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# 204
# 26-m Subnet Doppler and Ranging

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# *Change Log*

| Rev | Issue Date | Affected Paragraphs | Change Summary |
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# *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.

This module supersedes module TRK-40 in 810-005, Rev. D, dated March 15, 1990.

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# 1 Introduction

## 1.1 Purpose

This module describes the capabilities of the Deep Space Network (DSN) tracking capability as installed in the DSN 26-m Antenna Subnet. It is intended to provide sufficient information to enable telecommunications engineers to predict tracking system performance when using these elements of the DSN.

## 1.2 Scope

Discussion is limited to the performance of those telecommunications link elements that are exclusively used by the tracking system and are physically installed in the DSN 26-m Antenna Subnet. This module does not discuss capabilities of elements that are common to other systems. For information about these elements, refer to module 102, 26-m Subnet Telecommunications Interfaces.

## 1.3 General Information

The DSN 26-m Subnet is capable of receiving signals from spacecraft transmitting in the 2200 MHz to 2300 MHz band. This includes the capability to provide radio metric data (that is, Doppler and range) for spacecraft providing a residual carrier, which can be tracked by the DSN's phase-locked loop (PLL) receivers. Metric data for spacecraft that are being tracked by the DSN 34-m and 70-m subnets are discussed in Module 202, Block V Receiver Doppler, and 203, Sequential Ranging.

# 2 Doppler Measurement

The relative velocity of a spacecraft with respect to a tracking station can be measured by observing the change in frequency introduced on the radio link between the spacecraft and the tracking station. The reference for the frequency transmitted by the spacecraft and the reference used by the DSN to measure the received frequency determine the tracking mode of operation.

## 2.1 One-way RF Lock

The spacecraft generates the downlink signal from an onboard crystal oscillator. The DSN determines the received frequency by comparison against its reference frequency.

## 2.2 Coherent Two-way RF Lock

The DSN transmits a signal to the spacecraft. The spacecraft tracks the phase of the uplink and generates a downlink that is coherent with it. The DSN determines the received frequency by comparison against the same reference frequency from which the uplink was generated. Two-way tracking is the normal tracking mode and provides the most accurate Doppler measurements.

### *2.3 Non-coherent Two-way RF Lock*

The DSN transmits a signal to the spacecraft. The spacecraft tracks the phase of the uplink; however, the downlink signal is generated from an onboard crystal oscillator. The DSN determines the received frequency by comparison against its reference frequency

### *2.4 Three-way RF Lock*

Three-way tracking is performed when a station tracks a spacecraft that is receiving an uplink from a second tracking station and is transmitting a phase-coherent signal with respect to this second station.

## *3 Spacecraft Transponder Turn-around Requirements*

In order to be tracked in the two-way or three-way modes, the spacecraft communications system must be capable of receiving a carrier in the frequency range of 2025 to 2118 MHz (the range from 2109 MHz to 2118 MHz is restricted to deep space spacecraft) and transmitting a phase-coherent carrier that is 240/221 times the received frequency.

Before selecting operating frequencies for a future spacecraft mission, the telecommunication designer should consult the JPL Frequency Manager to avoid frequency interference with other present or planned spacecraft.

## *4 Doppler Readout*

Doppler is provided as a periodic readout (10/s) of a continuously accumulated count of cycle increments of a Doppler-plus-bias signal, which is related to spacecraft velocity by the equation given below.

$$\text{count}_i = \text{count}_{i-1} + T_i \left[ 240 \times 10^6 - 1000 \left( \frac{240}{221} \right) 32 f_t \left( \frac{\dot{r}_{up} + \dot{r}_{dn}}{c} \right) \right] \tag{1}$$

where:

$\text{count}_i$ = readout at end of current sample period

$\text{count}_{i-1}$ = readout at beginning of current sample period

$T_i$ = sample period (0.1 s)

$f_t$ = synthesizer frequency of transmitting station (1/32 of uplink frequency), Hz

$\dot{r}_{dn}$ = spacecraft radial\ velocity relative to the transmitting station, km/s

$\dot{r}_{dn}$ = spacecraft radial\ velocity relative to the receiving station, km/s

c = speed of light, km/s.

The data for external use are in the form of a 42-bit binary word. This provides an unambiguous count for 156 minutes at the maximum Doppler frequency as defined below.

## *4.1 Sense*

A trajectory with range increasing with time produces negative Doppler, which results in the count increasing by less than $240 \times 10^5$ each sample interval. A trajectory with range decreasing with time produces positive Doppler, which results in the count increasing by more than $240 \times 10^5$ each sample interval.

## *4.2 Resolution*

One Doppler count corresponds to 0.001 cycle of the input Doppler.

## *4.3 Maximum Doppler Shift Capability*

The maximum Doppler shift capability is –230 kHz to +230 kHz. The maximum Doppler rate capability is ±5.3 kHz/s.

## *4.4 Doppler Instrumental Accuracy*

The Doppler instrumental accuracy is 2.40-degrees or 0.0067 cycles, RSS. These values include all errors affecting cycle count measurements over the 0.1 s sampling interval. These are random errors since systematic errors are slowly varying and do not appreciably affect short-term measurements. Errors, contributed by sources outside the Doppler equipment, are not included.

## *4.5 Doppler Error due to Receiver Phase Noise*

Doppler accuracy consists of the Doppler instrumental accuracy plus the effects of receiver phase noise. In the absence of cycle slipping, the effect of receiver phase noise is to degrade the Doppler accuracy in accordance with the relation given below. The effect of receiver phase noise on Doppler accuracy is shown by Figure 1.

$$\sigma_{fd} = \frac{\sqrt{2}\sigma\phi}{360\Delta t} \tag{2}$$

where:

$\sigma_{fd}$ = Doppler frequency error, Hz

$\sigma_{\phi}$ = receiver phase noise, deg.

$\Delta t$ = sampling interval (0.1 s).

# 5 Receiving Equipment

The Multifunction Receiver (MFR) at the 26-m stations is a polarization diversity receiving system capable of receiving a signal with arbitrary polarization from a spacecraft and providing autotrack information to position a steerable antenna. Each 26-m station contains four MFRs. Each receiver contains a pair of sum channels (Sum-A and Sum-B) that are used to receive, and optimally combine, the orthogonally polarized components of a signal. Two of the MFRs at the 26-m stations also have two pairs of error channels, which provide the autotrack information.

The MFR has two basic modes of operation: open-loop and closed-loop. In the closed-loop mode, the receiver maintains frequency coherence between the spacecraft residual carrier and the station frequency standard. Doppler, ranging and autotrack information can be provided.

The open-loop mode is used when the spacecraft carrier is fully suppressed, as may be the case with frequency modulation (FM). Doppler and range data are not available, but autotrack information is provided. Table 1 summarizes the characteristics of the receiving equipment.

## 5.1 Closed-loop Operation

Three phase-locked loops (PLLs) (a primary and two secondary loops) are used to maintain zero phase difference between the two components of the received signal at the input to the diversity combiner. The primary loop compensates for Doppler and any other factors common to both receivers. The two secondary loops compensate for differences between the two received signals such as might occur due to fading or with a spinning spacecraft.

