TRACKING AND DATA RELAY SATELLITE SYSTEM

(TDRSS)

RANGE AND DOPPLER TRACKING SYSTEM

OBSERVATION MEASUREMENT AND MODELING

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ABSTRACT

This document gives detailed descriptions of the tracking services, signal generation and processing, range and Doppler extraction, and the principles and procedures involved in modeling range and Doppler observations via the Tracking and Data Relay Satellite System (TDRSS). Major topics discussed include the following:

- TDRSS telecommunication services.
- Functional description of the TDRSS.
- Tracking signal generation and processing.
- Range and Doppler observations modeling.
- Angular observed and computed measurement algorithms.
- Tracking data transmission format.

PREFACE

The purpose of this document is to describe all those aspects of the Tracking and Data Relay Satellite System (TDRSS) which relate to tracking and orbit determination. Signal generation and processing, range and Doppler extraction, signal path modeling, and the observed and computed measurements used for tracking via the TDRSS are traced and related to the specific components of the system.

Section 1 presents a general description of the telecommunication services of the TDRSS, and its relationship to the 1980's Spaceflight Tracking and Data Network (STDN).

Section 2 presents functional descriptions of the two major subsystems of the TDRSS: White Sands Ground Terminal, ground segment, and the Tracking and Data Relay Satellite (TDRS), space segment. The discussion includes TDRS transponder frequency analysis, forward and return signal designs, and user acquisition. These materials provide the necessary background for the development in section 3.

Section 3 provides detailed descriptions of tracking signal generation and processing through the TDRSS for closed- and open-loop tracking configurations. It is intended that this discussion provide the levels of analysis necessary to pinpoint each specific parameter as related to tracking measurements and the signal path modeling algorithms presented in section 4.

A discussion of the mathematical modeling of the tracking signal and the associated algorithms used in the tracking and orbit determination process are presented in section 4. This section should serve to bridge the gaps between TDRSS hardware specifics and the software used for orbit determination.

Section 5 discusses the observed and computed angular measurements of the TDRS space-to-space antennas.

The TDRSS tracking data format is presented in section 6; this material is included to make the document more complete by relating specific parameters to the observations discussed in previous sections.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Tommy A. Williams, Diane N. Miller, and Richard E. Campion of Bendix Field Engineering Corporation (BFEC), and Donald J. Cowan of Code 872 for the considerable assistance and valuable and constructive criticism rendered; to Irving M. Salzberg, Acting Head of Operational Orbit Support Branch, for continuous interest and support; to Kathleen C. Hendry and David M. Rechenbach of BFEC for their professional and careful editing; and to Charlotte R. Selby of BFEC for an excellent typing job.

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SECTION 1. INTRODUCTION

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1.1 A BRIEF DESCRIPTION OF THE TDRSS

1.1.1 GENERAL

1.1.1.1 The Tracking and Data Relay Satellite System (TDRSS) is a satellite communication signal relay system intended to provide telecommunication services between Earth-orbiting spacecraft and NASA user control and/or data processing facilities. The system will be capable of transmitting data to and receiving data from user spacecraft, and tracking user spacecraft over at least 85 percent of the user's orbit (reference 1).

1.1.1.2 The TDRSS is designed as part of the Shared Service Tracking and Data Relay Satellites System (SSTDRSS), which consists of four in-orbit satellites: two satellites serve TDRSS, one is assigned to Advanced Westar (AW) for domestic commercial satellite operation, and the fourth is an in-orbit spare shared by TDRSS and AW. All four satellites are identical and have the capability to support either mission, but, except for the shared spare, normally are dedicated to either TDRSS or AW operation. The configuration of the SSTDRSS is shown in figure 1-1.

1.1.1.3 The TDRSS will consist initially of two geosynchronous satellites, East and West, situated approximately 130 degrees apart at 41° W and 171° W longitude, respectively. A single-site TDRSS ground terminal is located at White Sands, New Mexico (WSGT). An in-orbit spare will be provided approximately 6 months later, as a replacement or as a supplement to the other two for special purposes (such as launch, maneuver support, peak loading, etc.). The TDRSS configuration and coverage limits are shown in figure 1-2.

1.1.1.4 The Tracking and Data Relay Satellite (TDRS) operates as a repeater, relaying signals to and from WSGT and user spacecraft. No signal processing is done on the TDRS except coherent frequency translation and Radio Frequency Interference (RFI) modification. All TDRS control functions not adversely affected by the 270-msec two-way transmission delay in addition to the ground segment processing delays have been implemented at WSGT. Functions implemented at WSGT include mode and redundancy control of satellite communications equipment, gain and power level control of all channels, antenna pointing, K-band autotrack, and acquisition search (reference 1).

1.1.2 TDRS ANTENNA SYSTEMS

1.1.2.1 General. Each TDRS will be equipped with seven antenna systems (see figure 1-3) to accommodate TDRSS and AW communication link requirements (references 2, 3, and 4).

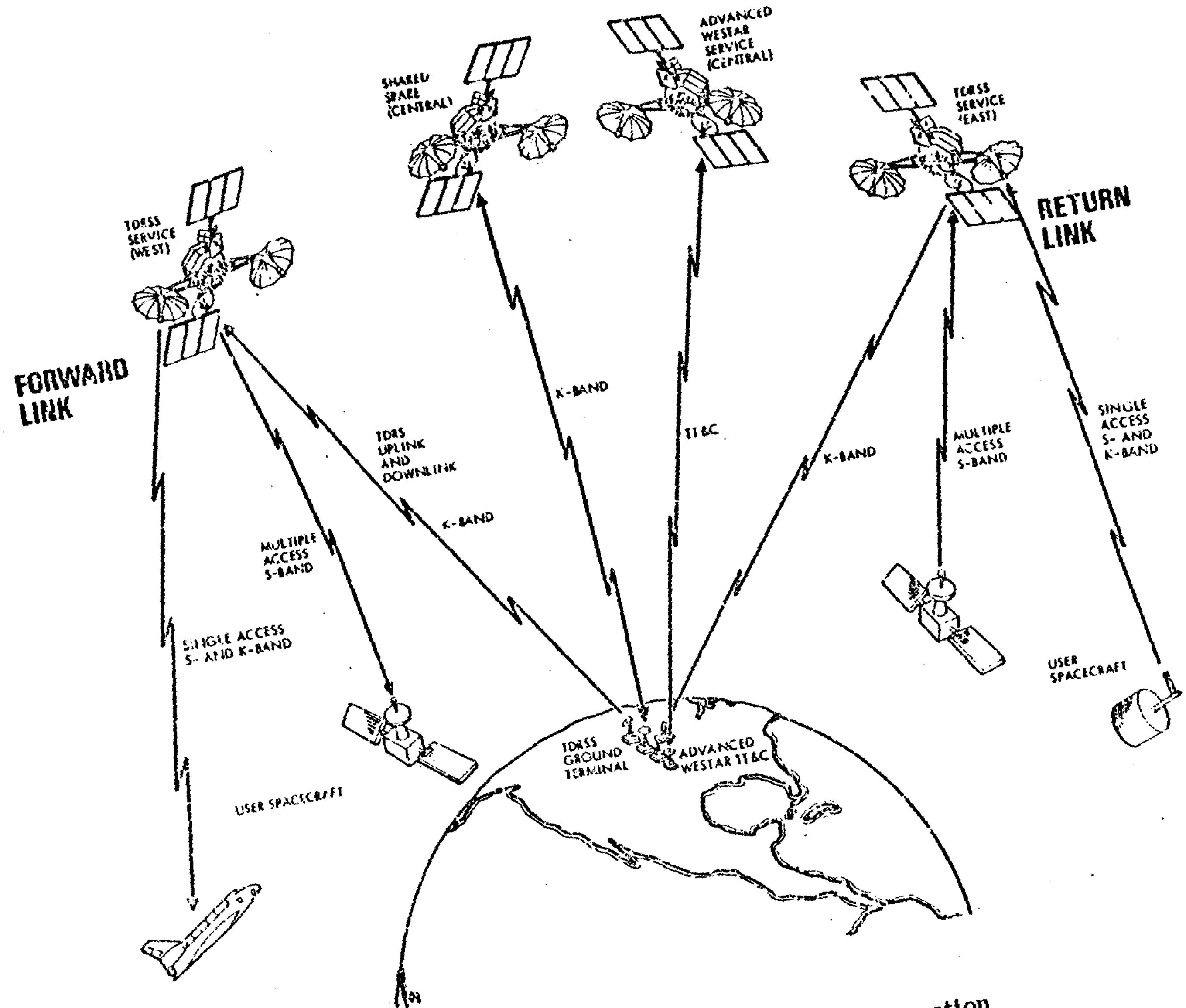

Figure 1-1. Shared Service TDRSS Configuration

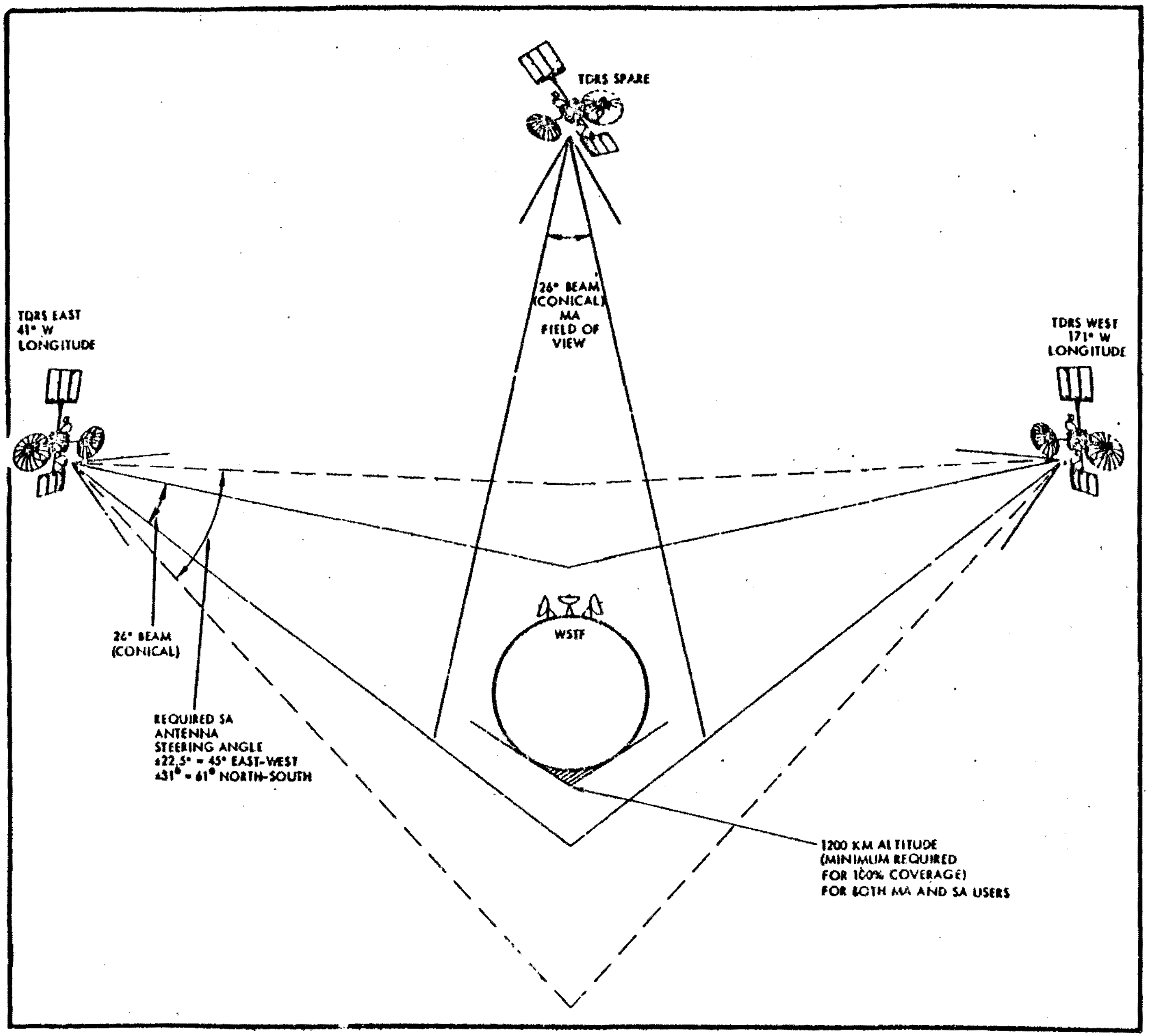

Figure 1-2. TDRSS Configuration and Coverage Limits

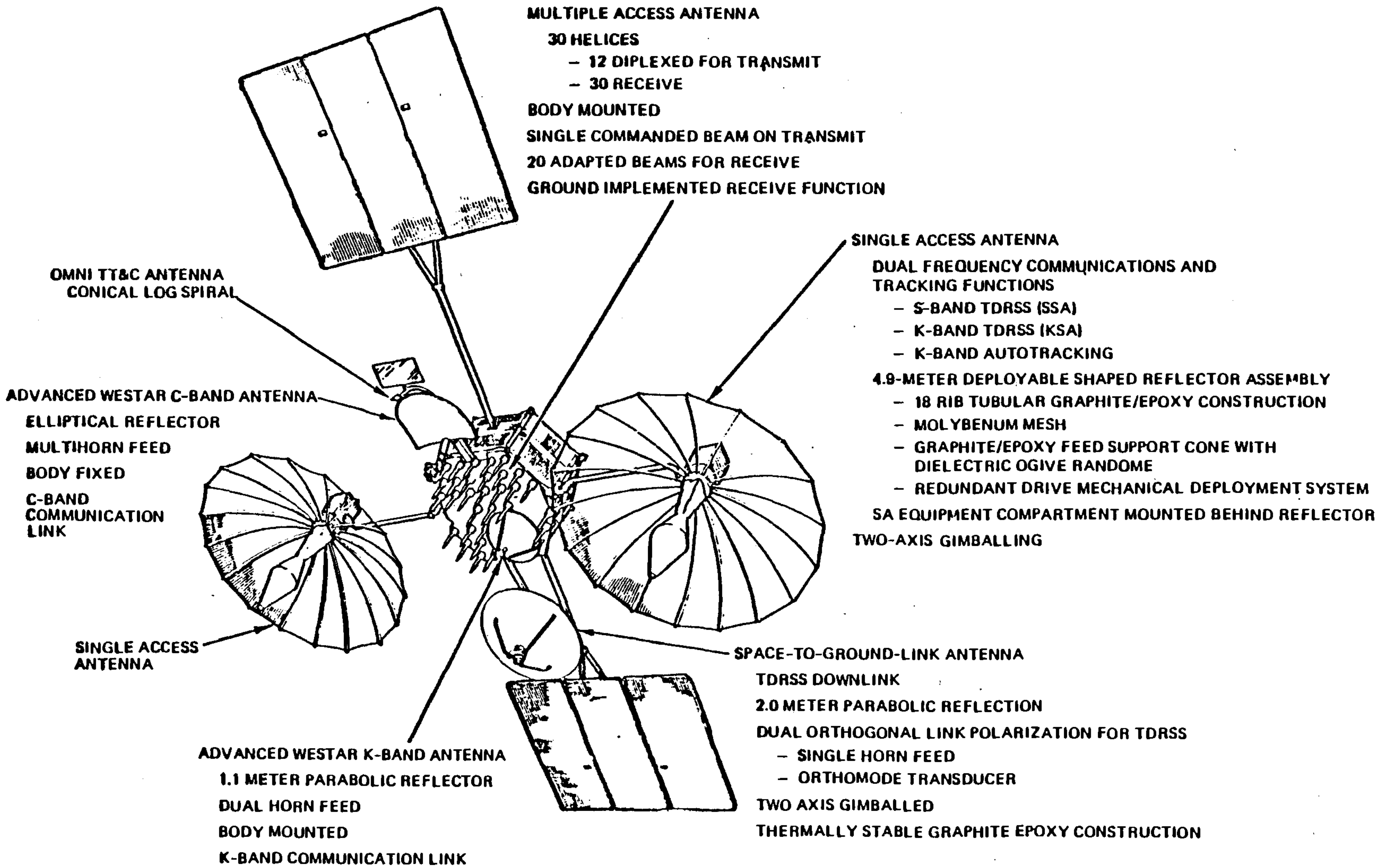

Figure 1-3 TDRS Antenna Equipment

1.1.2.2 Single-access Antenna. Single-access (SA) communications service is provided by two 4.9-meter, dual-feed, S- and K-band space-to-space parabolic antennas. Each SA antenna has an S-band focal point feed and a K-band Cassegrain feed with a dichroic subreflector which is transparent at S-band frequencies and reflective at K-band frequencies. The five-horn Cassegrain feed provides K-band autotrack capability. The SA antennas are open-loop pointed by ground command for S-band service, and are autotrack pointed for K-band.

1.1.2.3 Multiple-access Antenna. Multiple-access (MA) communications service is provided by a 30-element, S-band, phased array, space-to-space antenna system, including 12 diplexed elements for transmitting and receiving. The MA elements are body mounted. On transmit (forward link) the system generates a single electronically steered transmission beam. The beam is steered by adjusting the phase settings in each of the 12 transmit elements via ground command. On receive (return link) the system functions by transponding the composite signal received from all users at each of the 30 elements onto 30 separate downlink channels. The multiple received beams (one per user) are synthesized in the Ground Implemented Phased Array (GIPA) at WSGT.

1.1.2.4 Space-to-Ground-Link Antenna. A 2.0-meter K-band Space-to-Ground-Link (SGL) parabolic antenna serves as the prime link for relay of transmissions, including K-band Telemetry, Tracking, and Command (TTC), to and from WSGT during normal operations. The SGL antenna provides a high-gain beam and allows simultaneous operation of the transmit (13.4 to 14.05 GHz) and receive (14.6 to 15.25 GHz) functions. The uplink signal is received with vertical linear polarization. The downlink signal is transmitted with dual orthogonal linear polarization: vertical linear polarization for the dedicated KSA channel, and horizontal linear polarization for the composite channel. The SGL antenna is open-loop pointed toward WSGT by ground command.

1.1.2.5 Omni TTC Antenna. A TTC S-band omni-directional antenna is used to provide the primary TDRS-WSGT-GSTDN link from liftoff through initiation of K-band operation of the SGL on orbit. This system also serves as backup for the K-band TTC.

Note

> Due to insufficient gain, ranging via the S-band TTC from WSGT is not possible. TDRS will be tracked by GSTDN prior to initiation of K-band TTC.

1.1.2.6 Advanced Westar Antennas. A C-band elliptical and a K-band parabolic antenna provide the communications links for Advanced Westar operations.

1.1.3 TDRSS USER COVERAGE

1.1.3.1 The TDRSS provides near global real-time user-satellite coverage. The minimum average coverage is 85 percent for users at orbital altitudes greater than 200 km. TDRSS low-altitude coverage is limited by Earth shadow (see figure 1-2). High-altitude coverage is limited by the Fields of View (FOV) of the TDRS antennas (see figure 1-4). Coverage for the MA users is the ±13 degree conical FOV of the TDRS MA antenna. For SA users, the high-altitude user coverage constraint is the SA antenna gimbal angle pointing range, which is specified as ±22.5 degrees east-west and ±31.0 degrees north-south (references 1 and 5).

