errors inherent within the equipment of the various subsystems that constitute the total ground system of the NSP-Era Ranging System.

Table 2. One-Sigma Range Error for NSP-Era Ranging System

Subsystem	X-band		S-band	
	Round-trip Delay (ns)	One-way Distance (m)	Round-trip Delay (ns)	One-way Distance (m)
FTS	1.00	0.15	1.00	0.15
Receiver	2.00	0.30	2.00	0.30
Exciter and Transmitter	1.33	0.20	5.33	0.80
Microwave and Antenna	2.33	0.35	2.33	0.35
Uplink Ranging Board	2.00	0.30	2.00	0.30
Downlink Ranging Board	2.00	0.30	2.00	0.30
Cables	1.33	0.20	1.33	0.20
Calibration	2.66	0.40	2.66	0.40
Reserve	3.33	0.50	10.0	1.50
Root Sum Square	6.33	0.95	12.47	1.87

Appendix A

The Current DSN Ranging System

The current DSN ranging equipment has the same functional characteristics as the equipment previously described but does not provide optimum performance with the newer digital receivers. It is therefore being replaced at the 70-m, the 34-m HEF, and all 34-m BWG stations except DSS 27. This appendix describes the architecture and performance of the current sequential ranging equipment in the 26-m subnet and at the 34-m HSB station, DSS 27. It also identifies the performance differences between the NSP ranging equipment and the existing ranging equipment when it is used at the 70-m, the 34-m HEF, and the 34-m BWG stations.

A1.0 System Description Using the Sequential Ranging Assembly

The DSS Tracking Subsystem (DTK) comprises two items of equipment, the sequential ranging assembly (SRA) and the metric data assembly (MDA). This equipment performs the range measurement, formats the radiometric data, and sends it to the NAV at JPL. The NAV processes and provides the data to projects. The Network Support Subsystem (NSS) provides radiometric predicts to the DTK. Figure A-1 shows the current DSN ranging system configuration.

The SRA generates a sequence of square-wave frequencies (ranging code components) that are modulated onto the uplink carrier by the exciter and transmitted to the spacecraft. The spacecraft on-board transponder receives the signal , demodulates and filters it, and remodulates it onto the downlink carrier. The downlink is captured and amplified at the DSS, downconverted by the RID, and received by either a multi-function receiver (MFR) or Block V receiver (BVR). The SRA correlates the demodulated downlink signal with a Doppler-modified replica of the transmitted codes using the same process as was described earlier.

The SRA has two hardware interfaces with the exciter. The first provides the reference frequency, F_{66}, from the exciter to the SRA. The second supplies the square-wave ranging modulation signal derived from this reference to the phase modulator in the exciter. The SRA also has two hardware interfaces with the receiver. The first carries the received ranging codes while the second provides a representation of the received Doppler. Each SRA has two receive channels so there are actually two pairs of interfaces between the SRA and the two receivers at each station. SRA channel 1 is normally used to process S-band (or receiver 1) data and channel 2 is used to process X-band (or receiver 2) data.