The primary loop is a type 3 loop, and the secondary loops are type 2. Therefore, the composite loop is type 3. This is in contrast to the receivers at the remaining DSN stations, which permit operator selection of loop type. As is the case with other DSN receivers, there is no single limiter within the MFR tracking loop. This makes the loop bandwidth and other tracking characteristics independent of signal level.

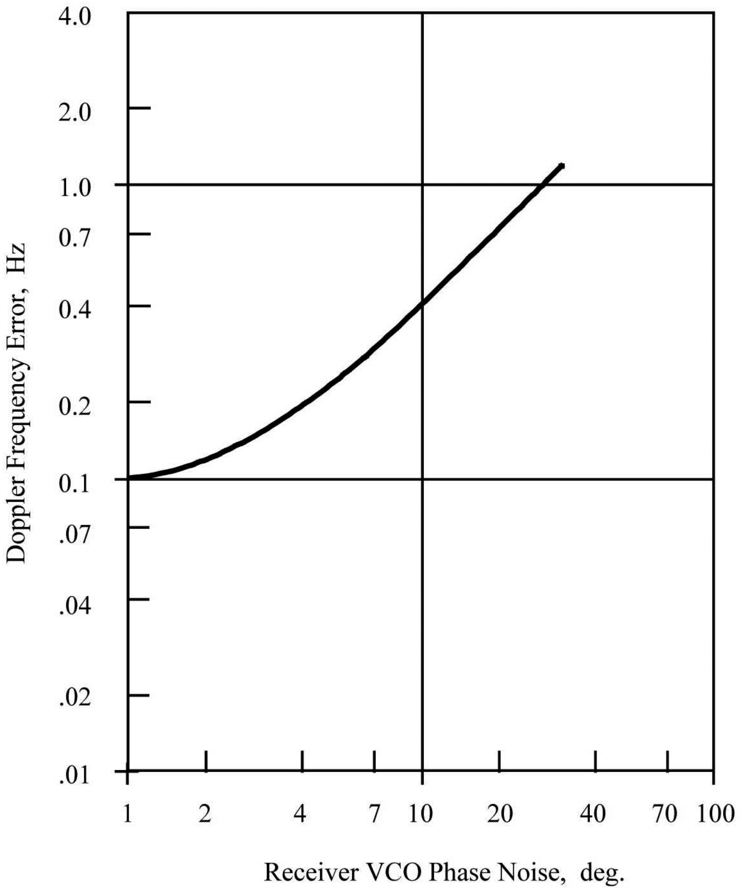


Figure 1. Doppler Frequency Error Versus Receiver Phase Noise

Type 3 loops have the capability to track linear variations of input frequency without static phase error; however, frequency rates will cause phase errors, which may cause loss of lock. Figure 2 illustrates the amount of static phase error produced by a frequency rate for the available tracking bandwidths. Tracking with static phase errors in excess of 30 degrees is not recommended.

## *5.2 Closed-loop Signal Acquisition*

The MFR provides for both manual and automatic signal acquisition. Manual acquisition uses the voltage from the Voltage Controlled Oscillator (VCO) Tuning control to vary the VCO frequency and tune the receiver about the selected center frequency. Automatic acquisition substitutes a triangular bias voltage whose range and rate are a function of the selected VCO bandwidth and tracking bandwidth. When lock is detected, the bias voltages are removed, and the loop coherently tracks the received signal.

Table 1. Receiver Characteristics

<table>
<tr><th>Parameter</th><th>Specification</th></tr>
<tr><td>Number of receivers</td><td>4 per station (for receiving more than one carrier simultaneously)</td></tr>
<tr><td>Input frequency</td><td>400–500 MHz (2200–2300 MHz before downconversion)</td></tr>
<tr><td>Tuning range</td><td>Center frequency tuning over 100 MHz band in 10 kHz steps. Continuously variable tuning around center frequency in two ranges of ± 300 kHz and ±15 kHz.</td></tr>
<tr><td>Telemetry IF bandwidths</td><td>10, 30, 60, 100, 300, & 600 kHz; 1, 1.5, 3.0, 6, 10, & 20 MHz</td></tr>
<tr><td>Telemetry demodulation</td><td>Phase modulation (PM) and frequency modulation (FM)</td></tr>
<tr><td>Video bandwidths</td><td>1.5, 5, 15, 30, 50, 75, 150, 300, 500, & 750kHz; 1.5, 3, 5, & 10 MHz</td></tr>
<tr><td>Receiver gain profile</td><td>Performance can be optimized for wide bandwidth, high-level signals or for low to moderate bandwidth and low level signals</td></tr>
<tr><td>Tracking modes</td><td>Closed loop and open loop</td></tr>
<tr><td>Gain control</td><td>Coherent and noncoherent automatic gain control (AGC) as well as manual gain control (MGC)</td></tr>
<tr><td>Primary phase-lock loop bandwidth (closed loop)</td><td>Selectable 30, 100, 300, 1000, & 3000 Hz (one-sided)</td></tr>
<tr><td>Secondary phase-lock loop bandwidth (closed loop)</td><td>1/3 of selected primary loop bandwidth</td></tr>
<tr><td>Closed-loop predetection bandwidth (depends on primary loop bandwidth selected)</td><td><table>
<tr><th>Loop B/W (Hz)</th><th>Predetection B/W kHz</th></tr>
<tr><td>10 & 30</td><td>1</td></tr>
<tr><td>100</td><td>10</td></tr>
<tr><td>300</td><td>30</td></tr>
<tr><td>1000</td><td>100</td></tr>
<tr><td>3000</td><td>300</td></tr>
</table></td></tr>
<tr><td>Phase-lock threshold</td><td>See Module 102, 26-m Antenna Subnet Telecommunications Interfaces</td></tr>
<tr><td>Dynamic signal range</td><td>See Module 102, 26-m Antenna Subnet Telecommunications Interfaces</td></tr>
<tr><td>Anti-sideband phase lock</td><td>When enabled, prevents phase lock on sideband located 100 Hz or more from carrier</td></tr>
<tr><td>Automatic acquisition mode, sweep time, & range</td><td><table>
<tr><th rowspan="2">Loop B/W (Hz)</th><th rowspan="2">Sweep Time (s)</th><th colspan="2">Sweep Range</th></tr>
<tr><th>300 kHz (VCO) (kHz)</th><th>15 kHz (VCO) (kHz)</th></tr>
<tr><td>30</td><td>20</td><td>1.0</td><td>0.1</td></tr>
<tr><td>100</td><td>6</td><td>3</td><td>1.0</td></tr>
<tr><td>300</td><td>6</td><td>10.0</td><td>6.0</td></tr>
<tr><td>1000</td><td>4</td><td>50.0</td><td>12.0</td></tr>
<tr><td>3000</td><td>200.0</td><td>200.0</td><td>15.0</td></tr>
</table></td></tr>
</table>

Table 1. Receiver Characteristics (Continued)