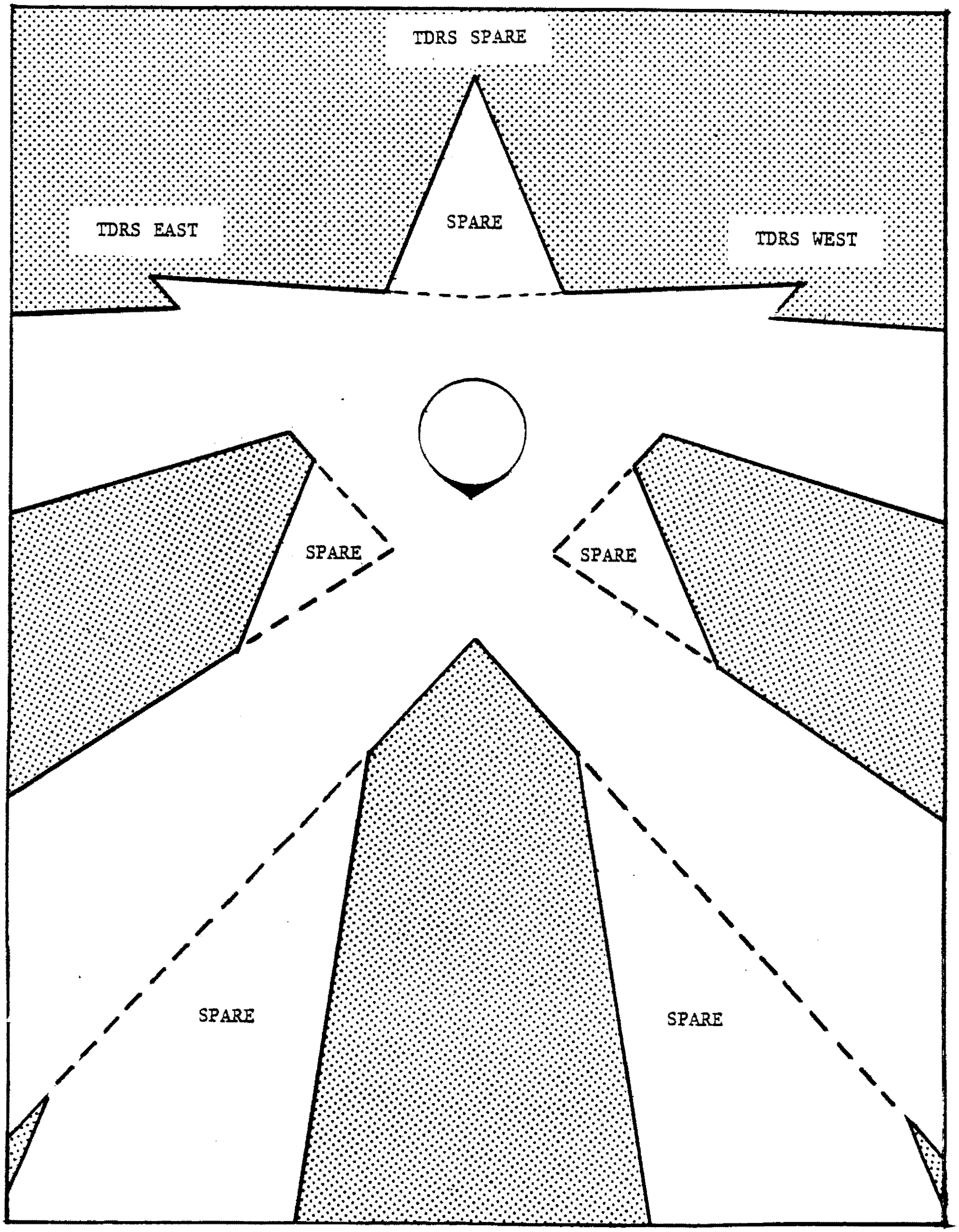

Figure 1-4. TDRSS Extended Visibility

1.1.3.2 User average coverage by the TDRSS, and the associated limiting factor, are summarized as follows:

a. MA Users

	Average Coverage	Altitude	Limiting Factor
(1)	85% (minimum)	200 km	Earth shadow
(2)	85% to 100%.	200 to 1200 km	Earth shadow
(3)	100%	1200 to 3200 km	None
(4)	Decreases <100%	>3200 km	FOV of MA antenna

b. SA Users

	Average Coverage	Altitude	Limiting Factor
(1)	85% (minimum)	200 km	Earth shadow
(2)	85% to 100%	200 to 1200 km	Earth shadow
(3)	100%	1200 to 9700 km	None
(4)	Decreases <100%	>9700 km	FOV of SA antenna

1.2 POST-1980 SPACEFLIGHT TRACKING AND DATA NETWORK

1.2.1 In the post-1980 era, TDRSS will be incorporated into the Spaceflight Tracking and Data Network (STDN). The primary STDN ground elements will be reduced and will consist of Goldstone, California (GDS); Madrid, Spain (MAD); Orroral, Australia (ORR); Fairbanks, Alaska (ULA); and Network Testing and Training Facility (NTTF) at Greenbelt, Maryland. Launch support facilities will be located at Merritt Island, Florida (MIL) and Bermuda (BDA). Data communications and tracking support for S- and K-band user spacecraft with orbital altitudes below 12,000 km will be provided primarily by the TDRSS. The ground stations will support higher altitude, high elliptical, synchronous, and deep-space mission spacecraft. ULA will support existing Earth-orbiting spacecraft not compatible with TDRSS and will be phased out circa 1984. The NTTF will provide additional support capability for special user spacecraft (references 3 and 5).

1.2.2 The primary difference of the post-1980 STDN will be in the change of telecommunication services from the existing store and forward concept to a real-time, throughput concept as shown in figure 1-5. Utilization of the post-1980 STDN in support of low-altitude spacecraft will no longer be restricted to short and infrequent periods of spacecraft - STDN mutual visibility. With the advent of TDRSS, increased orbital coverage will be realized. Figures 1-6 and 1-7 show the post-1980 STDN orbital average at 200 and 5000 km, respectively (references 3 and 5).

1.3 A SUMMARY OF THE TDRSS TELECOMMUNICATION SERVICES

1.3.1 GENERAL

The TDRSS will provide tracking and communication support to three classes of user spacecraft: MA users, K-band and S-band SA (KSA and SSA) users. Up to 19 MA, 6 KSA, and 6 SSA users can be supported by the TDRSS simultaneously. References 1 and 5.)

1.3.2 MULTIPLE-ACCESS SERVICES

MA services will provide simultaneous real-time and dedicated return link service to user spacecrafts with real-time data rates up to 50 kbps. Due to ground equipment limitation, return link support can be provided to 20 MA services (1 for calibration and 19 for MA users). Forward link service is time-shared with a maximum data rate of 10 kbps and supports one user per TDRS at a time. All MA user spacecraft will operate at the same frequency and polarization. Discrimination is made by user-unique PN code assignment, MA antenna beam pointing, and predicted return Doppler for signal demodulation.

1.3.3 SINGLE-ACCESS SERVICES

1.3.3.1 Each TDRS will be capable of supporting two K-band SA user spacecraft via the KSA-1 and KSA-2 services on the forward and return links. The two KSA links will be operated at fixed frequencies and will be discriminated by polarization, user-unique PN code assignment, SA antenna beam pointing, and predicted return Doppler for signal demodulation.

1.3.3.2 Each TDRS will be capable of supporting two S-band SA user spacecraft via the SSA-1 and SSA-2 services on the forward and return links. The two SSA links will be tunable within the allowed forward and return frequency spectrums. The SSA user spacecraft will be discriminated by frequency, user-unique PN code assignment, SA antenna beam pointing, and predicted return Doppler for signal demodulation.

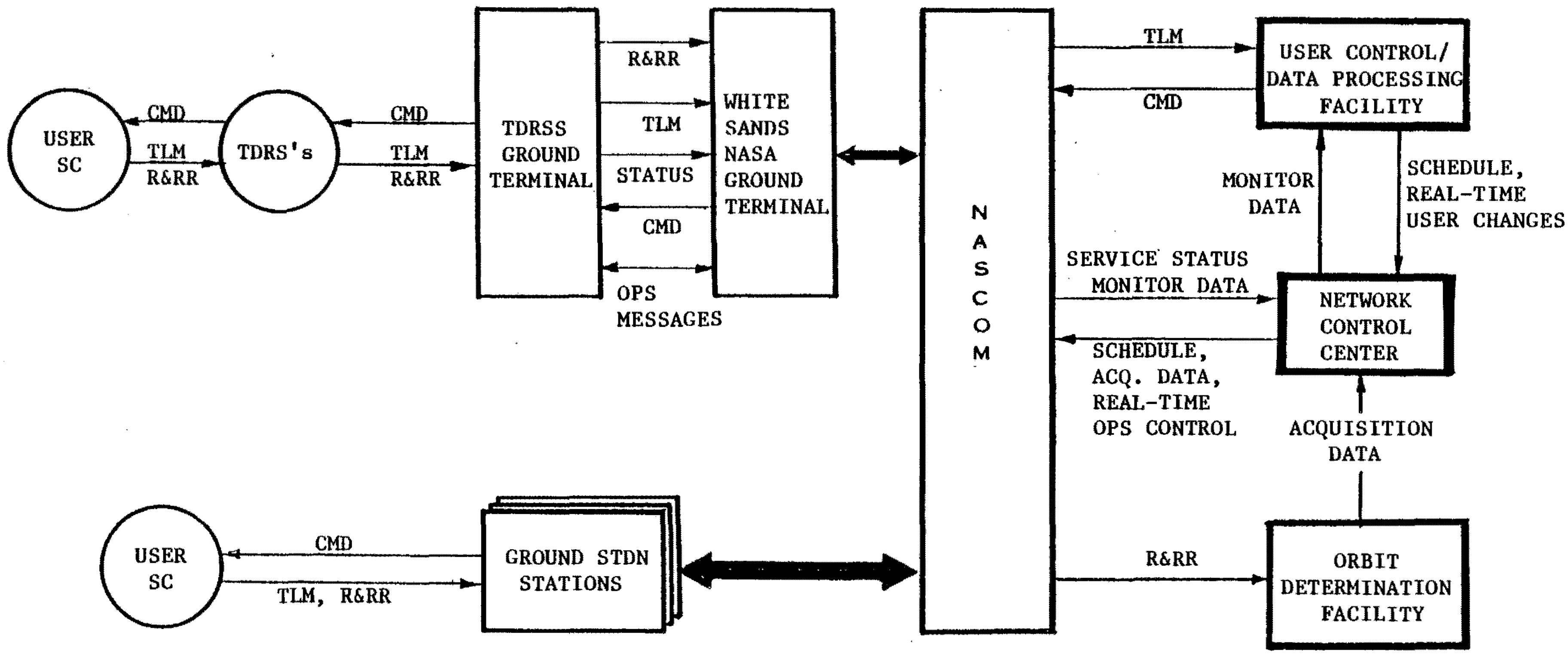

Figure 1-5. STDN Interfaces and Data Flow

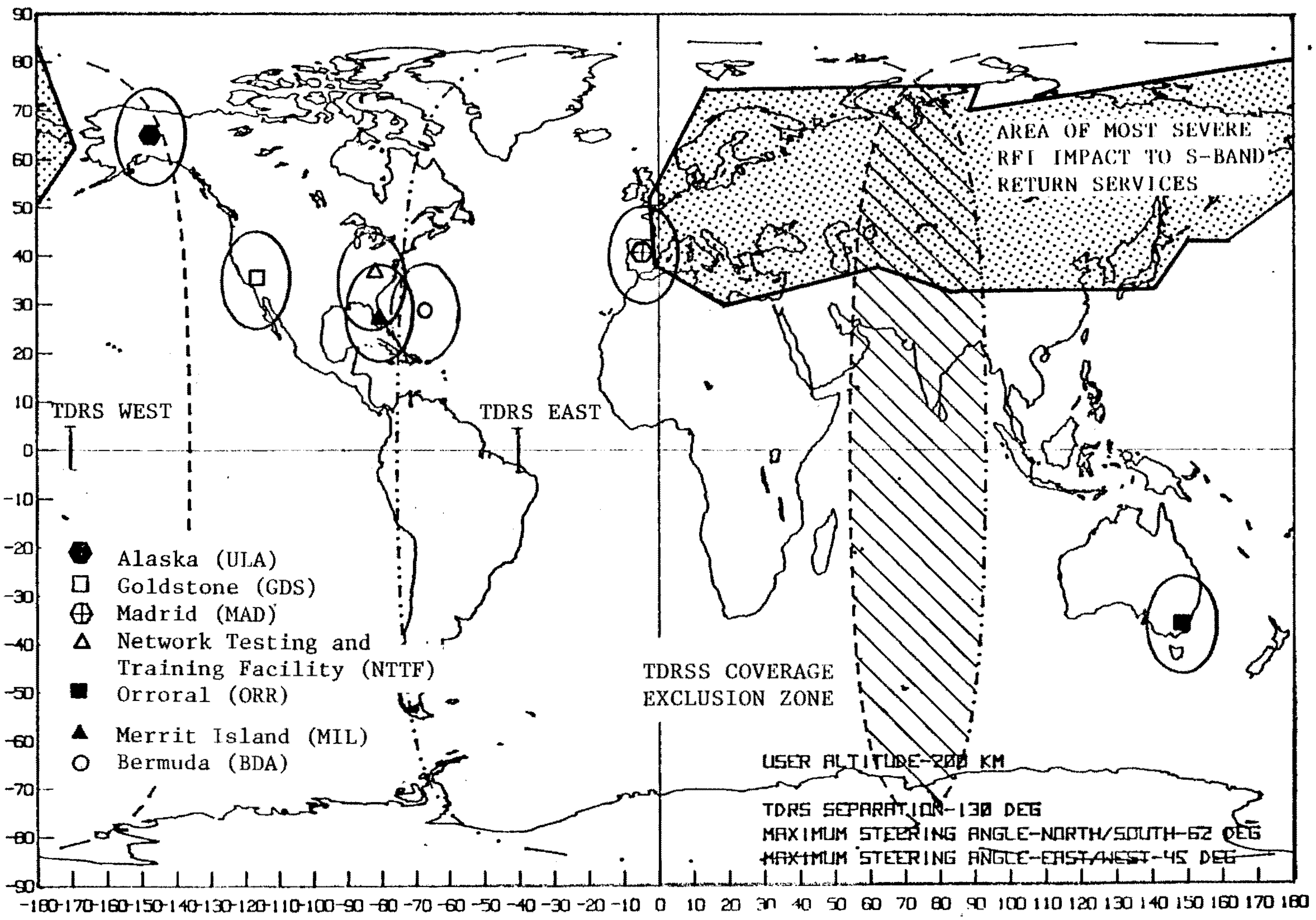

Figure 1-6. Post-1980 STDN Orbital Coverage at 200-km Altitude

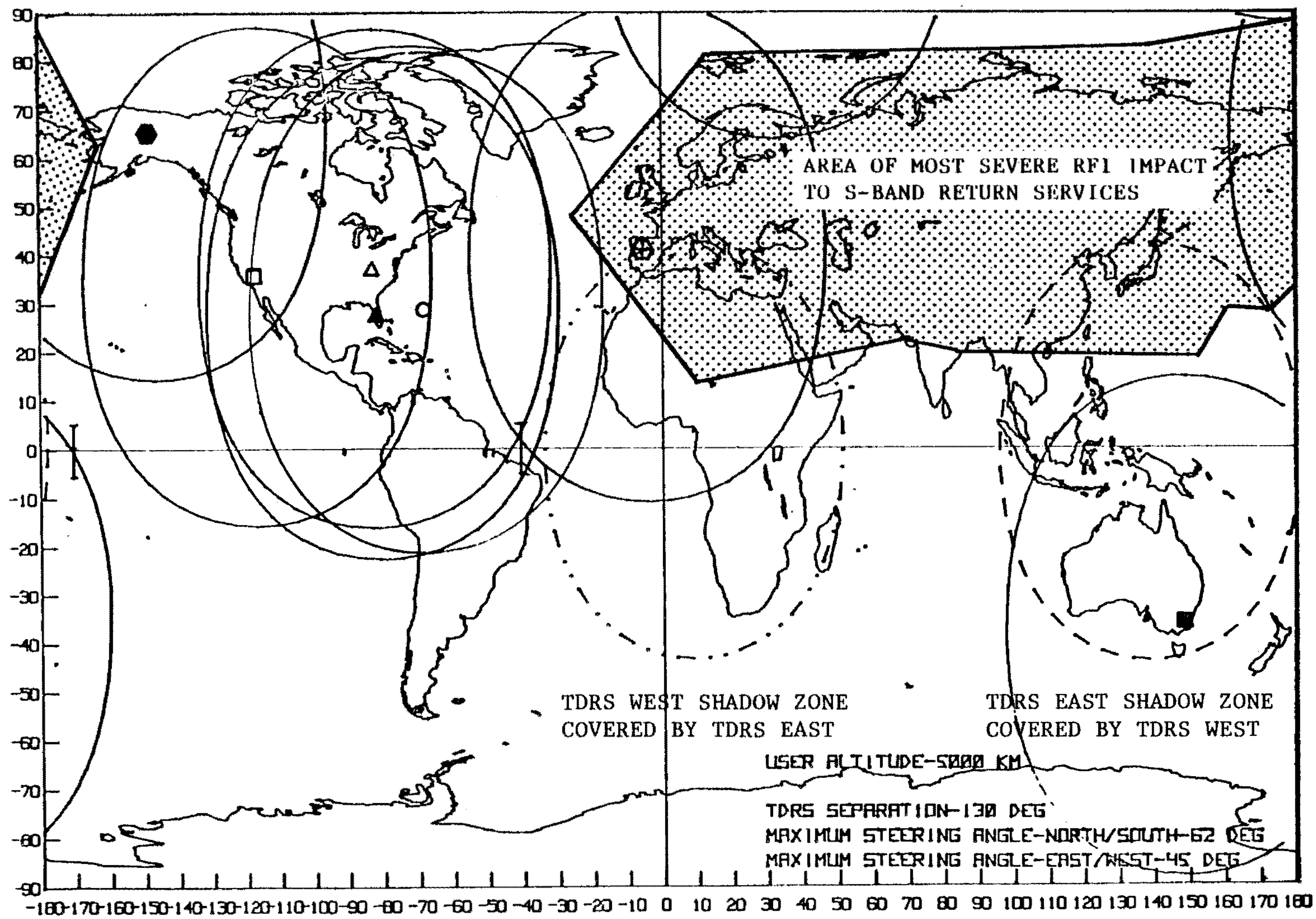

Figure 1-7. Post-1980 STDN Orbital Coverage at 5000-km Altitude

1.3.3.3 Up to two S- and K-band Shuttle services can be substituted for normal SSA or KSA services, respectively. The SA services will provide high data rate return link with real-time, playback, or science data requirements up to 300 Mbps for KSA and 3.15 Mbps for SSA. The SA services will be utilized on a priority scheduled basis and normally will not be used for dedicated support to any mission other than Shuttle.