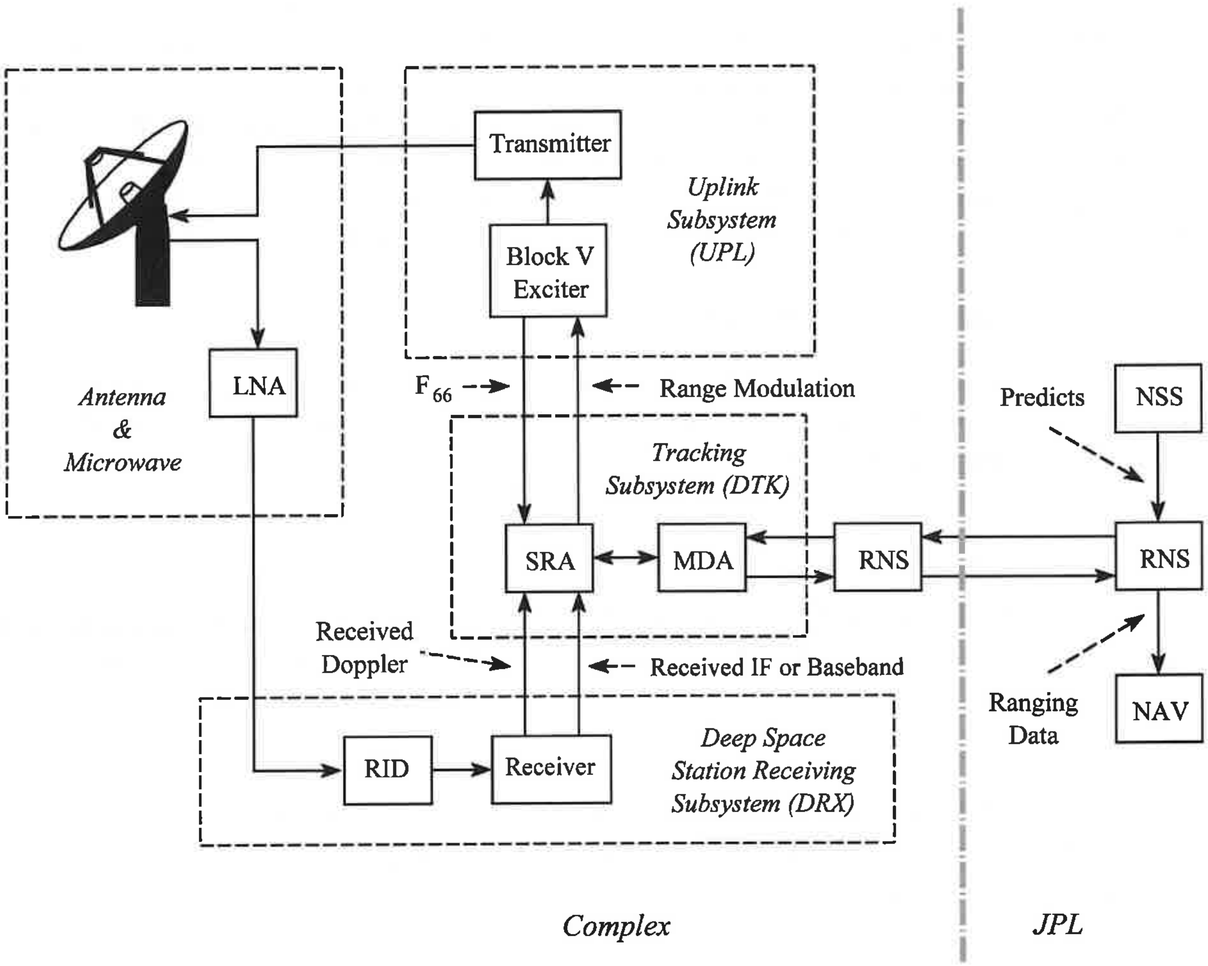

Figure A-1. Current DSN Ranging System

At the 26-m Subnet stations and the 34-m HSB antenna, the received ranging codes are provided to the SRA as a 10-MHz analog intermediate frequency (IF) from the MFR and demodulated within the SRA. At stations employing the BVR (the 70-m, the 34-m HEF, and the 34-m BWG stations), demodulation of the ranging codes are done within the receiver and the ranging baseband signal is sent to the SRA as digital data through an optical-fiber interface.

A2.0 Range Measurement Process Using the SRA

The SRA transmitter coder uses a reference frequency (denoted by F_{66} in this document) to generate a sequence of square waves (or binary codes). This code sequence is phase-modulated onto the uplink carrier. The measurement process begins at T_0 which is between 0 and 1 second before this signal is received by the SRA one RTLT later.

Prior to the receive time, T_0, the SRA receiver coder is referenced to the same F_{66} as the tramsnitter coder so it operates at the same frequency and phase. At T_0, a scaled Doppler reference from the tracking receiver is introduced to advance or retard the phase of the receiver coder. This has the effect of adding the frequency shift introduced by Earth-spacecraft relative Doppler to the receiver coder so the correlation can be accomplished. Having aligned the receiver coder frequency to the frequecny of the received code, the correlation to determine the phase of the received code proceeds by the same process described in paragraph 2.4.

A3.0 Performance Differences

The performance of the SRA and the NSP-era ranging are slightly different because of improvements incorporated into the new equipment and interface incompatabilitese between the SRA and digital receivers in 70-m, the 34-m HEF, and the 34-m BWG stations and the SRA. The following paragraphs summarize these differences.

A3.1 Integration Times

The SRA requires specification of the same three integration times as discussed in paragraph 2.3.4; however, their calculation and recommendations for selecting values are somewhat different.