<table>
<tr><th>Parameter</th><th>Specification</th></tr>
<tr><td>Tuning memory</td><td>When enabled, maintains receiver tuning to last frequency received for at least 1 minute</td></tr>
<tr><td>Closed-loop AGC B/W<br>Pre-lock<br>In-lock</td><td><br>Greater of predetection B/W or 10 kHz<br>1 kHz</td></tr>
<tr><td>Closed-loop autotrack B/W</td><td>1 kHz</td></tr>
<tr><td>Discriminator predetection bandwidth (open-loop only – depends on telemetry IF bandwidth selected)</td><td><table>
<tr><th>Telemetry IF B/W (kHz)</th><th>Predetection B/W (kHz)</th></tr>
<tr><td>10</td><td>10</td></tr>
<tr><td>30 & 60</td><td>30</td></tr>
<tr><td>100 & 150</td><td>100</td></tr>
<tr><td>300 & 600</td><td>300</td></tr>
<tr><td>1000 – 20,000</td><td>1000</td></tr>
</table></td></tr>
<tr><td>Tracking bandwidth (open loop)</td><td>300 Hz</td></tr>
<tr><td>Discriminator bandwidth (open-loop, only--depends on telemetry IF B/W selected</td><td><table>
<tr><th>Telemetry IF B/W (kHz)</th><th>Discriminator B/W (kHz)</th></tr>
<tr><td>10, 30, 60</td><td>30</td></tr>
<tr><td>> 60</td><td>300</td></tr>
</table></td></tr>
<tr><td>Discriminator threshold</td><td>SNR of +10 dB in discriminator predetection bandwidth</td></tr>
<tr><td>Open-loop AGC B/W<br>SNR enhancement disabled<br>SNR enhancement enabled (depends on telemetry IF B/W selected</td><td><br>Same as predetection B/W<br>Same as predetection B/W (10 kHz – 3 MHz IF B/W) or 10 MHz (6, 10, & 20 MHz IF B/W)</td></tr>
<tr><td>Open-loop autotrack B/W (depends on telemetry IF B/W selected)</td><td>Same as predetection B/W</td></tr>
<tr><td>Automatic gain control (AGC) response speeds for 10 dB change in signal level</td><td>3, 30 & 300 ms, 3.0 s</td></tr>
</table>

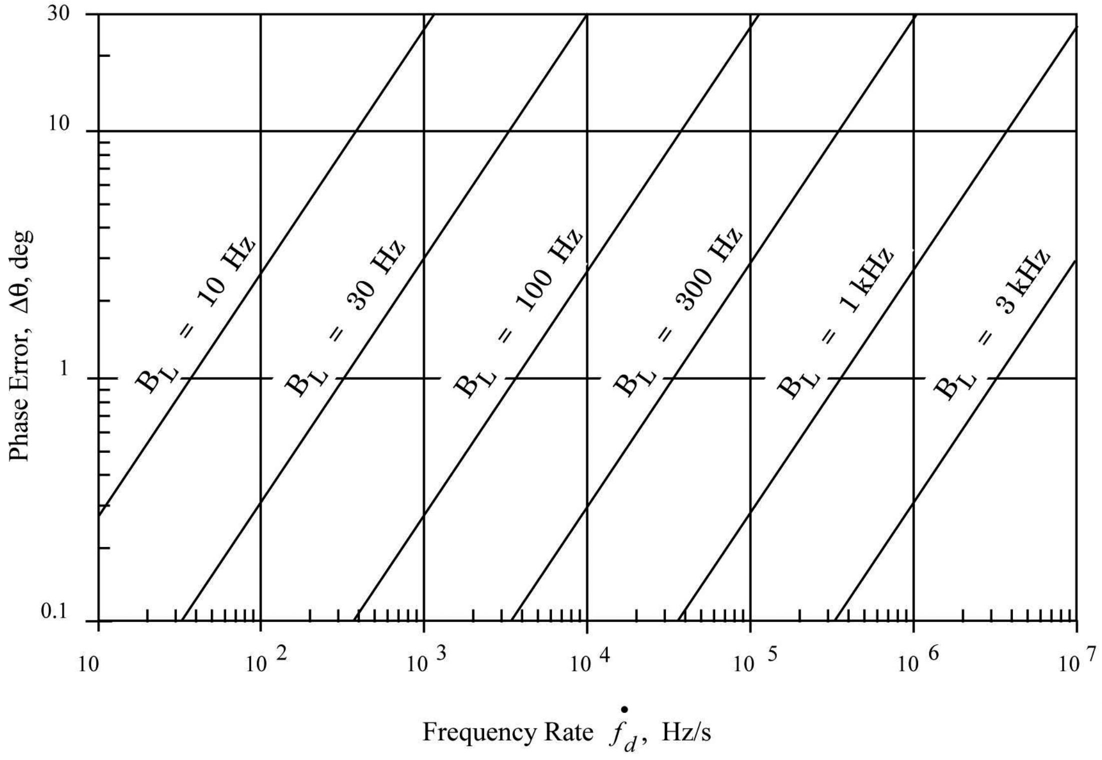


Figure 2. Frequency Rate Capability for Closed-loop Tracking Bandwidths

The input to the loop filter is also applied to three discriminators, which verify that the received spectrum is centered within the receiver pass band. If anti-sideband phase lock is enabled, the tracking loop cannot be closed until the received spectrum is appropriately centered.

## *5.3 Open-loop Operation*

When open-loop operation is selected the MFR uses one of two discriminators to track the frequency of the received signal. A 30-kHz discriminator is used for the 10-kHz, 30-kHz, and 60-kHz telemetry IF bandwidths, while a 300-kHz discriminator is used for IF bandwidths wider than 60 kHz. The discriminators include a delay circuit to prevent noise-induced effects from driving the VCO to its limit when the received signal is below the discriminator threshold.

Tuning information required to bring the two components of the received signal into phase coherence for combining is derived by using the sum channel-A secondary phase detector to cross-correlate the two sum signals and derive an error signal suitable for tuning the channel-A secondary VCO.

## *5.4 Open-loop Signal Acquisition*

Manual VCO tuning is available to assist or as a substitute for the automatic frequency control (AFC) provided by the discriminators. When AFC is enabled, manual tuning is only operational in the absence of a signal above the discriminator threshold.

## *5.5 Telemetry Demodulation*

The MFR includes wideband and narrowband demodulators for both PM and FM. The narrowband demodulators are used for IF bandwidths of 3 MHz and lower while the wideband demodulators are used for IF bandwidth wider than this. A complete discussion of the telemetry capability at the 26-m stations is contained in module 212, 26-m Subnet Telemetry.

The receiver gain profile can be modified to improve the signal-to-noise ratio at the telemetry demodulator when wideband (i.e., IF bandwidth of 6 MHz or higher), strong signals are being received. The function operates by increasing the signal level at the output of the AGC'd stage by 20 dB and compensating for this at the input of the wideband telemetry demodulator. The compromise for this action is that, as phase-lock threshold is approached, limiting will occur due to the high noise power. The overall effect will be to degrade the phase-lock threshold by 10 to 20 dB in the narrower tracking bandwidths.