1.3.4 CROSS-SUPPORT SERVICES

Any mission which is compatible with the MA service can receive forward or return link support from either the MA or SSA services. The maximum return data rate of 1.5 Mbps is available to MA users supported by a SSA return link service. Continuous MA support of a real-time return link and periodic SSA support of a high data rate experiment is a viable support mode for these services (reference 5).

1.3.5 TRACKING SERVICES

Services described in para 1.3.2, 1.3.3, and 1.3.4 can provide range and/or Doppler tracking data for each user spacecraft supported. The range measurement is obtained from the time delay between the transmitted and received Pseudonoise (PN) code. The Doppler measurement is obtained from the frequency shift of the reconstructed carrier (reference 5). Tables 1-1 through 1-5 summarize the TDRSS telecommunication capability and service characteristics of the MA, SSA, and KSA services (references 4 and 5).

Table 1-1. TDRSS Telecommunication Service Capability

Service	MA	SSA	KSA
Number of forward links/TDRS	1	2	2
Total forward links of TDRSS (3)	3	6	6
Number of return links/TDRS	19 ①	2	2
Total return links of TDRSS (3) ②	19 ①	6	6

Tracking Service	Per TDRS	Total for TDRSS
One-way Doppler	10 ③	10 ③
Two-way Range and Doppler (MA)	1	3
Two-way Range and Doppler (SA)	4	6 ③

① Limited by the receiver configuration at WSGT.
② There is a total of 32 return channels available at WSGT (20 for MA and 12 for SA).
③ Limited by the range and Doppler equipment at WSGT.

Table 1-2. Multiple-access (MA) Service Characteristics

FORWARD LINKS (From TDRS to user spacecraft)	
Nominal center transmit frequency	2106.41 MHz
Signal bandwidth	6 MHz
Antenna element gain	13 dB
Number of antenna elements	12
Transmit power	3.5 watts/element
Signal EIRP	+34 dBW min (normal power mode)
Polarization	LHC
Axial ratio (maximum)	1.5 dB over 3-dB beamwidth
Antenna beamwidth	~5° x 8° elliptical (3 dB)
Beam steering angle	±13 degree, conical
Transmit CNR	>10 dB in 5-MHz bandwidth
Spurious outputs	≤ -30 dB/MHz
RETURN LINKS (From user spacecraft to TDRS)	
Nominal center receive frequency	2287.5 MHz
Signal bandwidth	5 MHz
Antenna element gain	13 dB
Number of antenna elements	30
Receive	18
Transmit/Receive	12
Element gain-to-noise temperature ratio	-14.7 dB/°K (50° K antenna temperature)
Antenna beamwidth	~3° (3 dB)
Antenna beam coverage angle	± 13 degree, conical
Polarization	LHC
Axial ratio (maximum)	1.5 dB over 3-dB beamwidth

Table 1-3. S-band Single-access (SSA) Service Characteristics

FORWARD LINKS (From TDRS to user spacecraft)	
Nominal center transmit frequency	Selectable from 2030.435 to 2113.315 MHz (including Doppler effects up to ±0.110 MHz, maximum)
Signal bandwidth	20 MHz
Antenna gain	36 dB
Transmit power	26 watts
Signal EIRP	
Normal power mode	+43.5 dBW, minimum
High power mode	+46.0 dBW, minimum
EIRP adjustment	36.4 to 46.0 dBW by ground command
Polarization	LHC or RHC (command selectable)
Axial ratio (maximum)	1 dB over 3-dB antenna beamwidth
Antenna beamwidth	≃1.8 degrees (3 dB)
Antenna pointing	Adjustable over ±22.5 degrees east-west and ±31 degrees north-south in 0.02-degree increments, by ground command
Transmit CNR	>10 dB in 20-MHz bandwidth
Spurious output	≤ -30 dB/MHz
RETURN LINKS (From user spacecraft to TDRS)	
Nominal center receive frequency	Selectable from 2200 to 2295 MHz (including Doppler effects up to ±0.240 MHz maximum)
Signal bandwidth	10 MHz
Antenna gain	37 dB
Gain-to-noise temperature ratio	8.9 dB/°K (270°K antenna temperature)
Polarization	Same as forward channel
Axial ratio (maximum)	1 dB over 3-dB beamwidth
Antenna beamwidth	≃1.8 degrees (3 dB)
Antenna pointing	Same as forward channel

Table 1-4. K-band Single-access (KSA) Service Characteristics

FORWARD LINKS (From TDRS to user spacecraft)	
Nominal center transmit frequency	13,775 MHz
Signal bandwidth	50 MHz
Antenna gain	53 dB
Transmit power	1.5 watts
Sign-1 EIRP	
Normal power mode	+46.5 dBW minimum
High power mode	+48.5 dBW minimum
Acquisition mode	+40.0 dBW minimum
EIRP adjustment	Adjustable from +39.4 to 49.4 dBW (by ground command)
Polarization	LHC or RHC (command selectable)
Axial ratio (maximum)	1 dB over 3-dB beamwidth
Antenna beamwidth	$\simeq$0.27 degree (3 dB)
Antenna pointing	Adjustable over ±22.5 degrees east-west and ±31 degrees north-south in 0.02-degree increments, by ground command
RETURN LINKS (From user spacecraft to TDRS)	
Nominal center receive frequency	15,003.4 MHz
Signal bandwidth	225 MHz
Antenna gain	54 dB
Gain-to-noise temperature ratio	24.4 dB/°K (253°K antenna temperature)
Polarization	Same as forward channel
Axial ratio (maximum)	1 dB over 3-dB beamwidth
Antenna beamwidth	$\simeq$0.25 degree (3 dB)
Antenna pointing	Same as forward channel

Table 1-5. Space-to-Ground Link Characteristics

UPLINK (From WSGT to TDRS)	
TDRS receive center frequencies	
MA	14,826.4 MHz
SSA-1	14,679.5 MHz
SSA-2	14,719.5 MHz
KSA-1	14,625.0 MHz
KSA-2	15,200.0 MHz
Command	14,785.9625 MHz
Pilot	15,150.0 MHz
Bandwidth	625 MHz
Antenna gain	>44.5 dB
Gain-to-noise temperature ratio	> 9.0 dB (253 degree antenna temperature)
Polarization	Linear
Antenna beamwidth	0.68 degree (3 dB)
Antenna pointing	Adjustable over a ±30 degree conical angle in 0.02-degree increments by ground command

DOWNLINK (From TDRS to WSGT)	
TDRS transmit center frequencies	
Composite channel	
MA	13,513.75 MHz
SSA-1	13,677.5 MHz
SSA-2	13,697.5 MHz
KSA-2 or 1	13,928.4 MHz
Telemetry	13,731.0 MHz
Dedicated KSA channel	
KSA-1 or 2	13,528.40 MHz
Bandwidth	
Composite channel	650 MHz
Dedicated channel	225 MHz
Antenna gain	>44 dB
Available transmitter power	>18 watts/channel (saturated)

Table 1-5. Space-to-Ground Link Characteristics (cont)

Signal EIRP (for maximum input signal level)	
Composite channel	
MA	43.4 dBW (total)
SSA	39.9 dBW (each)
KSA-1 or 2	47.4 dBW
Telemetry	25.7 dBW
Dedicated channel	
KSA-1 or 2	50.8 dBW
Polarization	
Composite channel	Linear
Dedicated channel	Linear
Polarization isolation	28 dB
Antenna beamwidth	0.7 degree (3 dB)
Antenna pointing	Same as ground-to-TDRS link

SECTION 2. FUNCTIONAL DESCRIPTION OF THE TDRSS

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2.1 WHITE SANDS GROUND TERMINAL

2.1.1 GENERAL

The mission of TDRSS is to provide for the flow of data between NASA and user spacecraft. The White Sands Ground Terminal (WSGT) supports this mission by providing traffic carrying ground equipment and associated services between the NASCOM user traffic interface and the orbiting TDRS's. The WSGT transmits and receives user spacecraft forward and return traffic; provides tracking services for user spacecraft; and provides Telemetry, Tracking, and Command (TTC) services for on-orbit TDRS's. (Reference 6.)

2.1.2 WSGT FUNCTIONS

2.1.2.1 In support of TDRSS, the WSGT performs the following major functions:

a. Transmit user forward link traffic (as received from the NASCOM interface) to each TDRS for subsequent transmission to designated user spacecraft. The WSGT can simultaneously support three MA, six SSA, and six KSA forward services. A maximum of two S-band and K-band Shuttle services can be substituted for normal SSA or KSA services, respectively.

b. Receive and process user spacecraft return traffic from each TDRS. The WSGT can receive and process up to 19 MA, 6 SSA, and 6 KSA user spacecraft return signals simultaneously. A maximum of two S-band and K-band Shuttle return services can be substituted for normal SSA or KSA return services, respectively.

c. Measure the range and Doppler for up to 9 closed-loop tracking services (two-way and hybrid), and measure Doppler for up to 10 open-loop tracking services (one way), and transmit the measurements to the NASCOM interface.

d. Provide forward and return simulation and verification services. The WSGT can simulate up to 5 forward and return TDRSS services (one MA, one SSA, one SSA Shuttle, two KSA or one KSA and one KSA Shuttle) for the purposes of user spacecraft compatibility verification, TDRS calibration, and NASA data processing testing.

e. Configure and control WSGT and TDRSS. The WSGT receives mission assignments from NASA, configures and controls the ground segment and the TDRS's as necessary to perform the scheduled services, and reports system status to NASA.

2.1.2.2 The preceding functions are implemented by the following WSGT subsystems: an antenna subsystem, RF subsystem, data subsystem, software subsystem, TDRSS Operation Control Center (TOCC) subsystem, and simulation and verification test subsystem. The WSGT equipment is highly automated with manual override and/or manual control capability. The WSGT configuration is depicted in figure 2-1; a functional diagram of WSGT is presented in figure 2-2.

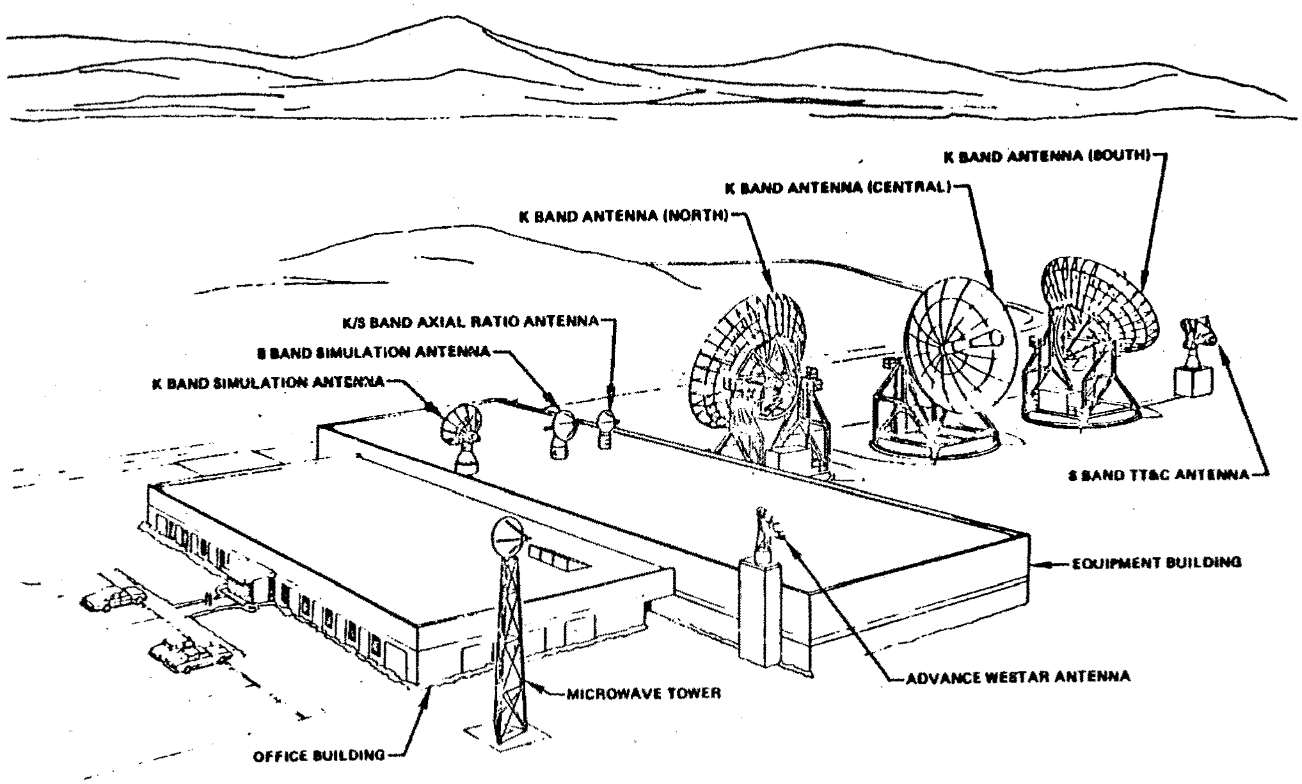


Figure 2-1. WSGT Configuration

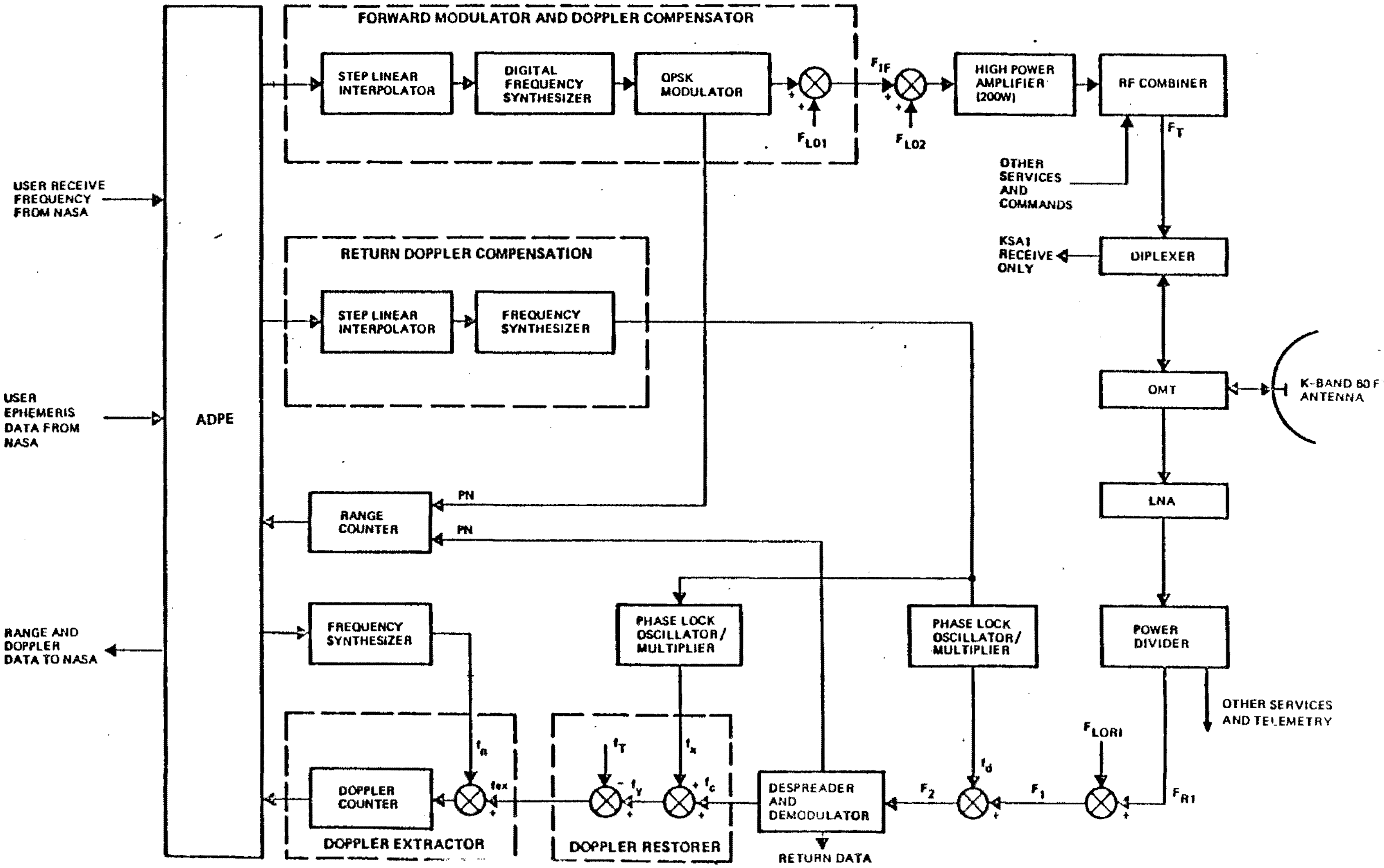


Figure 2-2. WSGT Functional Diagram

2.2 TDRS TRANSPONDER

2.2.1 GENERAL

2.2.1.1 TDRS is operated as a telecommunication signal relay station between WSGT and user spacecraft. No data processing, except coherent frequency translation and RFI modification, is involved during the relay process. The coherent frequency translation is provided by the TDRS transponder phase-locked circuitry which consists of the following:

a. Master Frequency Generator (MFG).
b. SSA Frequency Synthesizer (SSAFS).
c. MA Receiver Frequency Generator (MARFG).

Figure 2-3 is a simplified functional diagram of the TDRS transponder. (References 2 and 4.)

2.2.1.2 A composite uplink signal from WSGT is received by the TDRS via the 2-meter SGL K-band antenna. The signal is downconverted to IF, separated by the demultiplexer into different carrier signals, translated to forward frequencies spectrum via the forward processor, and then transmitted to user spacecraft by the S-band and K-band SA and MA antennas.

2.2.1.3 The return signals from user spacecraft are frequency translated by the return processor, combined by the multiplexer to form a composite signal, then upconverted and downlinked to WSGT. Two downlink channels are available: composite and dedicated. The dedicated channel is reserved for high data rate KSA return signals (either KSA-1 or KSA-2, selectable via ground command).

2.2.1.4 The forward and return KSA and the forward MA signals are translated by frequencies from the MFG. The return MA signals, from all MA user spacecraft, are simultaneously received by the 30-element phased-array antenna system and frequency translated via the MARFG. The forward and return SSA signals are frequency translated by the forward and return SSAFS, respectively. The SSAFS translation frequencies are selectable via ground command in steps of 0.5 MHz.

2.2.1.5 In the succeeding paragraph, the MFG, SSAFS, and MARFG are analyzed separately (only nominal center frequencies are considered, the effects of the Doppler shift will be derived in section 3). The results are then incorporated to give a detailed description of forward and return coherent frequency translations via the TDRS transponder.

2.2.2 MASTER FREQUENCY GENERATOR

2.2.2.1 General. The MFG provides coherent reference frequencies for downconversion, forward frequency translation, return frequency translation, and upconversion. The MFG also provides reference frequencies for all local oscillators on board the TDRS transponder. The frequencies range from 5 to 2800 MHz and are directly synthesized by a combination of frequency multiplication, division, and translation. The reference frequency for all frequency generation in the MFG is derived from a pilot tone (F_p), generated at WSGT from a 5-MHz cesium standard (Discipline Time Frequency Standard) and transmitted to the TDRS at 15150 MHz. The MFG consists of two subsystems: the MFG receiver and the MFG output section.