A3.1.1 T_1

T_1, the total time used to integrate the correlation samples for the clock component, is calculated by the equations provided in paragraph 2.3.4.1 with different constants. The modified expressions are:

Sine-wave operation:

$$T_1 = \frac{1}{56} \times \frac{1}{F_c^2} \times \frac{1}{\sigma^2(t)} \times \frac{1}{P_r / N_o}, \text{ s} \qquad \text{(A-1)}$$

Square-wave operation:

$$T_1 = \frac{8}{343} \times \frac{1}{F_c^2} \times \frac{1}{\sigma^2(t)} \times \frac{1}{P_r / N_o}, \text{ s} \qquad \text{(A-2)}$$

where

F_c = the clock frequency, Hz

$\sigma^2(t)$ = the desired variance of the RTLT measurements, s^2

P_r/N_o = the ranging signal to noise spectral density, Hz.

The above equations can be rewritten in terms of the uncertainty σ(*r*) in meters, by multiplying the uncertainty σ(*t*) in seconds by the speed of light and dividing by a factor of 2. This provides:

Sine-wave operation:

$$\sigma(r) = \sqrt{\frac{402}{F_c^2(\text{MHz}) \times T_1 \times {P_r}/{N_o}}}, \text{ m} \qquad \text{(A-3)}$$

Square-wave operation:

$$\sigma(r) = \sqrt{\frac{523}{F_c^2(\text{MHz}) \times T_1 \times {P_r}/{N_o}}}, \text{ m} \qquad \text{(A-4)}$$

where:

F_c = the clock frequency, MHz

T_1 = the clock component integration time, s

P_r/N_o = the ranging signal to noise spectral density, Hz.

Note: The uncertainty σ here is only due to thermal noise. Other errors must be added to this to get the total uncertainty (see paragraph A5.0).

Figure A-2 plots integration time (T_1) as a function of P_r/N_o with σ(*r*) as a parameter for the SRA usning sine-wave operation and a 1-MHz clock component. For a desired σ(*r*), the user may find the proper integration time, T_1, for an estimated P_r/N_o (in dB-Hz). Figure A-3 is a similar graph for square-wave operation using a 500-kHz clock component. This figure may also be used for lower frequency square-wave clocks by recognizing that dividing F_c by 2 will result in T_1, being multiplied by 4, etc.

Ranging is possible as long as the receiver remains in lock over the measurement time. However, there is a practical lower limit for P_r/N_o (usually about –10 dB-Hz) determined by the combination of integration times (cycle time) and the minimum number of range points needed by the project. See Cycle Time in Paragraph 2.3.4.4 for further details. A P_r/N_o of –10 dB-Hz is also the recommended limit when the SRA is used with the Block V Receiver because of inefficiencies in the interface between the two pieces of equipment.

A3.1.2 T_2

T_2, the integration time for each of the lower frequency components, is calculated by the equation provided in paragraph 2.3.4.2 (equation 9). The figures provided there are repeated as figures A-4 through A-6 to emphasize the recommendation that the SRA should not be operated at a P_r/N_0 of less than –10 dB-Hz when using the Block V Receiver.

A3.1.3 T_3

T_2, the integration time for DRVID measurements, is selected by the same reasoning discussed in paragraph 2.3.4.3 and is usually set at $7/8 \times T_1$, rounded to the nearest integer.

A3.2 Other SRA Ranging Parameters

The other SRA ranging parameters are the same as required by NSP-era ranging. This includes modulation index (paragraph 2.3.5), frequency chopping (paragraph 2.3.6), tolerance (paragraph 2.3.7.1), servo (paragraph 2.3.7.2), and pipe (paragraph 2.3.7.3).

A3.3 SRA Calculations

A3.3.1 Cycle Time

The cycle time calculated by the SRA uses the same algorithm as the NSP-era ranging discussed in paragraph 2.3.4.3.

A3.3.2 P_r/N_0

The actual ranging power-to-noise spectral density (P_r/N_0) is evaluated at the end of the integration of all in-phase and quadrature correlation values for the clock by the same proces that was described in paragraph 2.4.2. However, the process bandwidth of the SRA is 5 Hz as P_r/N_0 is evaluated using pairs of 0.1-second long correlation samples. Therefore, it is necessary to multiply P_n by the reciprocal of 2×0.1 s, or 5 Hz, in order to put it in the form of P_r/N_0.