## *5.6 Error Channels*

Two pairs of error channels are used to derive autotrack information for steering the antenna. One pair processes the two orthogonal components of the antenna X-axis error signal, and the other two process the components of the antenna Y-axis error signal. The two pairs of error components are then combined into X and Y error signals with the relative contribution of each component being based on the level of the corresponding sum channel component. The weaker component is turned off when its signal level is approximately 24 dB below the stronger component. The X and Y error signals are then demodulated to produce the control voltages for the antenna servos.

In the closed-loop mode, the reference for the error demodulators is the 10 MHz station frequency reference. In the open-loop mode, the error demodulator reference is the input to the discriminator that is tracking the sum signal.

The availability of the error signals depends on the presence of an adequate SNR in the error channel predetection bandwidth (which is the same as the sum channel predetection bandwidth). Table 2 provides the error channel threshold sensitivity for both the closed-loop and open-loop modes as a function of predetection bandwidth.

Table 2. Error Channel Threshold Sensitivity Versus Predetection Bandwidth

| Predetection Bandwidth | Threshold Sensitivity |
|---|---|
| 30 kHz (narrow band) | –132 dBm |
| 100 kHz (narrow band) | –127 dBm |
| 300 kHz (narrow band) | –122 dBm |
| 1.0 MHz (narrow band) | –117 dBm |
| 3.0 MHz (narrow band) | –117 dBm* |
| 6 MHz (wide band) | –117 dBm* |
| 10 MHz (wide band) | –117 dBm* |
| 20 MHz (wide band) | –117 dBm* |
| *The maximum required open-loop autotrack bandwidth is 1.0 MHz | |

### *5.7 Signal Level*

In the closed-loop mode, the received RF carrier signal level can be indirectly determined by comparing the AGC voltage due to a spacecraft signal to a calibrated AGC voltage plotted against input carrier signal level curve. In the open-loop mode, the AGC voltage is derived from peak signal level detectors, and so its relationship to signal power is a function of the characteristics of the signal being received.

### *5.8 Minimum Recommended RF Signal Level*

The minimum recommended signal levels as a function of receiver loop bandwidth are shown in the primary parameter tables of module 102, 26-m Antenna Subnet Telecommunications Interfaces. These recommendations are for situations where the static phase error in the receiver phase-locked loop is zero; that is, when no Doppler rate is present. The minimum RF signal level represents a carrier SNR of 10 dB in a noise bandwidth equal to the closed-loop bandwidth, $B_L$.

## *6 S-band Exciter*

Each 26-m station is equipped with two S-band exciters that can be operated as a primary and backup or as two simultaneous uplink carriers. The exciter output can be connected directly to the antenna or to a dummy load, but, in the normal configuration, it is routed to a klystron power amplifier before being radiated. Table 3, Exciter Characteristics, provides the

Table 3. Exciter Characteristics

| Parameter | Specification |
|---|---|
| Number of exciters | 2 per station |
| Number of uplink carriers | 1 or 2 (two-carrier operation requires both exciters) |
| Output frequency | 2025-2120 MHz selected in discrete increments of 100 Hz |
| Total output power | 42 dBm ± 0.5 dB (16 W) |
| VCO range | ±15 kHz and ±300 kHz |
| Acquisition search ranges (±300 VCO range) | kHz: 20, 40, 60, 80, 120, 160, 200, 240, 280, 320, 360, 400, 480, 520, 600 |
| Acquisition search ranges (±15 kHz VCO range) | 1 to 15 kHz in 1 kHz steps |
| Sweep time (in seconds) | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 20, 25, 50, 100, 200, 400, 800 |
| Exciter VCO bandwidth (referenced to S-band) | 4.0 kHz (wide), 400 Hz (medium), and 40 Hz (narrow) |
| Frequency stability | See Module 304, Frequency and Timing |
| RMS phase noise | 1-degree, maximum |

characteristics of the exciter equipment. Characteristics of the power amplifier are contained in module 102, 26-m Antenna Subnet Telecommunications Interfaces.

The exciter includes search tuning and acquisition circuits to permit the ground and spacecraft equipment to be brought into phase coherence prior to attempting range measurements. Acquisition search range and sweep time are selectable to permit the acquisition process to be optimized for various combinations of Doppler shift and spacecraft transponder characteristics. The VCO Range is normally set at ±300 kHz, but it may be set to ± 15 kHz if the Doppler shift and spacecraft transponder instability are known to be considerably less than this.

When spacecraft acquisition has been accomplished, tuning is suspended, and the exciter slowly returns to the selected center frequency at a rate determined by the selected VCO range and bandwidth. Table 4 provides typical time-to-lock values for representative values of these parameters.

Table 4. Typical Time-to-lock Values

| **Condition** | **Time-to-Lock (s)** | | |
|---|---|---|---|
| | **Wide B/W** | **Medium B/W** | **Narrow B/W** |
| 300 kHz VCO range from 150 kHz | 2.8 | 25 | -- |
| 15 kHz VCO range from 15 kHz | 1.8 | 10 | 180 |

# *7 Range Measurement*

The ranging equipment at the 26-m stations uses a hybrid ranging technique employing a harmonic tone waveform to provide maximum precision combined with a pseudo-random binary-encoded ambiguity resolving code (ARC) that minimizes the time to complete a range measurement. Each output range value is independent of all previous values and is an unambiguous measure of the total round-trip range in units of 1 ns (nominally 0.15 m). Table 5 summarizes the characteristics of the ranging equipment.

The available ranging tones are 500 kHz, 100 kHz, 20 kHz, 4 kHz, 800 Hz, 160 Hz, 40 Hz and 10 Hz. Any of the three highest frequency tones may be selected as the major range tone (MRT), which establishes the ranging data resolution. During ranging, the selected MRT is transmitted continuously, and the lower frequency (or minor tones) are sequentially applied to resolve range ambiguities. Minor tone frequencies of 100 kHz through 4 kHz are modulated directly on the carrier or the 1.70 MHz ranging subcarrier. Minor tones of 800 Hz through 10 Hz are transmitted using the 4 kHz tone as a subcarrier. This keeps the ranging components away from the carrier and avoids degradation of the receiver acquisition and tracking performance. The 800 Hz tone is transmitted single-sideband suppressed subcarrier, while the three lowest tones are transmitted double-sideband, suppressed-subcarrier.

The lowest sidetone, 10 Hz, gives an ambiguity interval of 0.1 s or approximately 15,000 km. To further resolve the range ambiguity, the 1023-bit ARC may be bi-phase modulated on the 4 kHz tone. The code bit rate of 160 b/s gives a code period of 6.39375 s, corresponding to an unambiguous range of approximately 958,000 km. However, the range word readout size is 32 bits, which limits the maximum range readout to approximately 644,000 km.

## *7.1 Range Modulation*

The range modulation signal may be phase-modulated directly on the uplink carrier or used to phase-modulate a 1.70-MHz subcarrier. This second alternative is to accommodate transponders that place baseband data directly on the downlink carrier.