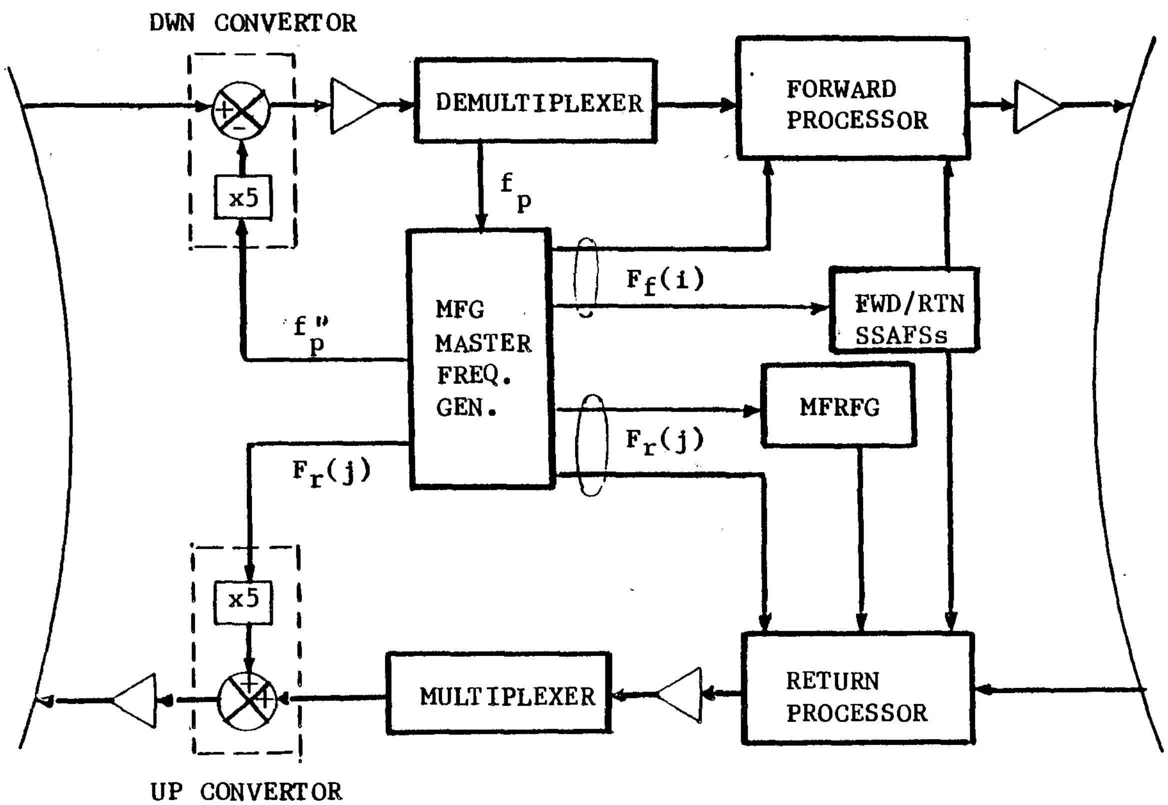
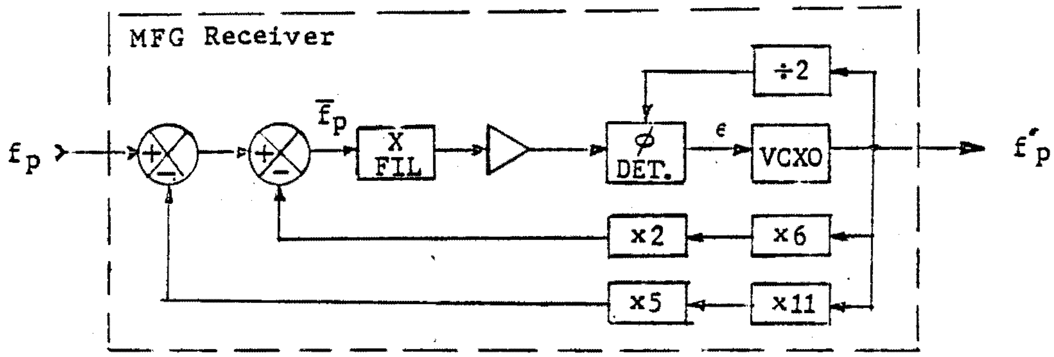


Figure 2-3. TDRS Transponder

2.2.2.2 The MFG Receiver

a. The MFG receiver contains phase-locked circuitry that locks to the IF pilot, f_p. Through a two-stage frequency translation, f_p is downconverted to $\bar{f}_p$. $\bar{f}_p$ is crystal filtered, amplified, and applied to a digital phase detector. The phase detector compares the phases of the reference $\bar{f}_p$ and the output f'_p of the Voltage-controlled Crystal Oscillator (VCXO). The phase difference is amplified, low-pass filtered, and applied as a phase error correction, ϵ, to the VCXO. The MFG receiver is schematically represented by the following diagram (references 2 and 4):



b. Under zero phase difference condition ($\epsilon = 0$), the frequency f'_p (input to the MFG output section) can be computed as follows:

$$\frac{1}{2} f'_p = f_p - 5 \times 11 \times f'_p - 2 \times 6 \times f'_p$$

or

$$(55 + 12 + \frac{1}{2})\ f'_p = f_p$$

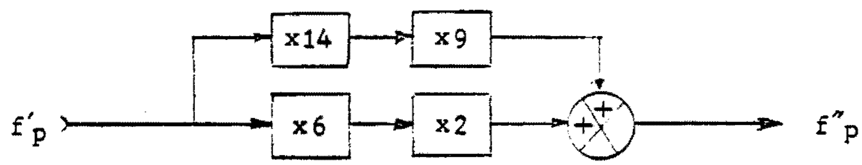
Therefore,

$$f'_p = \frac{2}{135} f_p$$

2.2.2.3 The MFG Output Section. For convenience of analysis, the MFG output section is separated into three subsections as follows:

a. Signal to Downconvertor, f''_p

(1) The frequency f''_p (input to the downconvertor) is used to downconvert the composite uplink signal to IF. The generation of f''_p is as follows:



$$f''_p = 6 \times 2 \times f'_p + 14 \times 9 \times f'_p$$

$$= (12 + 126)\, f'_p$$

$$= 138\, f'_p$$

Or, in terms of f_p,

$$f''_p = 138 \left(\frac{2}{135} f_p\right)$$

$$= \frac{276}{135} f_p$$

(2) If f''_p is known, the IF pilot f_p can now be calculated (see figure 2-3) as follows:

$$f_p = F_p - 5 \times f''_p$$

$$= F_p - 5 \times \frac{276}{135} f_p$$

$$= F_p - \frac{1380}{135} f_p$$

Solving for f_p in term of F_p,

$$f_p = \frac{135}{1515} F_p.$$

The nominal center frequency of the uplink pilot F_p is 15150 MHz; therefore,

$$f_p = 1350 \text{ MHz}$$

(3) f'_p and f''_p can be computed based on the value of f_p:

$$f'_p = \frac{2}{135} f_p$$

$$= \frac{2}{135} (1350 \text{ MHz})$$

$$= 20 \text{ MHz}$$

$$f''_p = \frac{276}{135} f_p$$

$$= \frac{276}{135} (1350 \text{ MHz})$$

$$= 2760 \text{ MHz.}$$

b. Reference Signals to the Forward Processor, $F_f(i)$

(1) The reference signals for the forward MA and KSA coherent frequency translations, and for the SSA frequency synthesizers, can now be calculated. Figure 2-4 shows the MFG output section to the forward processor.

(2) The translation frequency for the forward MA signal is as follows:

$$f = 6 \times 9 \times f'_p$$

$$= 54 \ f'_p$$

$$= 54 \ (20 \text{ MHz})$$

$$= 1080 \text{ MHz}$$

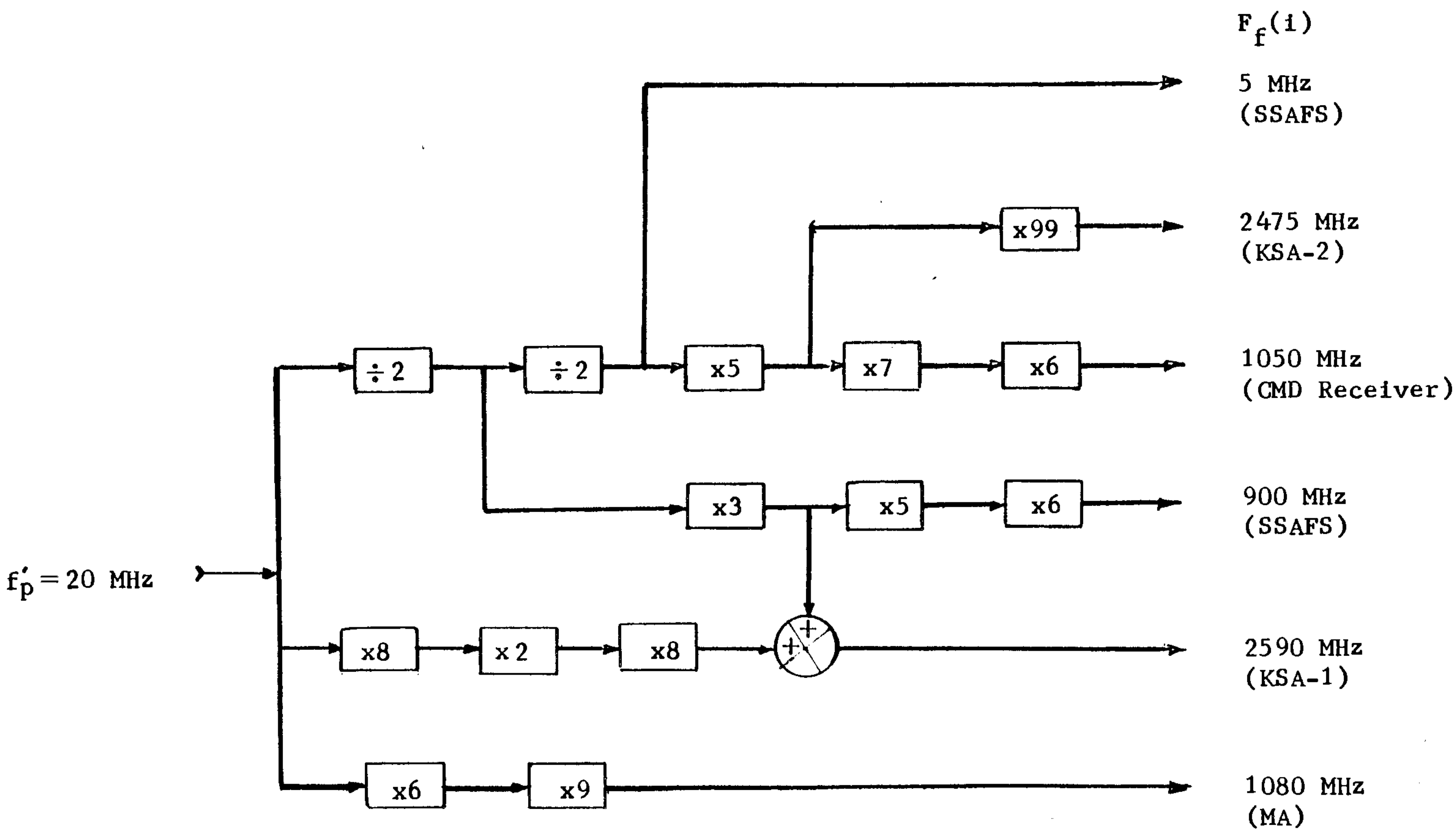


Figure 2-4. MFG Output Section To Forward Processor

(3) Reference signals for the forward KSA frequency translations are as follows:

$$f_{KSA1} = \frac{1}{2} \times 3 \times f'_p + 8 \times 2 \times 8 \times f'_p$$

$$= (\frac{3}{2} + 128)\ f'_p$$

$$= \frac{259}{2}\ f'_p$$

$$= \frac{259}{2}\ (20\ \text{MHz})$$

$$= 2590\ \text{MHz}$$

$$f_{KSA2} = \frac{1}{2} \times \frac{1}{2}\ 5 \times 99 \times f'_p$$

$$= \frac{495}{4}\ f'_p$$

$$= \frac{495}{4}\ (20\ \text{MHz})$$

$$= 2475\ \text{MHz.}$$

(4) Two signals from the MFG (f_1 and f_2) are used by the SSAFS's as reference to generate coherent forward and return frequency translation of the SSA signals (refer to para 2.2.3). The calculations for f_1 and f_2 are as follows:

$$f_1 = \frac{1}{2} \times \frac{1}{2} \times f'_p$$

$$= \frac{1}{4}\ f'_p$$

$$= \frac{1}{4}\ (20\ \text{MHz})$$

$$= 5\ \text{MHz}$$

$$f_2 = \frac{1}{2} \times 3 \times 5 \times 6 \times f'_p$$

$$= \frac{90}{2}\ f'_p$$

$$= \frac{90}{2}\ (20\ \text{MHz})$$

$$= 900\ \text{MHz}$$

(5) Translation frequency for the TDRS command receiver is as follows:

$$f = \frac{1}{2} \times \frac{1}{2} \times 5 \times 7 \times 6 \times f'_p$$

$$= \frac{210}{4} f'_p$$

$$= \frac{210}{4} (20 \text{ MHz})$$

$$= 1050 \text{ MHz.}$$

c. Reference Signals to the Upconvertor and Return Processor, F_r (i)

The return frequency translations provided by the MFG to KSA and TDRS telemetry signals, and the reference signal for the MARFG and the upconvertor, are calculated as follows (also see figure 2-5):

(1) Reference signals for the return KSA frequency translations are as follows:

$$f_{KSA1} = 13 \times f'_p - \frac{1}{2} \times 3 \times f'_p + 2560 \text{ MHz.}$$

$$= \frac{23}{2} (20 \text{ MHz}) + 2560 \text{ MHz}$$

$$= 2790 \text{ MHz.}$$

$$f_{KSA2} = \frac{1}{2} \times 3 \times 5 \times f'_p + 2560 \text{ MHz}$$

$$= \frac{15}{2} (20 \text{ MHz}) + 2560 \text{ MHz}$$

$$= 2710 \text{ MHz.}$$

(2) The translation frequency for the return TDRS telemetry signal is as follows:

$$f = -\frac{1}{2} \times \frac{1}{2} \times 5 \times 7 \times f'_p + 11 \times 5 \times f'_p + \frac{1}{2} \times 3 \times f'_p$$

$$= \left(-\frac{35}{4} + 55 + \frac{3}{2} \right) f'_p$$

$$= \frac{191}{4} (20 \text{ MHz})$$

$$= 955 \text{ MHz.}$$

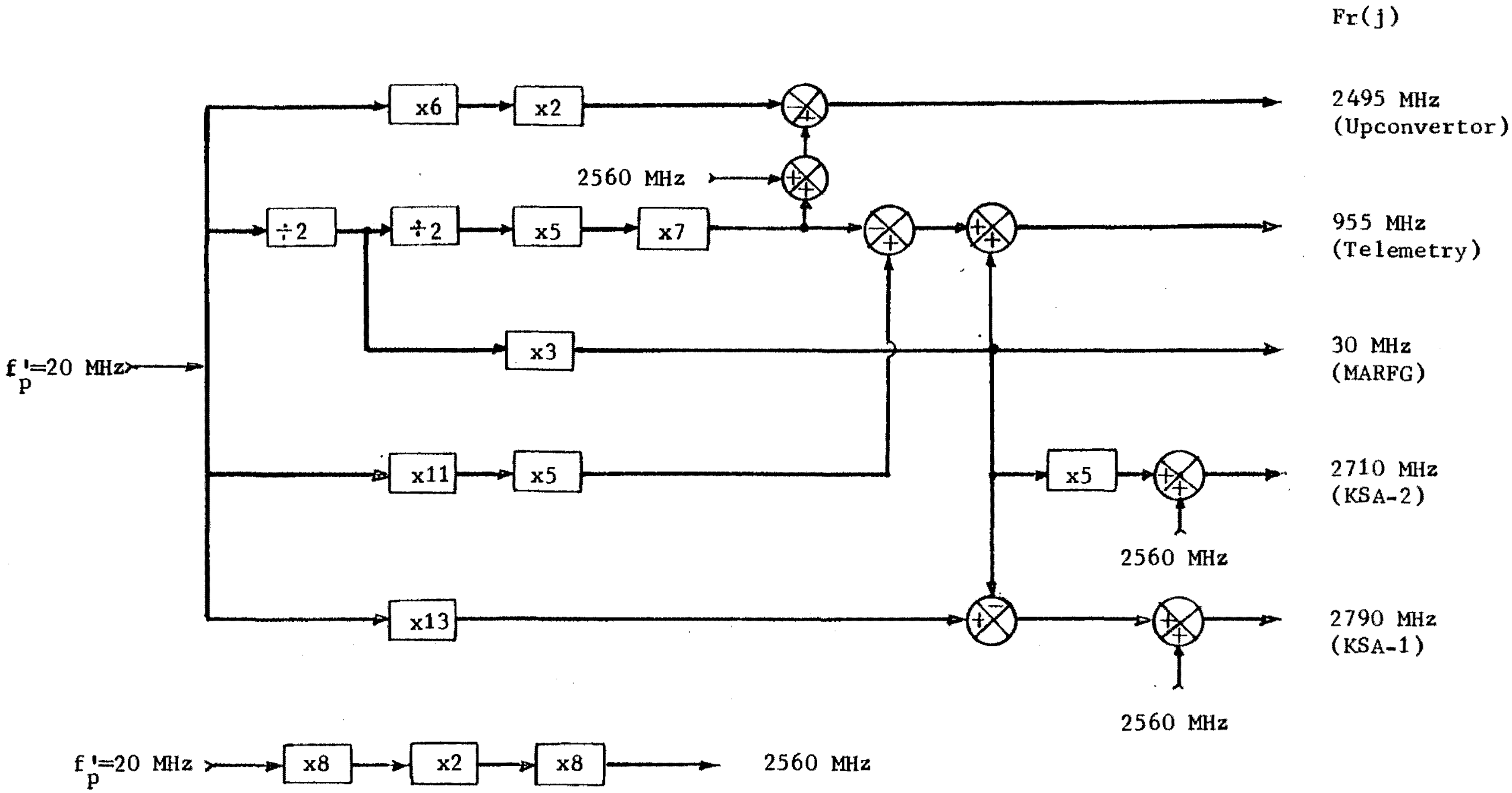


Figure 2-5. MFG Output Section To Return Processor

(3) The reference signal for the upconvertor from the MFG is used to upconvert the return signals to K-band for downlink transmission as follows:

$$f = -(6 \times 2 \times f'_p) + 2560 \text{ MHz} + \frac{1}{2} \times \frac{1}{2} \times 5 \times 7 \times f'_p$$

$$= (-12 + \frac{35}{4})\ f'_p + 2560 \text{ MHz}$$

$$= -\frac{13}{4}(20 \text{ MHz}) + 2560 \text{ MHz}$$

$$= 2495 \text{ MHz}$$

(4) Reference signals for the MARFG are used by the MRAFG to generate two sets of coherent frequencies (LO1 and LO2), which are used in the return MA signal processing (refer to para 2.2.4). The reference signal is as follows:

$$f = \frac{1}{2} \times 3 \times f'_p$$

$$= \frac{3}{2} f'_p$$

$$= \frac{3}{2}(20 \text{ MHz})$$

$$= 30 \text{ MHz.}$$

2.2.3 SSA FREQUENCY SYNTHESIZER

2.2.3.1 The SSA Frequency Synthesizers (SSAFS) provide coherent frequency translation and coarse tuning for the forward and return SSA signals. A synthesizer is required for each of the two forward SSA transmitters and for each of the two return SSA receivers. Each synthesizer uses as its references two input frequencies from the MFG and produces a discrete frequency with a 0.5-MHz quantization. The forward and return synthesizer frequency ranges overlap sufficiently so that a common synthesizer design that covers a range of 960 to 1240 MHz meets all requirements. The SSA frequency synthesizer functional diagram is shown in figure 2-6 (references 2 and 4).