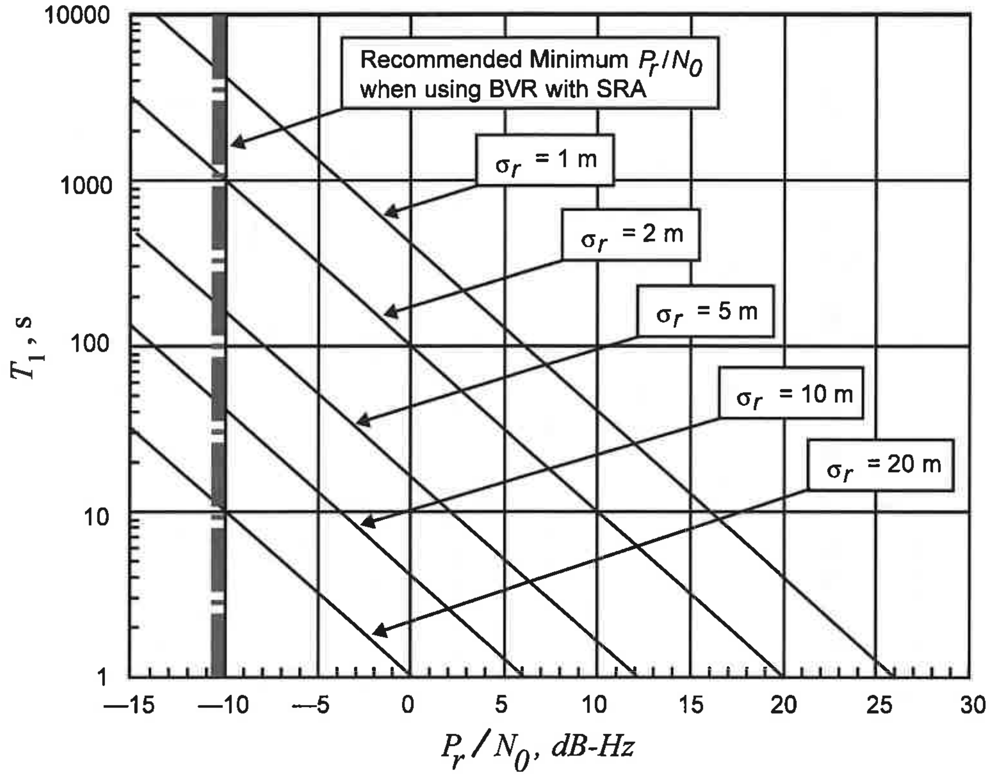

Figure A-2. Integration Time T_1 Versus P_r/N_0, Clock Frequency $F_c = 1$ MHz, for Sine-Wave Ranging Using the SRA