Table 5. Ranging Equipment Characteristics

| Parameter | Specification |
|---|---|
| One-way unambiguous range | 644,000 km |
| Range rate | Up to 15,000 m/s |
| Acceleration | Up to 150 m/$s^2$ |
| Strong-signal accuracy | 1.0 m RSS using 500 kHz primary tone |
| Resolution | 1.0 ns (-0.15 m) |
| Resolution (major) tones | 500 kHz, 100 kHz, 20 kHz |
| Ambiguity resolving (minor) tones | 100 kHz, 20 kHz, 4 kHz,<br>800 kHz, 160 Hz, 40 Hz,<br>10 Hz, 1023-bit PN code |
| Ranging Modulation | PM, 0.2 – 1.5 radians, peak on carrier or 0.3 – 1.2 radians, peak on 1.70 MHz subcarrier |
| Subcarrier Modulation | PM, 0.2 – 1.5 radians, peak on carrier |
| Acquisition threshold | Range tone S/N ≥12 dB-Hz |
| Acquisition modes and time | Fast < 15 s. (Range tone S/N ≥ 50 dB-Hz, Ranging modulation index ≥ 0.5 radian.)<br>Medium < 25 s. (Range tone S/N ≥ 30 dB-Hz, Ranging modulation index ≥ 0.3 radian.)<br>Slow < 75 s. (Range tone S/N ≥ 10 dB-Hz, Ranging modulation index ≥ 0.2 radian.) |
| Major tone tracking loop B/W (second-order loop) | 0.6 Hz (fast acquisition)<br>0.15 Hz (medium acquisition)<br>0.0375 Hz (slow acquisition) |
| Amplitude control | Automatic for modulation indices from 0.2 to 1.5 radian |
| Minor tone integration modes and times (Automatically selected depending on acquisition speed) | Fast:: 10 ms (100 kHz – 800 Hz tones)<br>100 ms (160 Hz – 100 Hz tones)<br>800 ms (ARC)<br>Medium: 50 ms (100 kHz – 800 Hz tones)<br>100 ms (160 Hz – 100 Hz tones)<br>800 ms (ARC)<br>Slow: 800 ms |
| Output data (in ns) | 32-bit parallel data to Tracking Data Processor<br>10-decimal digit display on front panel |

All range tones are transmitted as sine waves using filters to attenuate harmonics by a minimum of 40 dB. The process of modulating low-frequency tones on the 4-kHz tone attenuates all harmonics by a minimum of 40 dB except for the residual sideband of the 800-Hz tone at 3.2 kHz, which is attenuated at least 20 dB below the 4.8 kHz-sideband. The ARC is a square-wave signal that is biphase modulated to produce double sidebands of the suppressed 4-kHz tone. This spectrum is passed through a filter with a 3-dB bandpass of 3.5 to 4.5 kHz to remove any significant energy within 3.2 kHz of the carrier. Figure 3 provides examples of typical ranging spectra.

## *7.2 Modulation Index*

The uplink carrier modulation index (of the ranging tones or the 1.70-MHz subcarrier) is continuously adjustable over the range of 0.2 to 1.5 radians, peak. When the 1.70-MHz ranging subcarrier is used, the subcarrier modulation index is adjustable in 0.02-radian steps over the range of 0.3 to 1.2 radians, peak.

The relationship between modulation index and carrier-power suppression or ranging data-power suppression can be calculated from the following expressions:

$$\frac{P_C}{P_T} = 10\log\left[J_0^2(\theta_R)\right] \tag{3}$$

$$\frac{P_R}{P_T} = 10\log\left[2J_1^2(\theta_R)\right] \tag{4}$$

where:

$\theta_R$ = ranging modulation index, radians

$P_C$ = carrier power

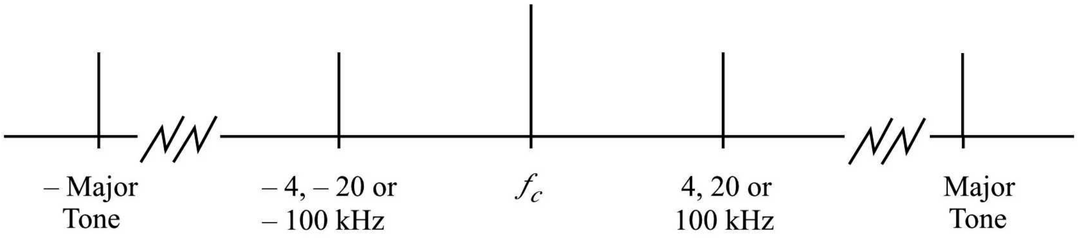
$P_T$ = total power

$P_R$ = ranging power (first upper and lower sideband)

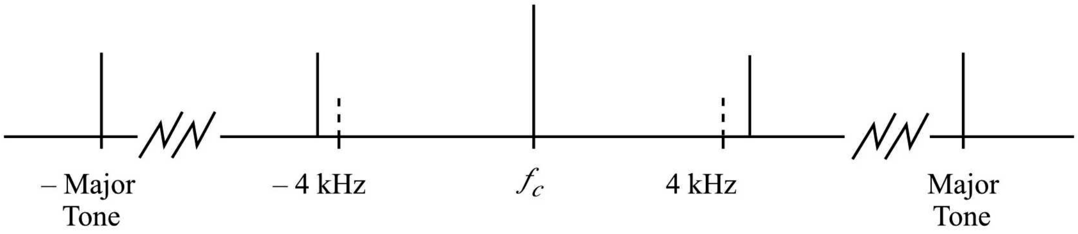
$J_0$ = zero-order Bessel function

$J_1$ = first-order Bessel function.

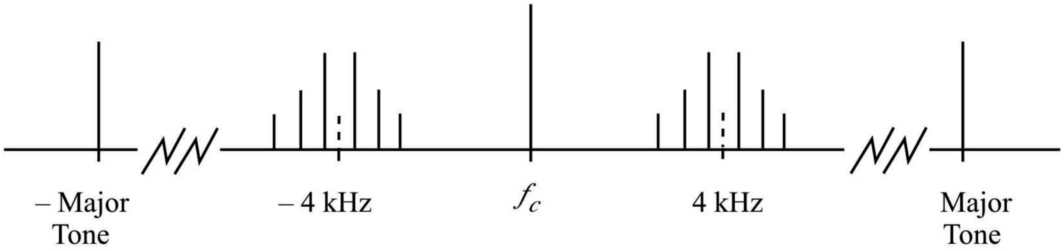
Carrier modulation index is set by observing a spectrum analyzer while adjusting the ratio between the carrier and the major range tone (or unmodulated ranging subcarrier) to a value read from a table. The granularity of the table is 0.05 radian, and the accuracy with which the modulation-to-carrier ratio can be measured is ±0.2 dB. Linear interpolation of the table adds an additional error at low modulation indices. Thus, the overall accuracy with which the modulation index can be set varies from ±0.01 radians at a modulation index of 0.2 radians to ±0.05 radians at a modulation index of 1.5 radians.