2.2.3.2 The programmable divider in the synthesizer provides digital tuning command capability for synthesizer output frequency selection. The output varacter tuned oscillator, stabilized in frequency and phase by the output of the loop filter, provides the required output frequency. A portion of the output, after proper isolation, is down-converted by a fixed offset signal (900 MHz from the MFG) to a frequency range compatible with the feedback divider input frequency requirements. The divider output is compared in frequency and phase to a fixed reference signal (5 MHz from the MFG) by the frequency discriminator and phase detector. Any difference between the two signals causes an error voltage which, after smoothing by the loop filter, causes the controlled oscillator to slew in a direction such that the error signal is minimized. (references 2 and 4.)

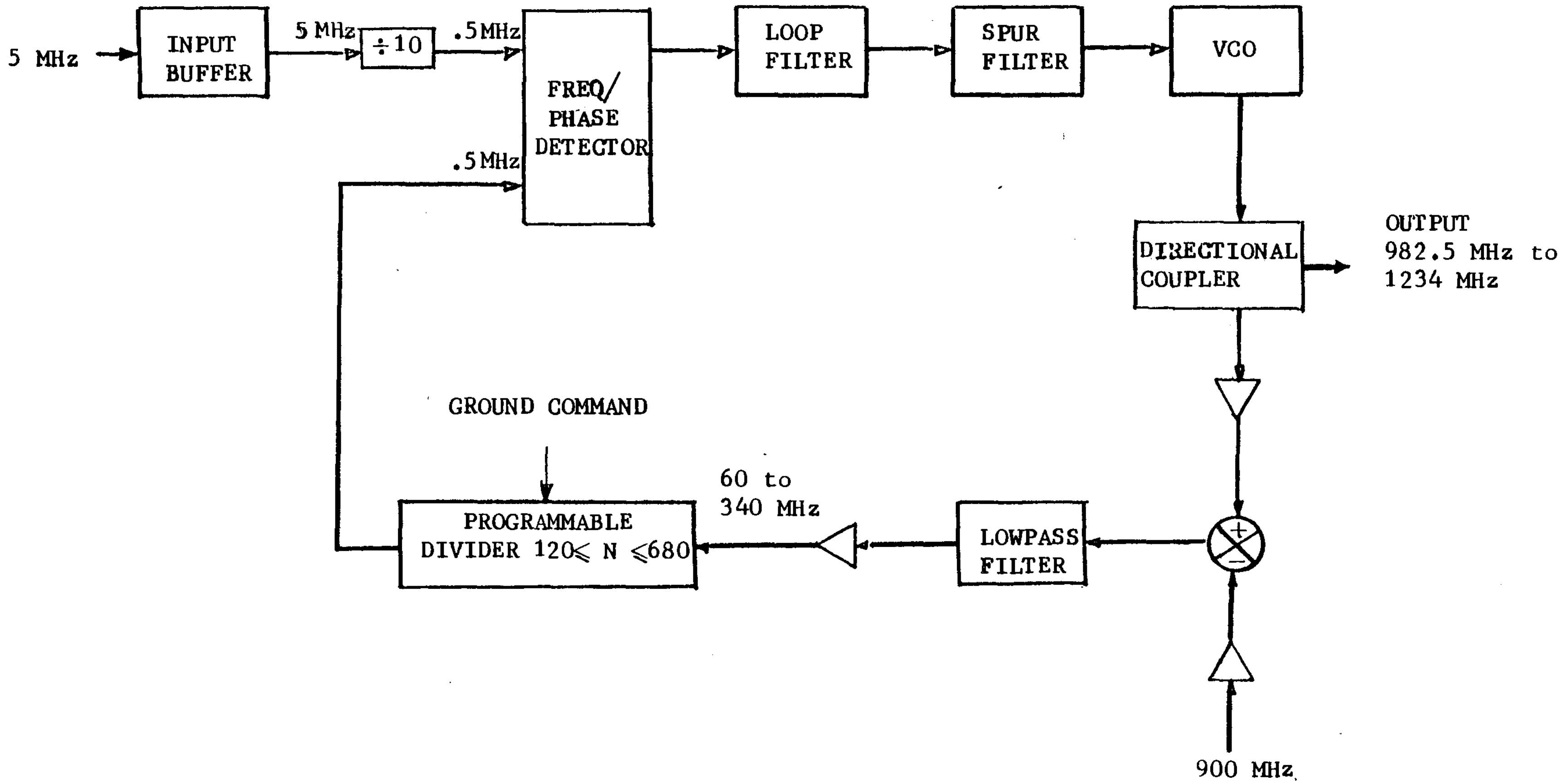


Figure 2-6. SSA Frequency Synthesizer

2.2.3.3 The forward and return frequency translations provided by the SSAFS's can be written in general as follows:

$$f = (900 + 0.5 \times N) \text{ MHz}$$

where $120 \leq N \leq 680$

a. The required ranges of the forward SSA translation frequency, f_F, are as follows:

(1) For SSA-1:

$$f_{F1} = 1150.5, 1151.0, 1151.5, \ldots, 1233.5, 1234.0 \text{ MHz}$$

or

$$f_{F1} = (900 + 0.5 \times n_1) \text{ MHz}$$

with

$$n_1 = 501, 502, \ldots, 668$$

(2) For SSA-2:

$$f_{F2} = 1110.5, 1111.0, 1111.5, \ldots, 1193.5, 1194.0 \text{ MHz}$$

or

$$f_{F2} = (900 + 0.5 \times n_2) \text{ MHz}$$

with

$$n_2 = 421, 422, \ldots, 588$$

b. The required ranges of the return SSA translation frequency, f_R, are as follows:

(1) For SSA-1:

$$f_{R1} = 1002.5, 1003.0, 1003.5, \ldots, 1092.0, 1092.5 \text{ MHz}$$

or

$$f_R = (900 + 0.5 \times m_1) \text{ MHz}$$

with

$$m_1 = 205, 206, \ldots, 385$$

(2) For SSA-2:

$$f_{R2} = 982.5,\ 983.0,\ 983.5, \ldots,\ 1072.0,\ 1072.5\ \text{MHz}$$

or

$$f_{R2} = (900 + 0.5 \times m_2)\ \text{MHz}$$

with

$$m_2 = 165,\ 166, \ldots,\ 345$$

c. Coarse tuning of the forward and return SSA signal is accomplished as follows:

(1) The forward and return SSA coarse tuning is selected to accommodate user spacecraft receive and transmit frequency ranges of 2030.435 to 2113.315 MHz and 2205 to 2295 MHz, respectively. The residual fine tuning is performed at WSGT. The values of the forward and return SSAFS tuning steps (n, m) and the corresponding tuning commands are determined by the ADPE prior to the start of each SSA service and (n, m) are stored for later use in frequency computation. The SSAFS tuning commands are transmitted to the TDRS via the uplink TTC service (reference 7).

(2) The SSAFS tuning steps (n, m) are computed by assuming:

(a) All Dopplers in the system are zero.

(b) Zero Doppler compensation and fine tuning.

Let F_{UR} be the user spacecraft receive frequency, specified in the SHO. The forward SSAFS tuning step, n, is determined as follows:

$$F_{UR} = F_{GT} - 13800 + (900 + 0.5\text{x}n)\ \text{MHz}$$

where:

F_{GT} is the nominal center frequency of the uplink SSA signal.

13800 MHz is the TDRS downconversion.

(900 + 0.5xn) MHz is the forward SSAFS translation frequency.

Solving for n and then rounding to the nearest integer value:

$$n = \text{round}\left[\frac{F_{UR} - F_{GT} + 12900}{0.5}\right]$$

Let F_{UT} be the user spacecraft transmit frequency, for coherent mode,

$F_{UT} = \frac{240}{221} F_{UR}$; for noncoherent mode F_{UT} is specified by the SHO. The return SSAFS tuning step, m, is determined as follows:

$$F_{GR} = F_{UT} - (900 + 0.5xm) + 12475 \text{ MHz}$$

where:

F_{GR} is the nominal center frequency of the downlink SSA signal.

(900 + 0.5xm) MHz is the return SSAFS translation frequency.

12475 MHz is the TDRS upconversion.

Solving for m and then rounding to the nearest integer value:

$$m = \text{round}\left[\frac{F_{UT} - F_{GR} + 11575}{0.5}\right]$$

Let $F_{UR}(n)$ and $F_{GR}(m)$ be the tuned frequencies corresponding to the computed n and m, then

$$\left| F_{UR} - F_{UR}(n) \right| \leq 0.25 \text{ MHz}$$

$$\left| F_{GR} - F_{GR}(m) \right| \leq 0.25 \text{ MHz}$$

The residual 0.25-MHz frequency uncertainty will be covered by the fine tuning allocation at WSGT.

2.2.4 MA RECEIVER FREQUENCY GENERATOR

2.2.4.1 The MA receiver (see figure 2-7) receives, amplifies, and frequency-division multiplexes the signals from the 30 antenna receive elements. The 30-channel MA signals are frequency translated by a two-stage conversion and mixing process to form a Frequency-division Multiplex (FDM) spectrum with 7.5-MHz channel spacing. The MA Receiver Frequency Generator (MARFG) uses a 30-MHz signal from the MFG as a reference, and coherently generates two combs of frequencies: 165 to 202.5 MHz (with 7.5-MHz spacings) for LO1(i), and 45 to 225 MHz (with 45-MHz spacings) for LO2(j). The combiner generator outputs are translated to the desired injection frequency region by 1200- and 2400-MHz offset signals (see figure 2-8).

2.2.4.2 In the MA receiver, the MA signals are partitioned into five 6-channel groups. Each group is downconverted to an IF band of 277.5 to 315 MHz by LO1 and combined via a six-way combiner. The five 6-channel groups are each upconverted by LO2 and subsequently combined via a five-way combiner. This procedure produces a composite output with 30 signals multiplexed at 7.5-MHz spacing covering the frequency band from 930 to 1147.5 MHz (references 2 and 4).

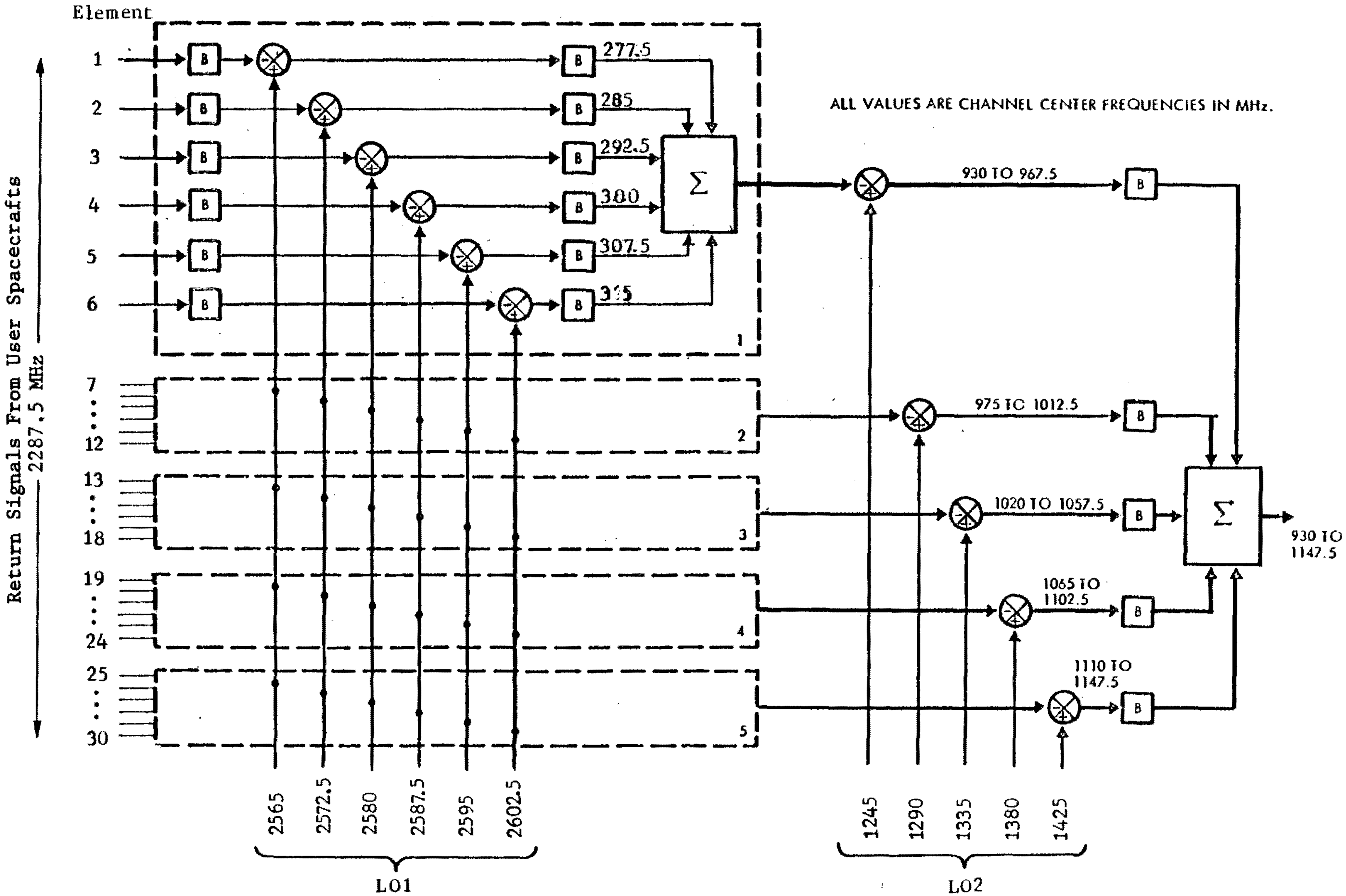


Figure 2-7. MA Receiver

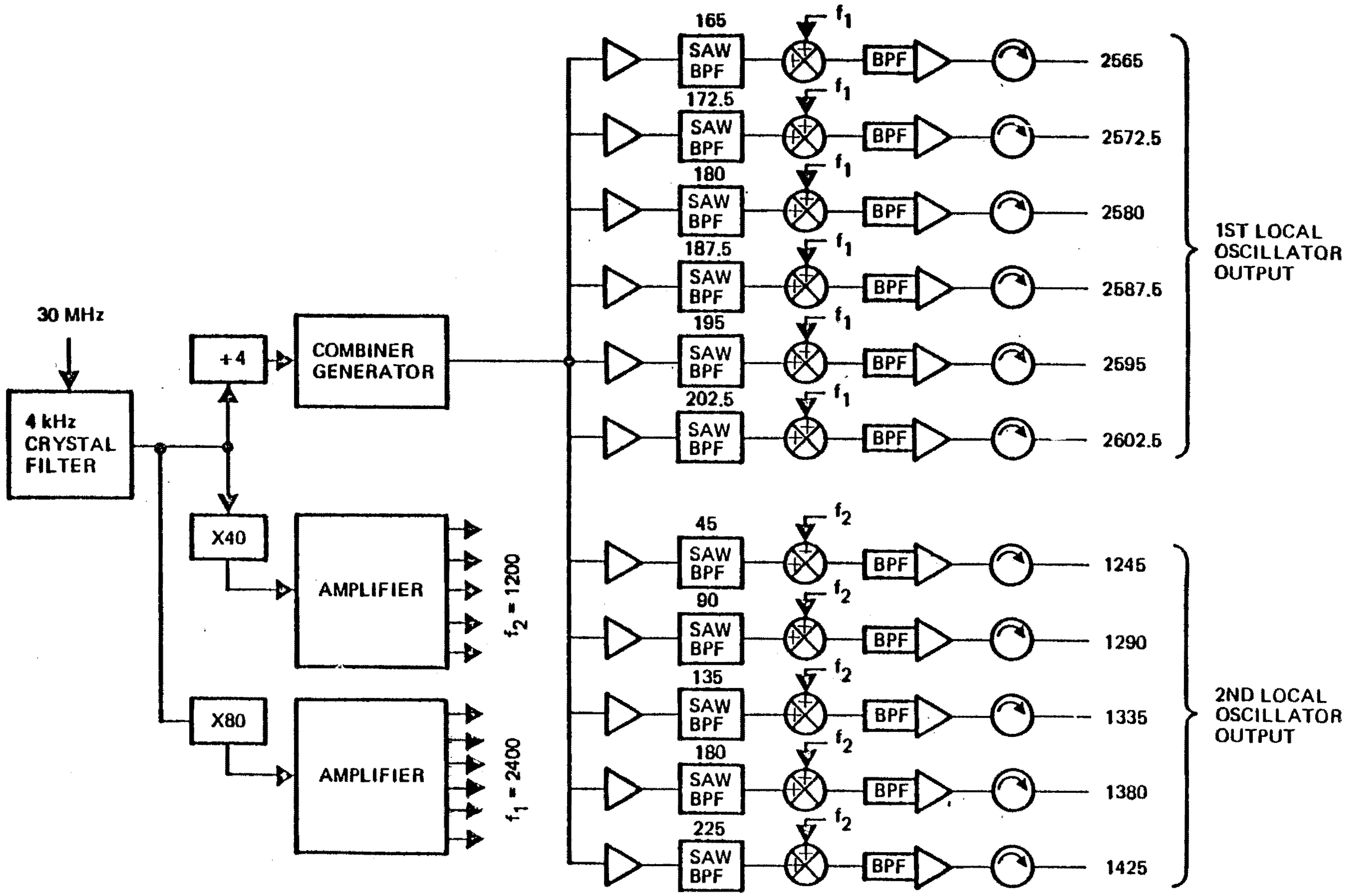


Figure 2-8. MA Receiver Frequency Generator

2.2.4.3 The MA receiver frequency translations (see figure 2-7) can be written as follows:

$$- [- (F_{MA}) + F_{LO1(i)}] + F_{LO2(j)}$$

or

$$(F_{MA}) + F_{LO2(j)} - F_{LO1(i)}$$

where (F_{MA}) is the return MA signal from the user spacecraft. The total frequency translation for each of the 30 channels within the MA receiver is

$$f = F_{LO2(j)} - F_{LO1(i)}$$

In accordance with figure 2-8:

$$F_{LO1(i)} = 2565,\ 2572.5,\ 2580,\ 2587.5,\ 2595,\ 2602.5 \text{ MHz}$$

$$= 2565 + 7.5 \times i, \text{ with } i = 0, 1, 2, \ldots, 5$$

$$F_{LO2(j)} = 1245,\ 1290,\ 1335,\ 1380,\ 1425 \text{ MHz}$$

$$= 1245 + 45 \times j, \text{ with } j = 0, 1, 2, \ldots, 4$$

Therefore, the 30-channel frequency translations can be written as follows:

$$f = F_{LO2(j)} - F_{LO1(i)}$$

$$= -1357.5,\ -1350.0,\ -1342.5, \ldots, -1155.,\ -1147.5,\ -1140 \text{ MHz}$$

or

$$f(l) = -(1140 + 7.5 \times l) \text{ MHz, with } l = 0, 1, 2, \ldots, 28, 29.$$

The FDM center frequency in the MAR is

$$(F_{MA})_c = \frac{1}{2}\left[(F_{MA} - 1357.5) + (F_{MA} - 1140)\right]$$

$$= F_{MA} - \frac{1357.5 + 1140}{2}$$

2.2.5 FREQUENCY TRANSLATION THROUGH THE TDRS TRANSPONDER

2.2.5.1 With results available from the MFG, SSAFS's, and MARFG, the downconversion, forward and return frequency translation, and upconversion of the carrier signals through the TDRS transponder can now be given. Figures 2-9 and 2-10 show the forward and return frequency translation through the TDRS.