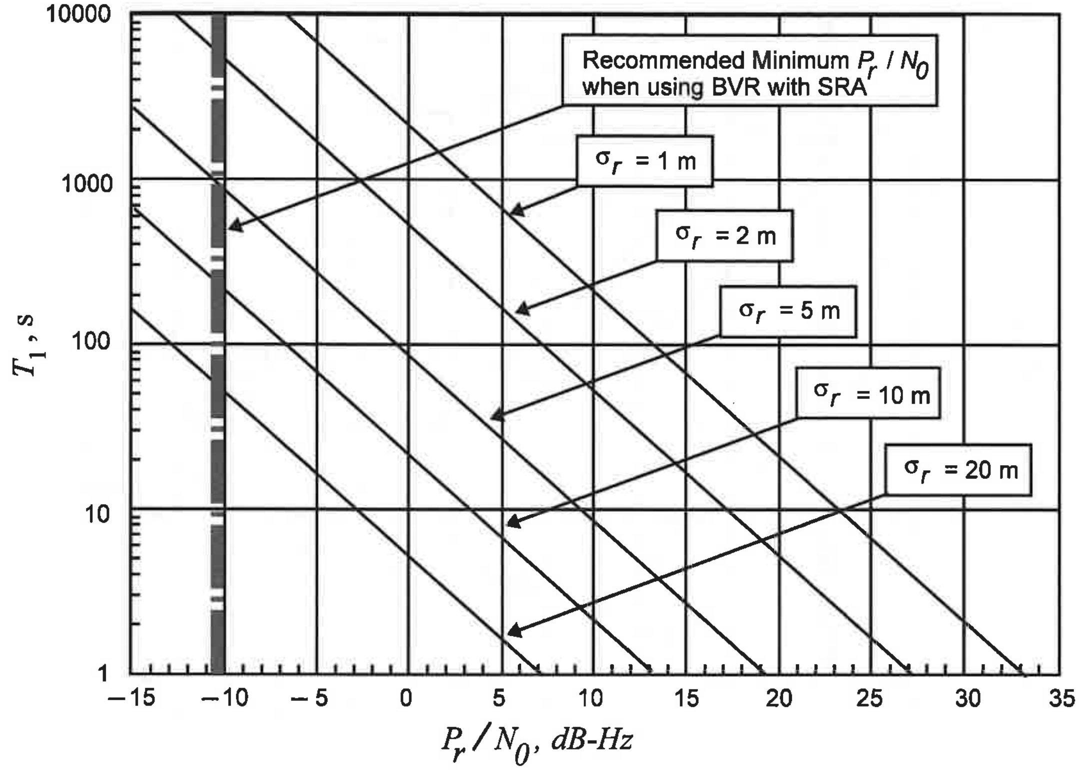

Figure A-3. Integration Time T_1 Versus P_r/N_0, Clock Frequency F_c = 500 kHz, for Square-Wave Ranging Using the SRA

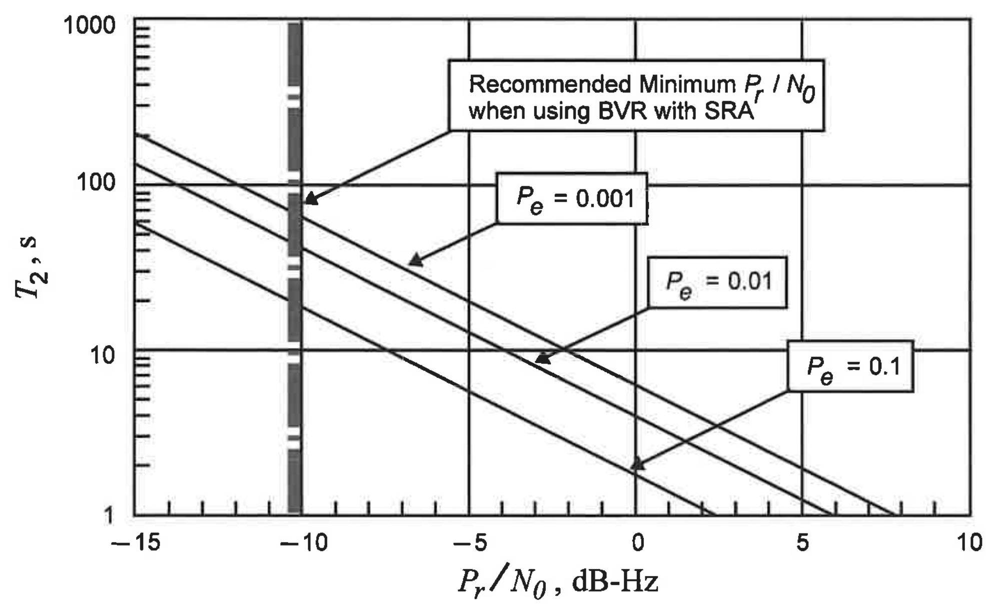

Figure A-4. Code Component Integration Time T_1 Versus P_r/N_0 for Various Probabilities of Error and n = 5