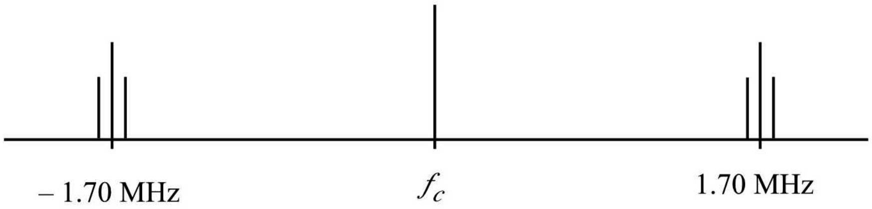
(a) Ranging Spectrum with Major Tone and 4-, 20- or 100-kHz Minor Tone



(b) Ranging Spectrum with Major Tone and 800-Hz Tone at 4.8 kHz



(c) Ranging Spectrum with Major Tone and 10-, 40- or 160-Hz Tones



(d) Ranging Spectrum (as shown above) on 1.70-MHz Subcarrier

Figure 3. Examples of Ranging Spectra

The modulation index stability is the product of the ranging equipment output voltage stability and the stability of the exciter phase-modulator voltage sensitivity. As both of these parameters are ±1%, the modulation index stability is approximately ±1.4%.

## *7.3 Range Readout*

Range is provided as a periodic readout (10/s) corresponding to the instantaneous round-trip delay, in nanoseconds, of the MRT from the DSS reference location at the time specified by the output data time tag within ±25 ns. The method by which the range readout is determined is illustrated by Figure 4. This value includes the spacecraft delay (item 3 in Figure 4), which must be removed by the user in order to compute the actual topocentric range.

The effect of delays within the DSS equipment (item 1 in Figure 4) is removed by calibrating the ranging system before each use. This is done by measuring the range to a test antenna, which has been located so the round-trip delay between it and the DSS reference location (item 2 in Figure 4) is accurately known. By adjusting the ranging calibration so the range to the test antenna indicates 48 ns, the range calibration will exactly compensate for the DSS delays.

## *7.4 Measurement Process*

Range measurements are made by estimating the phase and, hence, time delay of the received MRT. The 2-, 10-, or 50-ns ambiguity of this measurement is resolved by phase-matching the received minor range tones with a set of local tones generated from an oscillator which is phase-locked to the received major range tone. This modifies the local tone frequencies to compensate for uplink and downlink Doppler. Since the lowest frequency range tone is 10 Hz, a pseudo-random ambiguity resolving code (ARC) replaces the minor range tones to confirm ranges less than approximately 30,000 km or to resolve ambiguities in range measurements greater than this.

To enable the major tone phase-tracking loop to acquire and maintain lock in the presence of high Doppler dynamics, the Doppler on the major range tone is estimated from an approximation of the received frequency (to the nearest 125 kHz) and the measured carrier Doppler. When this estimate is combined with an appropriate bias frequency and subtracted from the Doppler modified range tone, the resultant signal has a frequency of 1.66 MHz, and the residual MRT Doppler is reduced to a maximum of 0.006 Hz. This enables all three major range tones to be tracked with a single phase-tracking loop operating at a frequency of 1.66 MHz. The loop employs a second-order digital loop filter because of the practical limitations of analog components for the required bandwidths and to eliminate the drift associated with an analog filter.

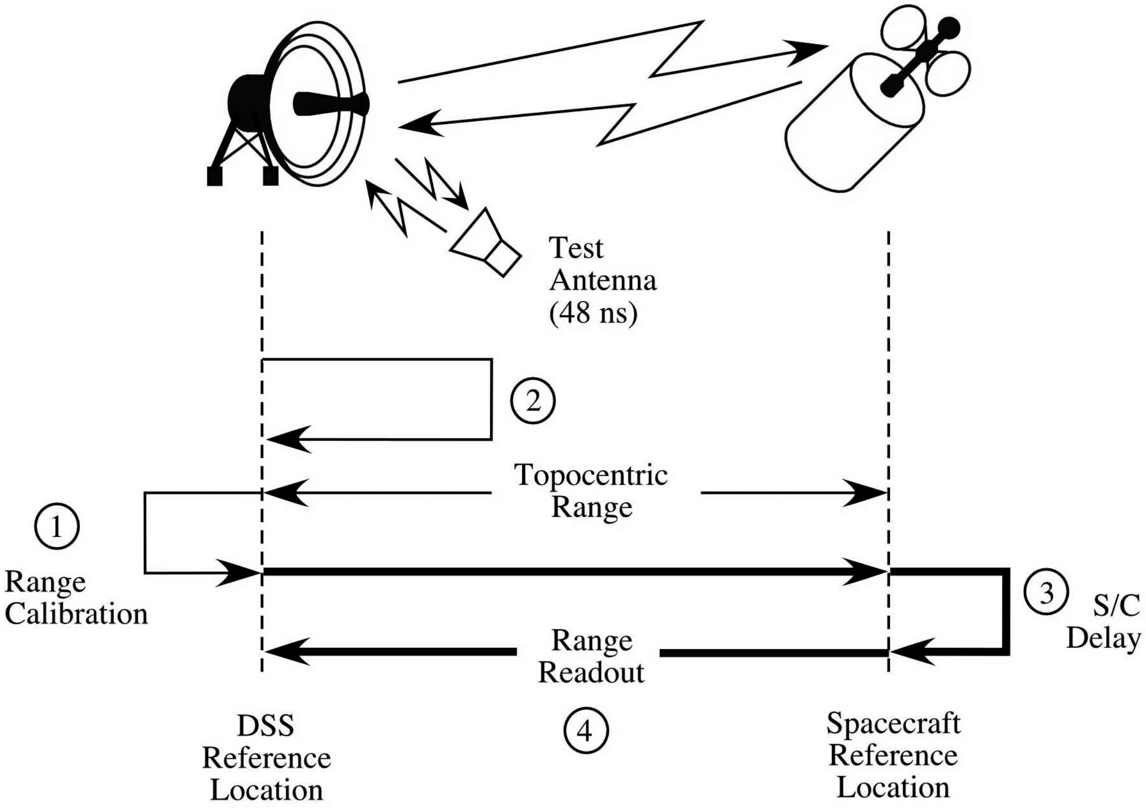


Figure 4. 26-m DSS Range Measurement

Range acquisition may be initiated as soon as two-way lock has been achieved with the spacecraft and the receiving equipment is in the configuration for which the ranging calibration was performed. The process consists of three tasks: 1) AGC of the MRT and slewing of the MRT phase-lock loop, 2) MRT phase-lock loop acquisition, and 3) ambiguity resolution. The second and third steps are conducted in parallel.

### *7.4.1 AGC Acquisition*

The AGC acquisition begins with an automatic measurement of the receiver noise level (ϕ) to determine if the initial setting for the ranging signal demodulator AGC bandwidth should be wide (ϕ < 40 dB/Hz) or narrow (ϕ ≥ 40 dB/Hz). The MRT is then applied to the uplink signal.