2.2.5.2 For the convenience of Doppler computation in section 3, the downconversion and forward frequency translation are represented by $a(k)F_p$, effective forward frequency translation; the return frequency translation and upconversion are represented by $b(k)F_p$, effective return frequency translation, where $k = 1, 2, 3, 4, 5$ is used to designate KSA-1. KSA-2, SSA-1, SSA-2, and MA, respectively.

2.2.5.3 All frequency translations via the TDRS transponder are coherently generated by the uplink pilot F_p. Therefore, if the uplink pilot is Doppler shifted by a factor α due to relative motion between WSGT and TDRS, then $a(k)F_p$ and $b(k)F_p$ so generated are Doppler shifted by α.

2.2.5.4 The calculations of $a(k)F_p$, Fref (user transmit frequency) $b(k)F_p$, and the downlink center frequency are summarized in tables 2-1 and 2-2.

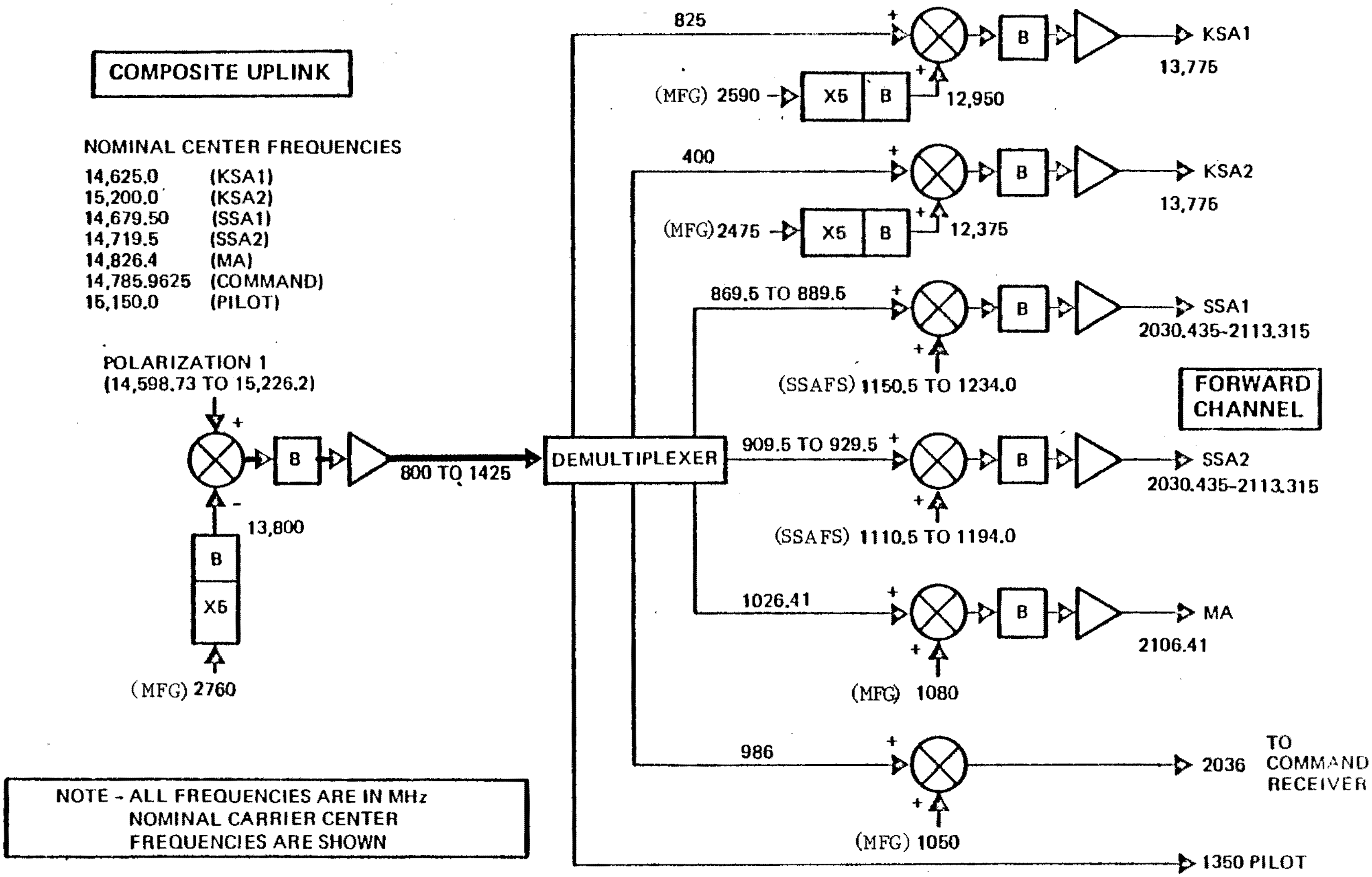


Figure 2-9. TDRS Forward Channel Frequency Translation

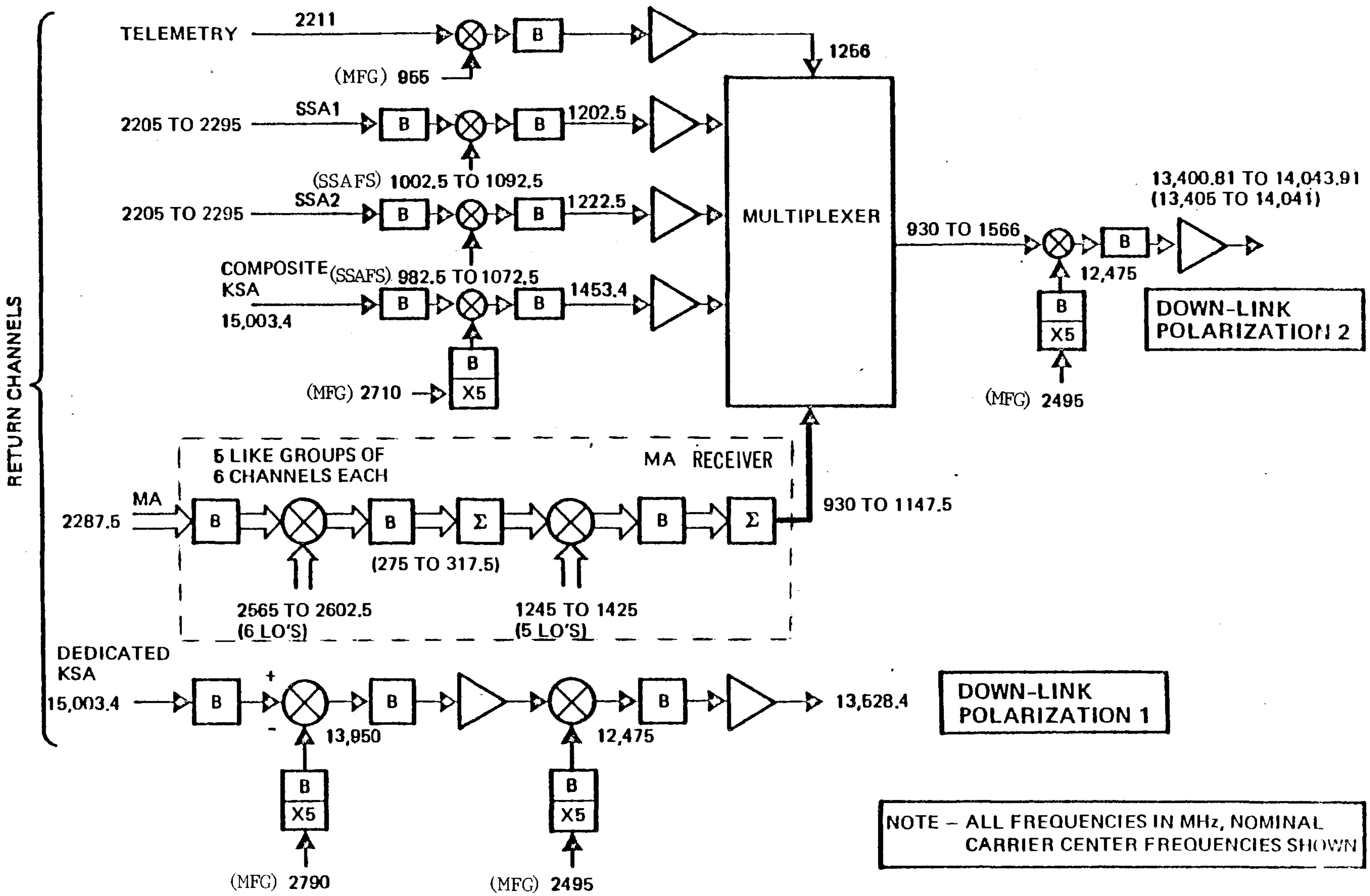


Figure 2-10. TDRS Return Channel Frequency Translation

Table 2-1. Forward Link Frequency Calculation[1]

Forward Parameter \ Service[2]	KSA-1	KSA-2	SSA-1	SSA-2	MA
WSGT Uplink carrier P (k)	14,625.0	15,200.0	14,679.5	14,719.5	14,826.4
TDRS • Down conversion	13,800	13,800	13,800	13,800	13,800
• Forward frequency translation By MFG	-12,950	-12,375	NA	NA	-1080
By SSAFS	NA	NA	From -1234.0 to -1150.5 in 0.5-MHz steps	From -1194.0 to -1110.5 in 0.5-MHz steps	NA
Effective forward frequency translation $a(k)F_p = \sum$	850	1425	From 12,566.0 to 12,649.5	From 12,606.0 to 12,689.5	12,720
User Spacecraft Receive frequency $Fref/K = P(k)-a(k)F_p$	13,775.0	13,775.0	2030.435 to 2113.315	2030.435 to 2113.315	2106.41
K	1600/1469	1600/1469	240/221	240/221	240/221
Transmit frequency Fref	15,003.4	15,003.4	2205 to 2295	2205 to 2295	2287.5

[1]Uplink pilot, F_p = 15,150 MHz.

[2]The number following the acronym KSA and SSA indicates either frequency or link designation, depending on whether or not a hyphen precedes the number. A hyphen indicates that the succeeding number (either 1 or 2) is a frequency designator. The lack of a hyphen indicates that the number is a link designator.

Table 2-2. Return Link Frequency Calculation[1]

Return Parameter \ Service[2]	KSA-1	KSA-2	SSA-1	SSA-2	MA
User spacecraft transmit frequency Fref	15,003.4	15,003.4	2205 to 2295	2205 to 2295	2287.5
TDRS • Return frequency translation By MFG	-13,950	-13,550	NA	NA	NA
By SSAFS	NA	NA	From -1092.5 to -1002.5 in 0.5-MHz steps	From -1072.5 to -982.5 in 0.5-MHz steps	NA
By MARFG	NA	NA	NA	NA	30 channels FDM -1357.5 to -1140
• Upconversion	12,475	12,475	12,475	12,475	12,475
Effective return frequency translation $b(k)F_p = \sum$	-1475	-1075	13,677.5 - Fref	13,697.5 - Fref	FDM center frequency 11,226.25
WSGT Downlink frequency $Fref + b(k)F_p$	13,528.4	13,928.4	13,677.5	13,697.5	Center of band 13,513.75

[1]All frequencies shown are nominal carrier center frequencies in MHz.

[2]The number following the acronym KSA and SSA indicates either frequency or link designation, depending on whether or not a hyphen precedes the number. A hyphen indicates that the succeeding number (either 1 or 2) is a frequency designator. The lack of a hyphen indicates that the number is a link designator.

2.3 FORWARD AND RETURN SIGNAL DESIGN

2.3.1 GENERAL

To satisfy TDRSS operation constraints and performance requirements, different signal designs are implemented for the forward and return links. All forward links are SQPN modulated and consist of two channels: range and command. The return links, depending on the service requirements, can utilize either Data Group 1 (DG1) modes 1, 2, and 3; or Data Group 2 (DG2) signal designs. (Information in the succeeding paragraphs was extracted from reference 5.)

2.3.2 FORWARD SIGNAL DESIGN

2.3.2.1 Each forward link service utilizes a single RF link consisting of a command channel and an independent range channel. The command channel is formed by BPSK modulating (0 and 180 degree) the carrier with either the modulo-2 sum of the input data and a short (command) PN code, or with the input data (for high bit rate). The range channel is formed by BPSK modulating (±90 degree) the delayed carrier with a long (ranging) PN code. All forward link data with a bit rate less than or equal to 300 kbps is modulo-2 added asynchronourly to the command PN code. Command data greater than 300 kbps will BPSK modulate the forward carrier; the range channel is not transmitted for this data rate.

2.3.2.2 The forward link signal parameters are defined in table 2-3. During the user acquisition process, the carrier frequency (F) transmitted by TDRS is Doppler compensated so that the carrier (F_R) arrives at the user spacecraft within a predictable tolerance (E) of the user receive center frequency (f_o). The Doppler compensation is inhibited during periods of coherent two-way Doppler measurement.

2.3.2.3 The PN chip rate is related to the transmitted carrier frequency as shown in table 2-3. This feature permits the user transponder to use the receiver PN clock to predict received carrier frequency, thereby minimizing transponder complexity and reducing acquisition time. The resolution of the PN chip rate is 0.01 Hz.

2.3.2.4 The range channel PN code length is 256 times longer than the command PN code. The all 1's condition of the range channel PN code is time synchronized to the command channel PN generator. Because the command channel acquisition must precede range channel acquisition, this feature reduces the range channel code search to only 256 chip positions while the code itself contains 261,888 chips.

2.3.2.5 The use of a short-cycled PN code for the range channel allows optimization of the command channel PN code. This feature permits use of gold codes for the command channel and allows generation of a code library with good cross-correlation properties. The TDRSS PN code library is sufficiently large to allow a unique code assignment for each user spacecraft.

2.3.2.6 The command channel to range channel power ratio for all forward link signals is 10 dB. This QPSK modulation minimizes the power in the range channel to a level adequate for range channel acquisition and tracking.

Parameter	Definition		
Transmit carrier frequency (Hz)	F		
Carrier frequency arriving at user spacecraft (Hz)[1]	F_R		
Command Channel Radiated Power / Range Channel Radiated Power	10 dB		
Range Channel			
Carrier frequency	Command channel carrier frequency delayed $\pi/2$ radians		
PN Modulation	PSK, $\pm\ \pi/2$ radians		
Carrier Suppression	30 dB minimum		
PN Chip Rate	Synchronized to command channel PN chip rate		
PN Code Length (chips)	$(2^{10} - 1) \times 256$		
PN Code Epoch Reference	All 1's condition synchronized to the command channel PN code		
PN Code Family	Truncated 18-stage shift register sequences		
Command Channel			
Carrier frequency (Hz)	Transmit carrier frequency (F)		
PN Modulation[2]	PSK, $\pm\ \pi/2$ radians		
Carrier Suppression	30 dB minimum		
PN Code Length (chips)	$2^{10} - 1$		
PN Code Family	Gold codes		
	MA	SSA	KSA
PN Chip Rate (chips/sec) (resolved to 0.01 Hz)	$\frac{31}{221 \times 96} \times F$	$\frac{31}{221 \times 96} \times F$	$\frac{31}{1469 \times 96} \times F$
Data Format	NRZ	NRZ	NRZ
Data Rate Restrictions[3]	0.1 - 10 kbps	0.1 - 300 kbps	1 kbps - 25 Mbps
Data Modulation	Modulo - 2 added asynchronously to PN code		

Note

Except during scheduled periods of Doppler compensation inhibit, $F_R = f_0 \pm E$; where f_0 = nominal center frequency of user spacecraft receiver as defined by the user and E is defined below. Doppler compensation will be available for $\dot{R} \leq 12$ km/sec.

Service	$\ddot{R} \leq 15$ m/sec	$\ddot{R} \leq 50$ m/sec
MA and SSA	$E = 700 \times \frac{\dot{R}}{10}$	
KSA	$E = 5{,}000 \times \frac{\dot{R}}{10}$	NA

[1] Forward link Doppler compensation for MA and SSA will not increase the peak phase error of a receiver (with a second order Costas loop, $B_L = 32$ Hz, at $C/N_0 = 33$ dB-Hz in the command channel) more than 3 degrees relative to the phase error for a Doppler-free carrier. Forward link Doppler compensation for KSA will not increase the peak phase error of a receiver (with a second-order Costas loop, $B_L = 110$ Hz, at a $C/N_0 = 41$ dB-Hz in the command channel) more than 3 degrees relative to the phase error for a Doppler-free carrier.

[2] For KSA data rates exceeding 300 kbps, PN modulation will not be used and the command channel data will directly PSK modulate the transmitted carrier $\pm\ \pi/2$ radians (BPSK). KSA signal EIRP as required by table 1-4 will be provided for data rates exceeding 300 kbps and NASA will coordinate this operation with the appropriate radio frequency regulatory organizations when required.

[3] For data rates of 300 kbps or less, NASA will have the ability to change the data rate without restriction. For data rates above 300 kbps, NASA must notify TDRSS of the data rate in the service support schedule.

2.3.3 RETURN SIGNAL DESIGN

2.3.3.1 General

There are two return signal designs available to return link service users: DG1, modes 1, 2, and 3; and DG2. Both signal designs can be utilized for a single return link data channel or for two return link data channels. Each data channel may be rate 1/2 convolutionally coded or uncoded subject to the applicable return link service constraints. Return link NRZ and biphase (Biϕ) data formats and biphase convolutional code output symbol format can be used subject to the applicable return link service constraints. The return link signal parameters are summarized in table 2-4. (reference 5.)