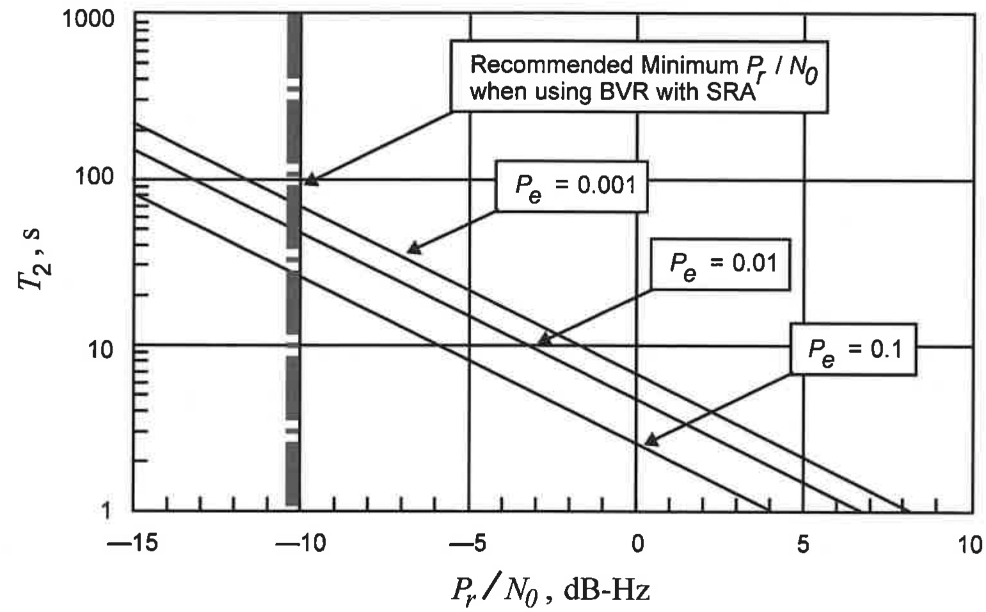

Figure A-5. Code Component Integration Time T_1 Versus P_r/N_0 for Various Probabilities of Error and $n = 10$

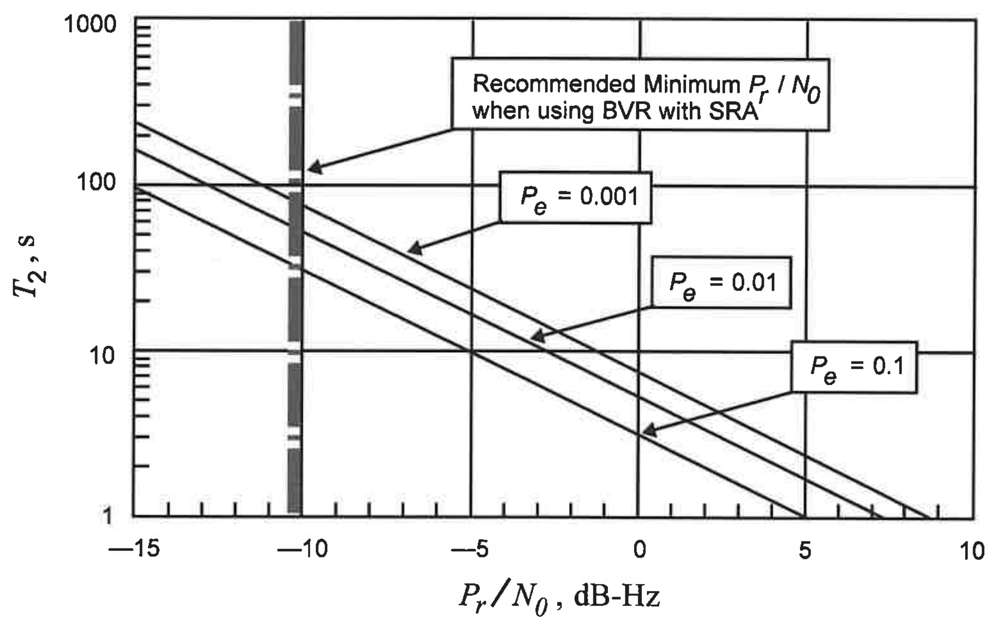

Figure A-6. Code Component Integration Time T_1 Versus P_r/N_0 for Various Probabilities of Error and $n = 20$

A4.0 Range Corrections Using the SRA

The following paragraphs discuss the DSS delay and antenna calibration when using the SRA. The Z-correction (paragraph 2.6.2) is the same for both types of ranging equipment.

A4.1 DSS Delay

The DSS Delay is measured by the same technique as discussed in paragraph 2.6.1; however, calibration path is different and is illustrated in Figure A-7. This figure assumes the uplink and downlink signals are in the same frequency band. When the uplink and downlink are at different frequencies, the downlink signal from the Test Translator is coupled into the receive path ahead of the LNA and as close to the feed as practical.

A4.2 Antenna Calibration

There are two types of structurally different antennas in the DSN. They are the Azimuth-Elevation (Az-El) mount, and the X-Y mount. The first type has an azimuth axis that perpendicularly intersects the elevation axis with the result being that the antenna correction is equal to zero. The DSN 70-m, 34-m HEF, 34-m BWG; and 34-m HSB antennas are of this type.