The intermediate frequency from the MFR is detected to produce a baseband containing either the MRT (as modified by Doppler) or a 1.7-MHz subcarrier modulated by the MRT (both as modified by Doppler). If the 1.7-MHz subcarrier is present, an additional phase-locked demodulator is used to remove it. The resultant Doppler-modified MRT is supplied to the MRT phase-tracking loop for processing.

Both the range demodulator and the 1.7-MHz demodulator contain variable gain stages, which are used to supply a constant signal level to the following phase-locked loop. This means that the gain of the range demodulator is controlled by the subcarrier tracking loop when a subcarrier is present and by the MRT tracking loop when no subcarrier is present. When a subcarrier is present, the MRT tracking loop controls the gain of the subcarrier demodulator.

In the subcarrier mode, the gain of both demodulators is fixed from the beginning of the AGC phase until the subcarrier tracking loop attains lock. The range demodulator AGC loop is closed at this time to provide a constant subcarrier amplitude to the subcarrier demodulator, and MRT AGC acquisition begins.

Since the MRT phase is initially unknown, a fixed AGC voltage is used to control the gain of either the range demodulator or the subcarrier demodulator. After allowing time for the AGC to stabilize, the MRT filter is set to one of the three initial acquisition bandwidths listed in Table 6, depending on the acquisition mode (slow, medium or fast) selected by the operator. The phase-difference between the MRT and the VCO is then estimated by analyzing the magnitude and sign of the voltage produced from in-phase and quadrature-phase detectors, the phase of the VCO is slewed so it is within 90 degrees of the MRT phase, and the loop closed. At this time, the output of the quadrature phase detector is an indication of the major range tone amplitude and is used for the range or subcarrier demodulator’s AGC. With the carrier power maintained constant by the AGC of the MFR, the MRT AGC is capable of maintaining a constant MRT amplitude for ranging modulation indices of 0.2 to 1.5 radians.

Table 6. Noise Bandwidths of MRT Phase-locked Loop

| **Acquisition Speed** | **Noise Bandwidth (One-sided)** | |
|---|---|---|
| | **Initial Bandwidth (Hz)** | **Tracking Bandwidth (Hz)** |
| Fast | 4.8 | 0.6 |
| Medium | 0.6 | 0.15 |
| Slow | 0.15 | 0.375 |

### *7.4.2 MRT Phase Acquisition*

MRT phase acquisition begins when the loop is first closed. It is considered to be complete after the loop bandwidth has been reduced to its final value and sufficient time has been provided for the transient errors to decay to the values required to meet specified performance. The total time required to complete the acquisition process is determined by the acquisition mode and is summarized in Table 7.

Table 7. MRT Acquisition Time

| Acquisition Mode | MRT Acquisition Time (s) |
|---|---|
| Fast | 1.0 |
| Medium | 8.0 |
| Slow | 32.0 |

### *7.4.3 Ambiguity Resolution*

Ambiguity resolution begins as soon as the MRT tracking loop is closed. It consists of synchronizing the locally generated minor range tones with the received minor range tones, starting with the highest minor tone and ending with the 10-Hz tone. Ambiguities greater than 0.1 second are resolved using a pseudo-random ARC. The synchronization process for each tone consists of:

a) Correlation (phase comparison) of the local tone with the received tone.

b) Deciding which of three possible states the correlation function lies in.

c) Correction of phase error by shifting the phase of the local tone.

d) Repetition of steps (a) through (c) until peak correlation is obtained.

In the absence of decision errors, at least two and not more than three correlations are required for each tone.

All minor tones are transmitted and received as sine waves. When these tones are correlated with the local square wave tones, a sinusoidal correlation function results. The 100-kHz through 160-Hz local tones are capable of being phase shifted in 72° increments. As a result, there are five nominal correlation values for these tones. The 40-Hz and 10-Hz tones are phase shifted in 90° increments. This provides four nominal correlation values. Figure 5 shows the correlation function normalized to unity with the nominal correlation values marked.

Actual correlation values will be distributed around these points because of amplitude errors and because the delay between the local and received tones will not usually be a multiple of 72 or 90 degrees.

The apparent phase difference between the local and received codes is determined by comparing the correlator output with two reference levels, which are chosen to categorize the correlation status into 3 states. In the presence of noise, the probability of making the correct decision depends on the noise level, the integration time, and the difference between the reference levels and the nominal correlator output. Since the reference levels are fixed, the

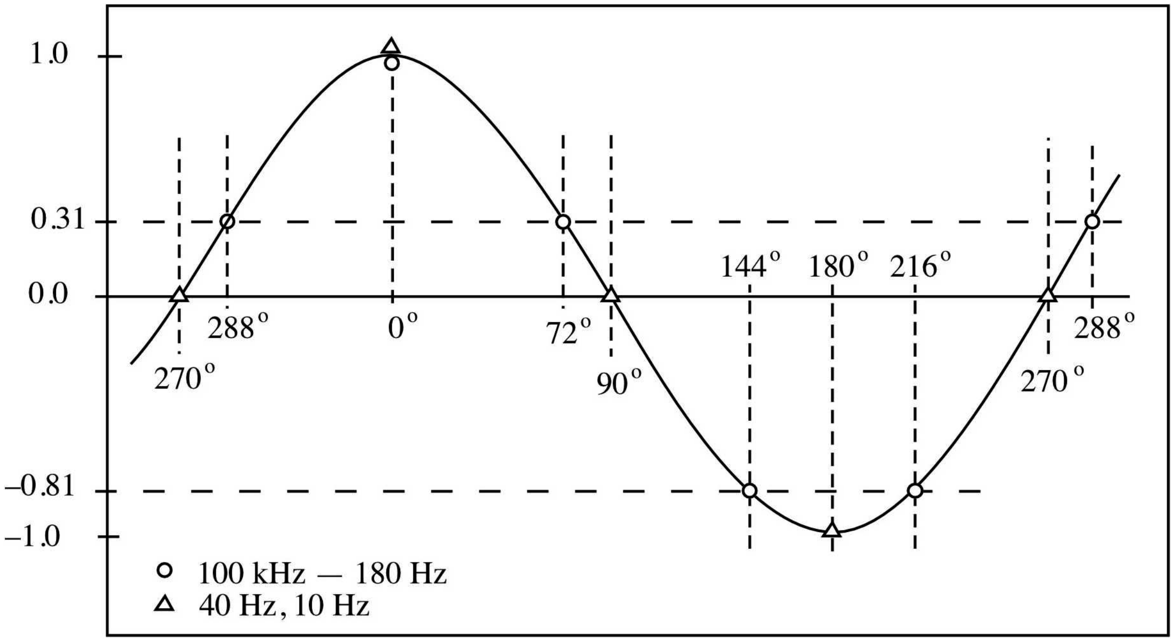


Figure 5. Normalized Correlator Output

integration time must be increased as the signal to noise level decreases. Table 8 lists actual minor tone integration times. These times are for a single integration of a single tone. To complete the minor tone acquisition, it is necessary to perform at least two but no more than three integrations for each tone on as many as seven tones.