2.3.3.2 Data Group 1

The DG1 signal design spreads the return link data spectrum utilizing PN codes. DG1 is subdivided into three modes:

a. Mode 1

(1) Mode 1 is a PN spread spectrum staggered quadriphase (SQPN) signal which consists of two data channels (I and Q). The I channel is supported by 0 and 180 degree phase modulation of the coherent turnaround reference carrier. The Q channel is supported by ± 90 degree phase modulation of the coherent turnaround reference carrier. The I and Q channel PN codes are generated from a single linear shift register. The channels are identical but offset by at least 20,000 chips to allow for unique identification of each data channel by the TDRSS. The return link data is modulo-2 added asynchronously to the PN codes prior to BPSK modulations.

(2) Mode 1 can be used when two-way range and Doppler measurements are required. The PN code length is identical to and time-synchronized with the forward link PN code received from TDRS. Return link acquisition for mode 1 is possible only when the forward link from TDRS is present and the PN code and carrier transmitted by the user is coherently related to the forward link from TDRS. However, once the return link is established in mode 1, synchronization to the forward link is required for two-way range and Doppler tracking only. Subsequent reacquisition by the user and use of the forward link will not affect the return link mode 1, provided the user transponder does not automatically offset the return link carrier and the PN code for coherent transponding. If tracking is again required, the transponder must switch to coherent transpond operation, thereby unlocking the return link which requires return link reacquisition.

b. Mode 2

(1) Mode 2 is also a PN spread spectrum SQPN signal with I and Q channels. Mode 2 uses a noncoherent carrier generated by the user spacecraft Thermally Controlled Crystal Oscillator (TCXO, no forward link is required), and two short PN codes BPSK modulate quadrature phases of the carrier. The Q channel is delayed 1/2 PN chip period with respect to the I channel. The return data is modulo-2 added asynchronously to the PN codes prior to BPSK modulation.

Table 2-4. Return Link Signal Parameters

Parameter	Definition
Transmit carrier frequency (Hz)	
Data Group 1	F_1
Data Group 2	F_2
Data Group 1	
PN Modulation	
Mode 1 and 2	SQPN
Mode 3, I channel	PSK, ± π/2 radians
PN Code Length (chips)	
Mode 1 and 3	$(2^{10} - 1) \times 256$
Mode 2	$2^{11} - 1$
PN Code Epoch Reference	
Mode 1	
I Channel	All 1's condition synchronized to all 1's condition of received forward link range channel
[1]Q Channel	All 1's condition delayed x + 1/2 PN chips relative to I channel epoch
Mode 2	
I Channel	Spacecraft oscillator
Q Channel	Delayed 1/2 PN chip period relative to I channel epoch
Mode 3, I Channel	Same as mode 1, I channel
PN Code Family	
Mode 1 and 3	Truncated 18 stage shift register sequences
Mode 2	Gold codes
Data Format	
Without convolutional coding	NRZ-L, NRZ-M, NRZ-S, Biø-L, Biø-M, Biø-S
[2]With convolutional coding	NRZ-L, NRZ-M, NRZ-S
Data Modulation	
Mode 1 and 2	Modulo - 2 added asynchronously to PN code
Mode 3	
I Channel	Modulo - 2 added asynchronously to PN code
Q Channel	PSK, ± π/2 radians

[1]Q channel PN code is identical to I channel PN code offset x + 1/2 PN chips, where $x \geq 20{,}000$. Value of x is determined by code and tap connection assignments for a particular user spacecraft.
[2]At the option of the user, the output of the convolutional encoder may be NRZ to Biø-L converted. This format conversion capability will be utilized only with data rates ≤ 5 Mbps.

Table 2-4. Return Link Signal Parameters (cont)

Parameter	Definition		
	MA	SSA	KSA
PN Chip Rate (chips/sec)	$\frac{31}{240 \times 96} \times F_1$	$\frac{31}{240 \times 96} \times F_1$	$\frac{31}{1600 \times 96} \times F_1$
Mode 1 Data Rate Restrictions			
[1]Total	0.1 - 50 kbps	0.1 - 300 kbps	1 - 600 kbps
I Channel	0.1 - 50 kbps	0.1 - 150 kbps	1 - 300 kbps
Q Channel	0.1 - 50 kbps	0.1 - 150 kbps	1 - 300 kbps
Mode 2 Data Rate Restrictions			
[1]Total	1 - 50 kbps	1 - 300 kbps	1 - 600 kbps
I Channel	1 - 50 kbps	1 - 150 kbps	1 - 300 kbps
Q Channel	1 - 50 kbps	1 - 150 kbps	1 - 300 kbps
[2]Mode 3 Data Rate Restrictions			
[1]Total	I + Q	I + Q	I + Q
I Channel	0.1 - 150 kbps	0.1 - 150 kbps	1 - 300 kbps
Q Channel	1 kbps - 1.5 Mbps	1 kbps - 3 Mbps	1 kbps - 150 Mbps
Carrier (F_1) Reference (Hz)			
Mode 1 and 3	$\frac{240}{221} \times F_R$	$\frac{240}{221} \times F_R$	$\frac{1600}{1469} \times F_R$
Mode 2	Spacecraft Oscillator		
Data Group 2			
Carrier (F_2) Reference (Hz)	NA	$\frac{240}{221} \times F_R$ or Spacecraft oscillator	$\frac{1600}{1469} \times F_R$ or Spacecraft oscillator
Data Format			
Without convolutional coding	NA	NA	NRZ-L, NRZ-M, NRZ-S, BiØ-L, BiØ-M, BiØ-S
With convolutional coding	NA	NRZ-L, NRZ-M, NRZ-S	NRZ-L, NRZ-M, NRZ-S
Data Rate Restrictions			
[1]Total	NA	1 kbps - 3.15 Mbps	1 kbps - 300 Mbps
I Channel	NA	1 kbps - 3 Mbps	1 kbps - 150 Mbps
Q Channel	NA	1 kbps - 150 kbps	1 kbps - 150 Mbps
[3]Data Modulation	NA	Quadriphase PSK or BPSK	Quadriphase PSK or BPSK

[1]Data signals on I and Q channels may be independent and asynchronous. If the I and Q channel data signals are independent, the sum of the data rates on the I and Q channel will not exceed the total. In Data Group 2, identical data rates on the I and Q channels are offset relative to one another by one-half data bit period or, if convolutionally coded, one-half encoded data bit period. For MA modes 1, 2, and 3, convolutional coding is used in all cases. For SA DG1 and DG2, maximum data rates for the I channel, the Q channel, and the total are reduced by a factor of 2 when data is either biphase formatted or convolutionally coded. When convolutional coding and biphase format conversion are used, the maximum data rates for the I channel, the Q channel, and the total are reduced by a factor of 4 for SA DG1 and SA DG2. For KSA, biphase data format is not used for data rates exceeding 5 Mbps.
[2]For MA users, mode 3 is available only when supported by SSA service.
[3]BPSK may be used for a single KSA data channel with data rates up to 100 Mbps (500 Mbps if coded). BPSK may be used for a single SSA data channel for baud rates $\leq$ 6 Mbaud/sec.

(2) Mode 2 is used when return link acquisition is desired without the requirement for prior forward link acquisition. Return link acquisition can be accomplished by searching the entire short code uncertainty. This mode of operation assumes that the user spacecraft can radiate sufficient EIRP in the direction of TDRS to support its return link data rate. The carrier frequency transmitted by the user spacecraft must be defined by the user to a tolerance of ±700 Hz for MA or SSA and ±5 kHz for KSA prior to initiation of the acquisition process. Mode 2 can be used for open-loop tracking only.

c. Mode 3

(1) Mode 3 is a quadrature PSK modulated signal. It is a hybrid design which contains on one quadrature channel of the carrier (I channel) the same signal design as the I channel of mode 1, and on the other quadrature channel of the carrier (Q channel) a non-spread spectrum signal with the return link data directly BPSK, SQPSK, or QPSK modulating the carrier. The Q-channel carrier may be either coherent or noncoherent with the received forward link.

(2) Mode 3 can be used when two-way range and Doppler or open-loop Doppler measurements are required simultaneously with high-rate telemetry data. Restrictions on mode 3 acquisition are identical to that for mode 1. In mode 3, the Q channel contains only data and is not restricted by the PN rate. For MA users, mode 3 is available when supported by SSA service.

Note

For all mode 1, 2, 3 operations, the return link can have either a single telemetry data signal or two independent data signals. For a single telemetry data signal, identical data must appear simultaneously on the I and Q channels in mode 1 and 2; in mode 3 operation the single telemetry data signal must appear only on the Q channel while the I channel is used for range tracking. For two independent data signals, one data signal will appear on the I channel and the other on the Q channel. The I and Q channel power division in the user spacecraft transmitter can be weighted to a maximum of 4:1 for either a single data signal or two independent data signals.

2.3.3.3 Data Group 2 (For SA User Only)

a. The DG2 signal design does not utilize spread spectrum techniques. The return link data directly BPSK, SQPSK, or QPSK modulates the carrier. The carrier may be either the coherent turnaround reference carrier or the noncoherent carrier generated by the TCXO (no forward link is required). The type of modulation that can be used is dependent upon the following characteristics of the return link: the number of data channels, the data rate or rates, the utilization of convolutional coding, the utilization of biphase data format, and the utilization of biphase-L format for the convolutional coder output symbols. BPSK modulation can be used for a single data channel, and must be used for two coherent independent data channels. QPSK modulation is used for two independent data channels.

b. DG2 signal parameters are used when the data rate requirement exceeds the capability of DG1. DG2 operation cannot provide range tracking because PN modulation is not used for DG2. The DG2 carrier can be either coherently related to or independent of the forward link carrier frequency. Two-way Doppler tracking can be provided when the DG2 carrier is coherently related to the forward link carrier frequency. When the DG2 carrier is independent of the forward link (one-way Doppler tracking), the carrier frequency transmitted by the user spacecraft must be defined by the user to a tolerance of ±700 Hz for SSA and ±5 kHz for KSA prior to initiation of the acquisition process.

2.3.4 USER SPACECRAFT RETURN CHANNEL ASSIGNMENT

2.3.4.1 MA Users

MA users must use convolutional coding for all return link data. MA users supported by MA return link service may utilize only DG1, modes 1 and 2, signal designs. The maximum return link data rate for mode 1 and 2 service is 50 kbps. MA users may utilize only DG1, mode 3, signal design, if supported by an SSA return link service. The maximum return link data rate for this cross-support service is 1.5 Mbps. Each MA user's EIRP is restricted to the minimum required for transmission of the return link data rate (plus a reasonable EIRP margin) to minimize interference with other MA users.

2.3.4.2 SA Users

SSA and KSA users can utilize DG1 (modes 1, 2, and 3) and DG2 signal designs depending upon the user's return link data requirements. The maximum return link data rate is 3.15 Mbps for DG2 SSA return link service, and 300 Mbps for DG2 KSA return link service.

2.4 USER SPACECRAFT ACQUISITION

2.4.1 GENERAL

2.4.1.1 Acquisition is the process of establishing any two-way communications, range tracking, and Doppler tracking service; or any one-way return link communications and Doppler tracking service. The actions taken to acquire a user service are: pointing the correct TDRS antenna at the position where the user is expected to be at the scheduled service start time, proper alignment of the PN code and carrier phases, bit synchronization, decoder synchronization when convolutional coding of the return link data is scheduled; I/Q channel ambiguity resolution, combining dual channel data from two SSA return links if combining is scheduled, and interleaving dual channel data to reconstruct single channel data if such action is required.

2.4.1.2 Unaided open-loop antenna pointing accuracy is sufficient for acquisition of S-band services. Aided open-loop antenna pointing is required for acquisition of K-band services. The details of user acquisition for all possible user service configurations are given in the succeeding paragraphs. (Reference 1.)

2.4.2 ACQUISITION PROCEDURES

2.4.2.1 MA Forward Link Acquisition Sequence. The following procedure is used for MA forward link acquisition; this procedure is independent of return link status (references 5 and 6):

(1) The WSGT transmits the MA antenna phasing commands to the TDRS.

(2) The TDRS radiates a normal power mode signal at +34 dBW minimum in the direction of the user spacecraft. The signal EIRP is compatible with the forward link signal parameters listed in table 2-3. The S-band carrier and PN clock include Doppler compensation, as scheduled.

(3) When the user spacecraft detects the acquisition signal, the command channel PN code and carrier are acquired within 20 seconds. The command channel includes command data provided by NASA.

(4) Upon acquisition of the command channel PN code and carrier, the user spacecraft searches for and acquires the range channel PN code within 10 seconds after acquisition of the command channel.

(5) The TDRSS continues Doppler compensation until requested by NASA to inhibit the Doppler compensation.

2.4.2.2 MA Return Link Acquisition Sequence

a. The following return link acquisition procedure is used for MA data group 1, mode 1 or 3. Mode 3 is available only when supported by SSA. (References 5 and 6.)

(1) A forward link must be established prior to return link acquisition. The return link PN code and carrier is coherently locked to the TDRS forward link signal so that the TDRSS ground terminal can predict the return signal using its range and Doppler estimates.

(2) At the time specified in the service schedule, the ground segment searches for the user spacecraft signal while adjusting the demodulator for predicted range and Doppler.

(3) The user spacecraft radiates in the direction of the TDRS with an S-band EIRP compatible with its data rate and the return link signal parameters listed in table 2-4.

(4) The WSGT acquires the user PN code and carrier within 15 seconds (Pacq = 0.9) and tracks the return signal (user EIRP $\geq$ + 4 dBW).

(5) After initial return link acquisition in these modes, the forward link signal is not required. If forward link service is terminated, the user spacecraft may maintain the existing mode (mode 1 or 3) return link, or reconfigure to mode 2 return link operation if so scheduled by NASA.

(6) To reestablish a coherent turnaround, the return link is relocked by the user spacecraft to the forward link. NASA will send a user reconfiguration message to TDRSS designating either mode 1 or mode 3 return link operation.

b. The following return link acquisition procedure is used for MA data group 1, mode 2. This mode of return link acquisition does not require an established forward link. (References 5 and 6.)

(1) The WSGT initiates dynamic Doppler corrections on the carrier and PN chip rate settings at the demodulator.

(2) The user spacecraft radiates in the direction of the TDRS with an S-band EIRP compatible with its data rate and the return link signal parameters listed in table 2-4.

(3) Searching for the user signal begins at the scheduled time and continues while the user is in view of the TDRS. PN code and carrier acquisition occurs within 15 seconds (Pacq = 0.9) for user EIRP $\geq$ + 4 dBW.

2.4.2.3 SSA Forward Link Acquisition

The SSA forward link acquisition procedure is independent of return link status and is established as follows (references 5 and 6):

(1) The WSGT transmits commands to the TDRS to slew the SA antenna toward the user spacecraft position. (The antenna slew period requires 2 minutes or less for slew angles of 26 degrees or smaller. Up to 5 minutes may be required for angle changes greater than 26 degrees.)

(2) The WSGT transmits the uplink carrier with the calculated initial Doppler precorrections for PN chip rate and carrier frequency.

(3) The TDRS radiates the forward link signal, in the direction of the user spacecraft, at either normal power or high power mode signal EIRP at S-band as scheduled by NASA. The signal is compatible with the forward link parameters listed in table 2-3.

(4) The user spacecraft searches for and acquires the command channel PN code and carrier within 20 seconds. The command channel includes command data provided by NASA.

(5) Upon acquisition of the command channel PN code and carrier, the user spacecraft searches for and acquires the range channel PN code within 10 seconds after acquisition of the command channel.

(6) The TDRS continues forward transmission with Doppler compensation unless NASA has scheduled Doppler compensation inhibit.

2.4.2.4 SSA Return Link Acquisition

a. The following return link acquisition procedure is used for SSA data group 1, mode 1 or 3 (references 5 and 6):

(1) At the time specified in the service schedule, the ground segment searches for the user spacecraft signal while adjusting the demodulator for predicted range and Doppler.

(2) The user spacecraft radiates, in the direction of the TDRS, an EIRP compatible with its bit rate and the return link signal parameters listed in table 2-4.

(3) The ground segment acquires the PN code and carrier signal within 5 seconds for user EIRP $\geq + 4$ dBW, within 15 seconds for user EIRP $\geq - 6$ but $\leq + 4$ dBW.

(4) Forward link traffic may be terminated at this time if so scheduled.

(5) The user spacecraft may maintain mode 1 or mode 3, or reconfigure to mode 2 return link operation if so scheduled by NASA. DG1 is not available simultaneously with DG2.

Note

A forward link is established prior to return link acquisition in these modes. Return link PN code and carrier are coherently locked to TDRS forward link signal so that the WSGT can predict the return signal using its range and Doppler estimates.

b. The return link acquisition procedure for SSA data group 1, mode 2 is as follows:

(1) The user spacecraft radiates, in the direction of the TDRS, an EIRP compatible with its bit rate.

(2) The ground segment initiates Doppler correction on the downlink and the PN rate at the demodulator. Acquisition occurs within 5 seconds of user turn-on for user EIRP $\geq + 4$ dBW, within 15 seconds for user EIRP ≥ -6 but $\leq + 4$ dBW.

Note

This mode of return link does not require an established forward link.

c. The return link acquisition procedure for SSA data group 2 can be summarized as follows:

(1) When the user is in a coherent turnaround configuration, the return link acquisition is identical to SSA DG1, mode 1, except that DG2 signal parameters, time-to-acquire capabilities, and acquisition restrictions apply.

(2) When the user is in a noncoherent configuration, the return link acquisition is identical to SSA DG1, mode 2, except that DG2 signal parameters, time-to-acquire capabilities, and acquisition restrictions apply.

2.4.2.5 KSA Link Acquisition Sequences. At the discretion of the user, KSA link acquisition is accomplished using either of two sequences. (Reference 5.)

a. KSA Acquisition Sequence No. 1

(1) The TDRS radiates, in the direction of the user spacecraft, Ku-band acquisition EIRP compatible with the forward link signal parameters listed in table 2-3. The Ku-band carrier and PN clock include Doppler compensation, as scheduled.

(2) The user spacecraft acquires the TDRS Ku-band signal, and begins auto-tracking and transmitting a Ku-band EIRP of +30 dBW (minimum) in the direction of TDRS.

(3) The TDRS then performs the following:

(a) Autotracks the user Ku-band signal within 5 seconds of user turn-on (Pacq = 0.99 for user EIRP = +30 dBW).

(b) Begins radiating normal power mode signal EIRP or high-power mode signal EIRP as scheduled.

(c) Establishes either return link DG1 or DG2 service within 5 seconds.

b. KSA Acquisition Sequence No. 2

(1) An SSA forward link is established by the user spacecraft using the normal SSA acquisition. The user spacecraft is commanded to point its Ku-band antenna at TDRS. (This step is optional for user spacecraft.)

(2) The user spacecraft begins transmitting a Ku-band EIRP compatible with the EIRP requirements and the return link signal parameters listed in table 2-4.

(3) The TDRS searches for the K-band signal and begins autotracking within 10 seconds of user turn-on (Pacq = 0.99).

(4) The TDRS radiates normal power or high-power EIRP at Ku-band, in the direction of the user spacecraft (as scheduled), compatible with the appropriate forward link signal parameters. The Ku-band carrier and PN clock include Doppler compensation, as scheduled.