The X-Y antennas of the 26-m subnet have a primary axis and a secondary axis that are offset from each other. This offset causes the secondary axis (the Y-axis) to move relative to the Earth as the antenna rotates and adjusts its elevation about the primary axis (the X-axis). The change of distance is calculated by the following antenna correction expression:

$$\Delta\rho_A = -6.706\cos\theta \text{, m} \qquad \text{(A-5)}$$

where

θ = the angle of the Y-axis.

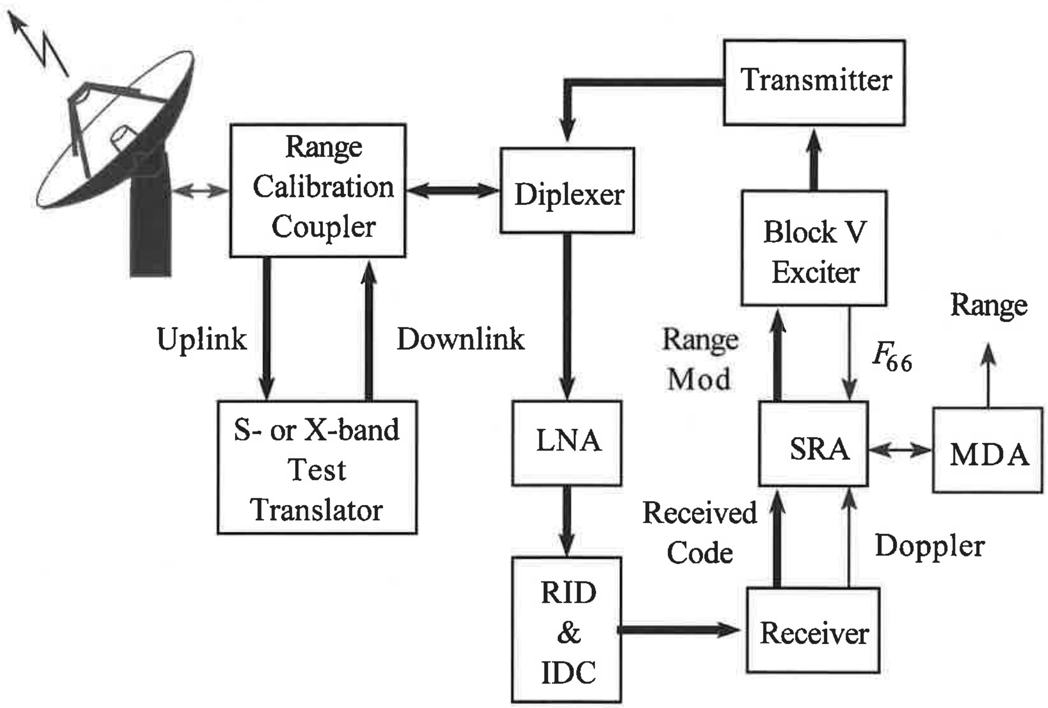

Figure A-7. Typical Range Calibration Signal Path for DSS Using SRA and MDA Ranging Equipment

A5.0 Error Contributions for Ranging Using the SRA

The round-trip one-sigma-delay error of the DSN ranging system over a ranging pass has been estimated for the X-band system as 6.3 nanoseconds (about 1.0 m one-way). The S-band system error has been estimated as 14.5 nanoseconds (about 2.2 m one-way).

Table A1 shows a breakdown of long-term error contributions due to calibration and errors inherent within the equipment of the various subsystems that constitute the total ground system using the SRA and MDA ranging equipment.

Table A-1. One-Sigma Range Error for SRA/MDA-Equipped Ranging System

Subsystem	X-band		S-band	
	Round-trip Delay (ns)	One-way Distance (m)	Round-trip Delay (ns)	One-way Distance (m)
Frequency and Timing	1.00	0.15	1.00	0.15
Receiver	2.67	0.40	2.67	0.40
Exciter and Transmitter	1.33	0.20	5.33	0.80
Microwave and Antenna	2.33	0.35	2.33	0.35
Tracking	0.67	0.10	0.67	0.10
Cables	1.33	0.20	1.33	0.20
Calibration	3.33	0.50	3.33	0.50
Reserve	3.33	0.50	12.47	1.87
Root Sum Square	6.30	0.95	14.52	2.18