Table 8. Minor Tone Integration Times

| **Minor Tone** | **Acquisition Mode** | | |
|---|---|---|---|
| | **Fast** | **Medium** | **Slow** |
| 160 Hz, 40 Hz, 10 Hz | 100 ms | 100 ms | 800 ms |
| 100 kHz – 800 Hz | 10 ms | 50 ms | 800 ms |

The synchronization process for the pseudo-random ARC is similar to that used for the minor tones and consists of:

a) Correlation (phase comparison) of the local ARC with the received ARC.

b) Deciding if the ARC is matched.

c) Correction of phase error by delaying the local ARC by 16-bit positions.

d) Repetition of steps (a) through (c) until (b) is satisfied.

An 800-ms integration time is used for all signal levels and a maximum of 42 integrations will be required if the spacecraft is at the maximum range of 644,000 km.

## *7.5 Acquisition Time Summary*

The three steps required to achieve range data acquisition (that is, AGC, MRT phase acquisition, and ambiguity resolution) have been described. Table 9 is a summary of the total time required to perform these three steps for the minimum permissible Range Tone to Noise Spectral Density ratio (S/ø, dB-Hz) in each acquisition mode. The propagation delay times (which depend on range and the round-trip propagation time) are approximately 2.47 seconds. Since there may be as many as eight range tones plus the ARC transmitted sequentially, the total time lost due to propagation would be about 22.3 seconds.

Table 9: Total Acquisition Time Summary

| **Phase** | **Time (s)** | | |
|---|---|---|---|
| | **Fast**<br>**s/ ø = 50 dB-Hz** | **Medium**<br>**s/ ø = 30 dB-Hz** | **Slow**<br>**s/ ø = 12 dB-Hz** |
| AGC Allocation | 1.4 | 6.1 | 21.5 |
| MRT Phase Lock Loop Acquisition | 1.0 | 8.0 | 32.0 |
| Ambiguity Resolution | 1.8 | 9.5 | 50.4 |
| Total Acquisition Time | 3.2 | 15.6 | 71.9 |

In developing Table 9, the worst-case scenario for acquisition of the minor range tones has been assumed. That is, three correlation and correction cycles are required for each tone, and that all seven tones must be acquired. For the strong signal case, the range is assumed to be within the 10-Hz ambiguity range, and only one ARC correlation is required to confirm that fact. For the medium signal strength, it is assumed that the ARC can be preset so that, at most, 10 correlation and correction cycles are required. For the weak signal case, no preset knowledge is assumed, and 42 correlation and correction cycles are required.

## 7.6 Range Resolution

The range resolution is set by the number of increments per cycle used in measuring the phase delay of the major range tone and can be calculated by the following expression:

$$\Delta R = \frac{c}{2Mf_m} \tag{5}$$

where:

$\Delta R$ = resolution (increment size in m)

c = speed of light ≈ ($3 \times 10^8$ m/s)

$M$ = number of delay increments per cycle

$f_m$ = measurement frequency.

As the phase measurement is always made at 500 kHz (independent of the MRT frequency) and there are 2000 phase measurement increments per cycle,

$$\Delta R \approx \frac{3 \times 10^8}{2 \cdot 2 \times 10^3 \cdot 5 \times 10^5} = 0.15\text{m}. \tag{6}$$

## 7.7 Range Accuracy

Range accuracy is limited by systematic and random errors associated with the measurement of the MRT phase and the effect of receiver input thermal noise. Figure 6 depicts range accuracy for each major tone as a function of S/ø for each of the two possible final tracking bandwidths. This figure does not include calibration errors or the effects of other equipment (such as the exciter, transmitter, and receiver) in the ranging signal path.

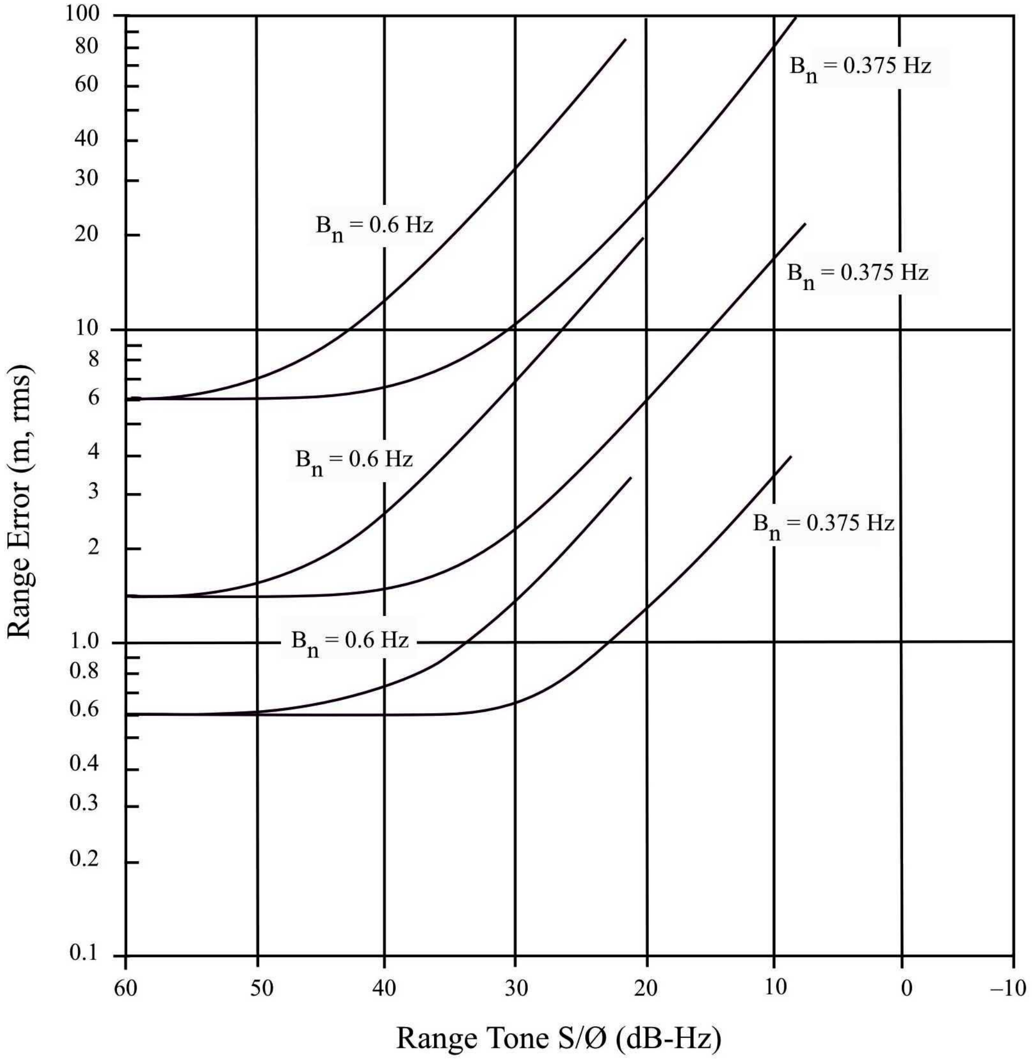


Figure 6. Range Accuracy for Major Tones