(5) The user spacecraft acquires the TDRS Ku-band signal and begins autotracking.

(6) TDRS either establishes return link DG1 or DG2 services.

2.4.3 ACQUISITION METHODS

Descriptions of the techniques used for achieving PN code acquisition and carrier acquisition are summarized in the succeeding paragraphs, all of which was extracted from reference 1.

2.4.3.1 PN Code Acquisition

a. Acquisition of the return link PN code is accomplished using a sequential detector. The basic block diagram for such a detector is shown in figure 2-11. The sequential PN acquisition procedure employs a variable integration time to hasten the dismissal of improper synchronization of the incoming and local reference PN codes. It is designed so that the out-of-sync test statistic at the output of the postdetection integrator rapidly approaches the dismissal threshold. The reference channel allows the detection threshold to adapt to the channel noise environment, thereby assuring proper detection.

b. The local code is advanced or retarded in 1/2-chip steps following each dismissal. This PN code phase shifting scheme implies that the maximum possible phase error between the incoming and local PN codes is 1/4 chip. A 1/4-chip error results in a worst-case correlation loss of 2.5 dB. However, this worst-case correlation loss is largely offset by the two successive opportunities to detect PN sync (corresponding to the ± 1/4 chip phase error in synchronization).

c. The strategy employed in the search process differs according to PN code length. The short PN code length of 2047 chips matches the uncertainty in phase. The search, therefore, spans the entire short code length. The search direction (advance or retard) is selected so that PN acquisition is most likely in the presence of any residual PN code Doppler (the local PN generator clock is compensated for Doppler effects).

d. For the long PN code length of $256 \times (2^{10}-1)$ chips, the search spans a precomputed window of phase uncertainty that is less than 4600 chips in size. Such a bounded search is necessary to meet the acquisition time requirements. The maximum window size for any acquisition or reacquisition attempt is based on the predicted user spacecraft position uncertainty. The center position of the phase uncertainty window relative to the PN code epoch position (the all 1's state of the cyclic code) is determined by computing the two-way propagation delay between the time the forward link PN epoch is transmitted from the ground segment and received by the ground segment. The time of occurrence of the next forward link PN epoch after the scheduled return service start time is computed, and the sum of this number with the two-way propagation delay is provided to the return link demodulator so that the search will begin at the center of the window (the most likely region for achieving code synchronization).

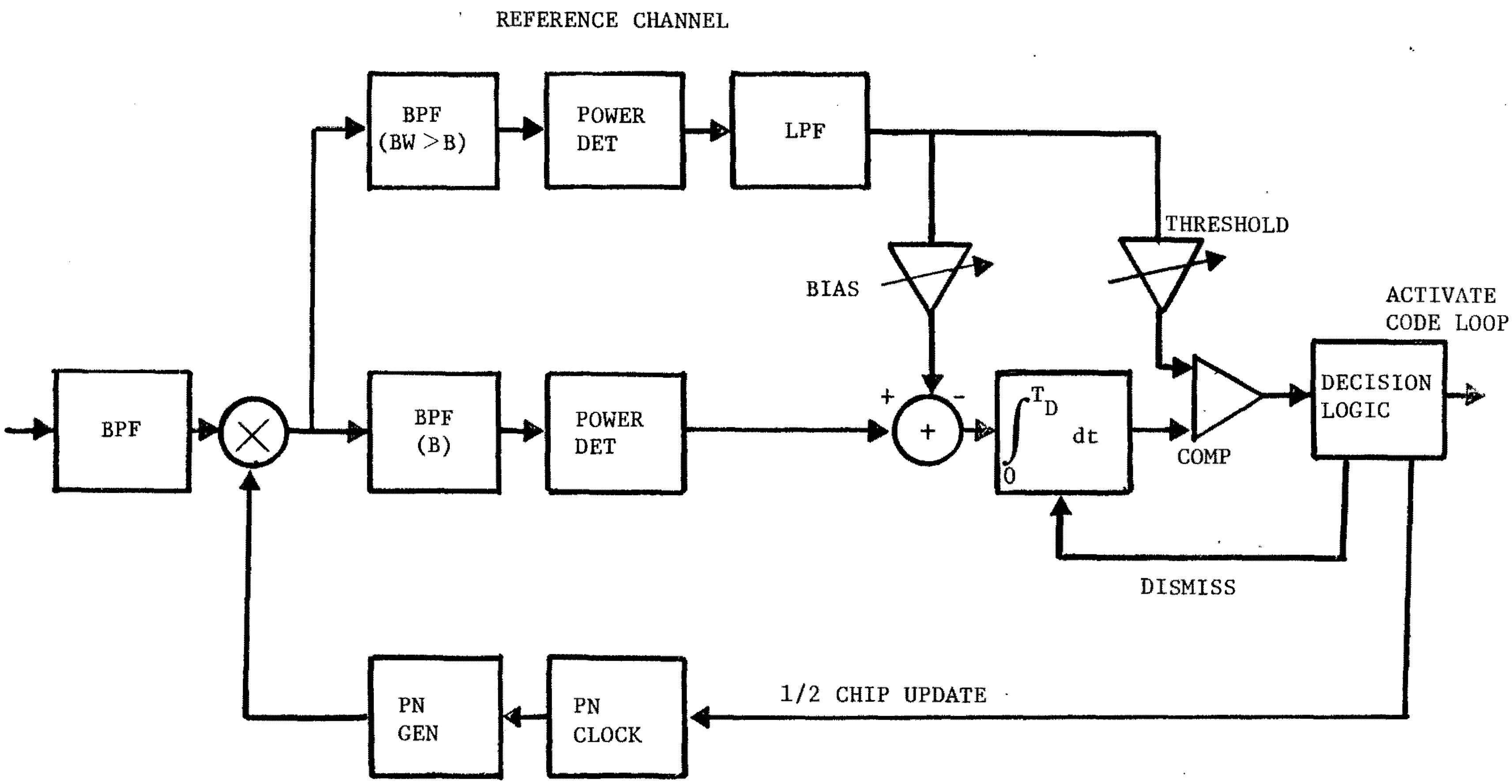


Figure 2-11. Sequential Detection Acquisition Circuit

e. For low signal-to-noise ratio conditions, an expanding window search is implemented to exploit the short dismissal time performance of the sequential detector. The window size can increase up to a predetermined maximum size and thereafter the search repeatably continues within this fixed phase uncertainty window (changing direction at the boundaries of the window) until the return link PN code is acquired.

2.4.3.2 Carrier Acquisition. All data modulation schemes use BPSK and QPSK suppressed carrier modulation. The QPSK carrier for MA and DG1, modes 1 and 2, services is recovered using a Costas loop locked to the higher power quadraphase channel. Carrier recovery of a DG2 BPSK signal is accomplished using a Costas loop, and carrier recovery of a DG2 QPSK signal is accomplished using a hard-limit and cross-multiply loop design (described in the literature as a quadraphase decision feedback loop).

SECTION 3. TRACKING SIGNAL GENERATION AND PROCESSING THROUGH THE TDRSS

SECTION 3. TRACKING SIGNAL GENERATION AND PROCESSING THROUGH THE TDRSS

3.1 TDRSS TRACKING SERVICES

3.1.1 GENERAL

The TDRSS will provide open-loop (one-way) Doppler measurements and closed-loop (two-way or hybrid) range and/or Doppler measurements. One-way Doppler measurements will be available on return channels for all mode and/or data group configurations. Closed-loop Doppler measurements will be available to all user spacecraft for which the coherent transmit and receive carrier frequency turnaround ratio is 240:221 for MA and SSA, or 1600:1469 for KSA. Closed-loop range measurements will be available to user spacecraft operating in DG1, modes 1 and 3, when the user-transmitted PN code is synchronized to the PN code received from a TDRS. Closed-loop hybrid Doppler and range measurements will be available to S-band users only. For Shuttle tracking service, closed-loop and open-loop Doppler measurements will be available but no range measurement will be required. The TDRSS tracking services and tracking service configurations are shown in tables 3-1 and 3-2, respectively. (References 5 and 8.)

3.1.2 RANGE TRACKING

3.1.2.1 Range tracking services will provide accurate and independent (sample-to-sample) range data with Doppler frequencies up to ±230 kHz at S-band and ±1.6 MHz at K-band. Doppler rates up to 1.5 kHz/sec at S-band and 10.5 kHz/sec at K-band can be accommodated. The specified rms error contribution to range measurements resulting from TDRS and WSGT equipment is summarized as follows (reference 9):

Data Rate	Maximum rms Range Error (nanosecond)		
	MA	SSA	KSA
<1000 bps	20	20	NA
≥1000 bps	10	10	10

Note

These specifications apply with the understanding that, if studies and analyses currently underway reveal that these values are physically unachievable with the current design (while preserving current margins) due to the introduction of the RFI modification and that if the contractor can demonstrate this to NASA by analysis, they will be modified by mutual agreement to be not worse than the following values: 40 for data rates <1000 bps (MA and SSA) and 20 for data rates >1000 bps (MA, SSA and KSA).

3.1.2.2 The specified systematic range error contribution from the TDRS is less than ±35 nanoseconds based upon prelaunch measurement and predicted onorbit performance. The specified systematic range error contribution from WSGT is less than ±30 nanoseconds for all three classes of service (reference 9). These specifications will be revised due to the introduction of the RFI modification.

3.1.2.3 The smallest discrete output of the range extractor is 1.0 nanosecond. The range ambiguity interval is equal to the period of the range channel PN code, which is approximately 87 milliseconds. The WSGT and TDRS delays will be removed from the ranging system via software zero-set adjustment. The range zero-set correction

Table 3-1. TDRSS Tracking Services

<table>
<tr><th rowspan="2">TRACKING SERVICE</th><th colspan="4" rowspan="2">OPEN-LOOP ONE-WAY DOPPLER</th><th colspan="8">CLOSED-LOOP</th></tr>
<tr><th colspan="4">DOPPLER</th><th colspan="4">RANGE</th></tr>
<tr><th>DATA GROUP-MODE / SERVICE</th><th>DG1-1</th><th>DG1-2</th><th>DG1-3</th><th>DG2</th><th>DG1-1</th><th>DG1-3</th><th>DG2</th><th>DG1-2</th><th>DG1-1</th><th>DG1-3</th><th>DG2</th><th>DG1-2</th></tr>
<tr><td>MULTIPLE ACCESS (MA)</td><td colspan="3"></td><td>N/A</td><td colspan="2">3 MA CHANNELS (ONE PER TDRS)</td><td>N/A</td><td rowspan="3">NOT REQD.</td><td colspan="2">3 MA CHANNELS (ONE PER TDRS)</td><td colspan="2" rowspan="3">NOT REQUIRED</td></tr>
<tr><td>S-BAND SINGLE ACCESS (SSA)</td><td colspan="4" rowspan="2">ANY 10 CHANNELS (INCLUDING SHUTTLE)</td><td colspan="3">MA/SSA & SSA/MA CROSS AND TDRS HYBRID SUPPORT</td><td colspan="2">MA/SSA & SSA/MA CROSS AND TDRS HYBRID SUPPORT</td></tr>
<tr><td>KU-BAND SINGLE ACCESS (KSA)</td><td colspan="3">6 SA CHANNELS (INCLUDING SHUTTLE)</td><td colspan="2">6 SA CHANNELS</td></tr>
</table>

<table>
<tr><th>SHUTTLE MODE / SERVICE</th><th>1</th><th>2</th><th>3</th><th>1</th><th>2</th><th>3</th><th>1</th><th>2</th><th>3</th></tr>
<tr><td>K-BAND</td><td></td><td>NOT REQUIRED</td><td>N/A</td><td></td><td>NOT REQUIRED</td><td>N/A</td><td colspan="3" rowspan="2">NOT REQUIRED</td></tr>
<tr><td>S-BAND</td><td colspan="2">REQUIRED</td><td>UNMODULATED RETURN CARRIER</td><td colspan="2">REQUIRED</td><td>UNMODULATED RETURN CARRIER</td></tr>
</table>

Table 3-2. TDRSS Tracking Service Configurations

FORWARD \ RETURN		NORMAL SUPPORT			HYBRID SUPPORT	
		S-BAND		K-BAND	S-BAND	
		MA	SSA	KSA	MA	SSA
MA	MA	2-WAY TRACKING	2-WAY CROSS-SUPPORT TRACKING		HYBRID TRACKING	HYBRID CROSS-SUPPORT TRACKING
	NONE	OPEN-LOOP 1-WAY DOPPLER				
SSA	SSA	2-WAY CROSS-SUPPORT TRACKING	2-WAY TRACKING		HYBRID CROSS-SUPPORT TRACKING	HYBRID TRACKING
	NONE		OPEN-LOOP 1-WAY DOPPLER			
KSA	KSA			2-WAY TRACKING		
	NONE			OPEN-LOOP 1-WAY DOPPLER		

values are determined from premeasurement of the time delays through applicable equipment or equipment groups. These values are subtracted from the range readings in the automatic data processing equipment (reference 9).

3.1.3 DOPPLER TRACKING

3.1.3.1 The tracking service provides Doppler data for Doppler frequencies up to ±230 kHz at S-band and ±1.6 MHz at K-band. Doppler rates up to 1.5 kHz/sec at S-band and 10.5 kHz/sec at K-band can be accommodated. The Doppler signal is biased and processed such that a signal of $240.\bar{0}$ MHz + 1000 Fd for S-band and $240.\bar{0}$ MHz + 100 Fd for K-band is obtained, where Fd is the Doppler frequency. The Doppler count is nondestruct with the capability of maintaining a continuous count for a minimum of 50 minutes. The counter will be set to zero at the time of receiver lock. The specified rms phase noise contributions to Doppler tracking, resulting from TDRS and from WSGT equipment, are listed in table 3-3 (references 8 and 9).

3.1.3.2 For closed-loop (two-way or hybrid) Doppler measurements, the reference frequency for the Doppler extractor (Fref) is coherently related to the forward link frequency, consistent with the appropriate frequency turnaround ratio. Fref is an integer multiple of 240 Hz for S-band or 160 Hz for K-band.

3.1.3.3 For open-loop (one-way) Doppler measurements, the reference frequency for the Doppler extractor (Fref) is the user transmit frequency as defined by NASA in the Service Schedule Order (SHO). The accuracy of Fref is consistent with the ground terminal standard (reference 5).

3.1.4 MEASUREMENT TIMING

3.1.4.1 The WSGT sampling time for range and Doppler measurements is synchronized to the Universal Time Code (UTC), as determined and maintained by the U.S. Naval Observatory. Timing accuracy will be maintained to within ±5 microseconds.

3.1.4.2 The tracking data will be sampled "on-time" to within ±25 nanoseconds for Doppler and 0 to 336 nanoseconds for range. The term "on-time" refers to that portion (leading or trailing edge) of the timing signal which is synchronized with UTC and is used for sampling the tracking data. Sample rates (in seconds/sample) of 1, 5, 10, 60, and 300 will be available for both the range and Doppler data (reference 5).

3.1.5 CROSS-SUPPORT TRACKING

The TDRSS is capable of providing cross-support tracking which provides two-way range and Doppler measurements of an MA user spacecraft, either supported by SSA service on the forward link and MA service on the return link, or supported by MA service on the forward link and SSA service on the return link. Cross-support tracking imposes no restrictions on the achievable data rates for the appropriate forward and return link services (reference 5).

3.1.6 HYBRID TRACKING

The TDRSS is capable of providing hybrid tracking which provides two-way range and Doppler measurement to a user supported by forward link service from one TDRS and by return link service from another TDRS. Hybrid tracking is provided to only MA and SSA users. Hybrid tracking to MA users is supported by either SSA or MA forward link

Table 3-3. Specified Maximum rms Phase Noise

Data Rate	Maximum rms Phase Noise (Radians)		
	MA	SSA	KSA
≤ 500 bps	0.4	0.4	NA
> 500 bps ≤ 1000 bps	0.3	0.3	NA
> 1000 bps	0.2	0.2	0.2

service from one TDRS and by either SSA or MA return link service from another TDRS. Hybrid tracking does not restrict the simultaneous availability of MA, SSA, or cross-support tracking service to the same user from the TDRS providing forward link service to that user. Hybrid tracking imposes no restrictions on the achievable data rates for the appropriate forward and return link services (reference 5).

3.2 CLOSED-LOOP TRACKING (TWO-WAY AND HYBRID)

3.2.1 GENERAL

Closed-loop tracking consists of uplink signal generation, forward and return frequency translation via the TDRS, signal processing by the user transponder, and downlink signal processing at WSGT. Two-way tracking involves the same TDRS on both forward and return links. Hybrid tracking involves two TDRS's, one on the forward link and one on the return link. Hybrid tracking is available to S-band users only. Closed-loop tracking provides two-way or hybrid range and/or Doppler measurements. A TDRS closed-loop tracking configuration and a simplified diagram of the signal generation and processing are shown in figures 3-1 and 3-2, respectively.

3.2.2 UPLINK SIGNAL GENERATION

3.2.2.1 Uplink signal generation includes service configuration switching, modulation, upconversion, power amplification, and transmission. There is a total of 15 service links between the NASCOM interface and the three 18-meter K-band antennas. The uplink services are divided into five independent service groups: KSA-1, KSA-2, SSA-1, SSA-2, and MA. Each service group consists of three service strings designated as North (N), South (S), and Central (C). Any service string in a group is capable of sparing any other service string in the same group. Any one of the three service strings can be connected to any one of the three uplink antennas via the forward configuration switch. The WSGT can support three MA, six SSA, and six KSA forward services simultaneously. Up to two S-band and K-band Shuttle services can be substituted for normal SSA or KSA services, respectively. The configuration switching for the uplink services is shown in figure 3-3 (references 6 and 8).

3.2.2.2 Each of the 15 service links consists of an equipment chain plus related baseband IF. The equipment chain consists of a linear interpolator, a frequency synthesizer, a forward modulator, an upconvertor, and a power amplifier. The equipment chains for SA service can be operated in two different modes: internal modulation mode or external modulation mode. The MA equipment chains can be operated in the internal modulation mode only. (The uplink signal generation process is shown in figure 3-4.)

3.2.2.3 To establish the communication link between WSGT and a particular user spacecraft, user acquisition is required. During the user acquisition process, the forward signal from TDRS to a user spacecraft can be Doppler-compensated to account for spacecraft dynamics and to place the acquisition signal within the user spacecraft receiver bandwidth. The compensated forward carrier frequency profile is computed by the Automatic Data Processing Equipment (ADPE) based on WSGT-generated TDRS ephemeris data and receive center frequency and user ephemeris data.

3.2.2.4 During each 1-second interval, defined by 1-pps tic's entering the linear interpolator from the Common Timing and Frequency Standard (CTFS), a computed value, F_o, and two frequency deltas, based on the ideal compensation profile, are sent to the linear interpolator from the ADPE. F_o is the start frequency of the frequency synthesizer and is transferred to the synthesizer on the next 1-pps tic, denoted as t_n. The two frequency deltas are defined as:

$$\Delta F_1 = F_o\,(t_n + 0.5) - F_o$$

$$\Delta F_2 = F_o\,(t_n + 1.0) - F_o\,(t_n + 0.5)$$

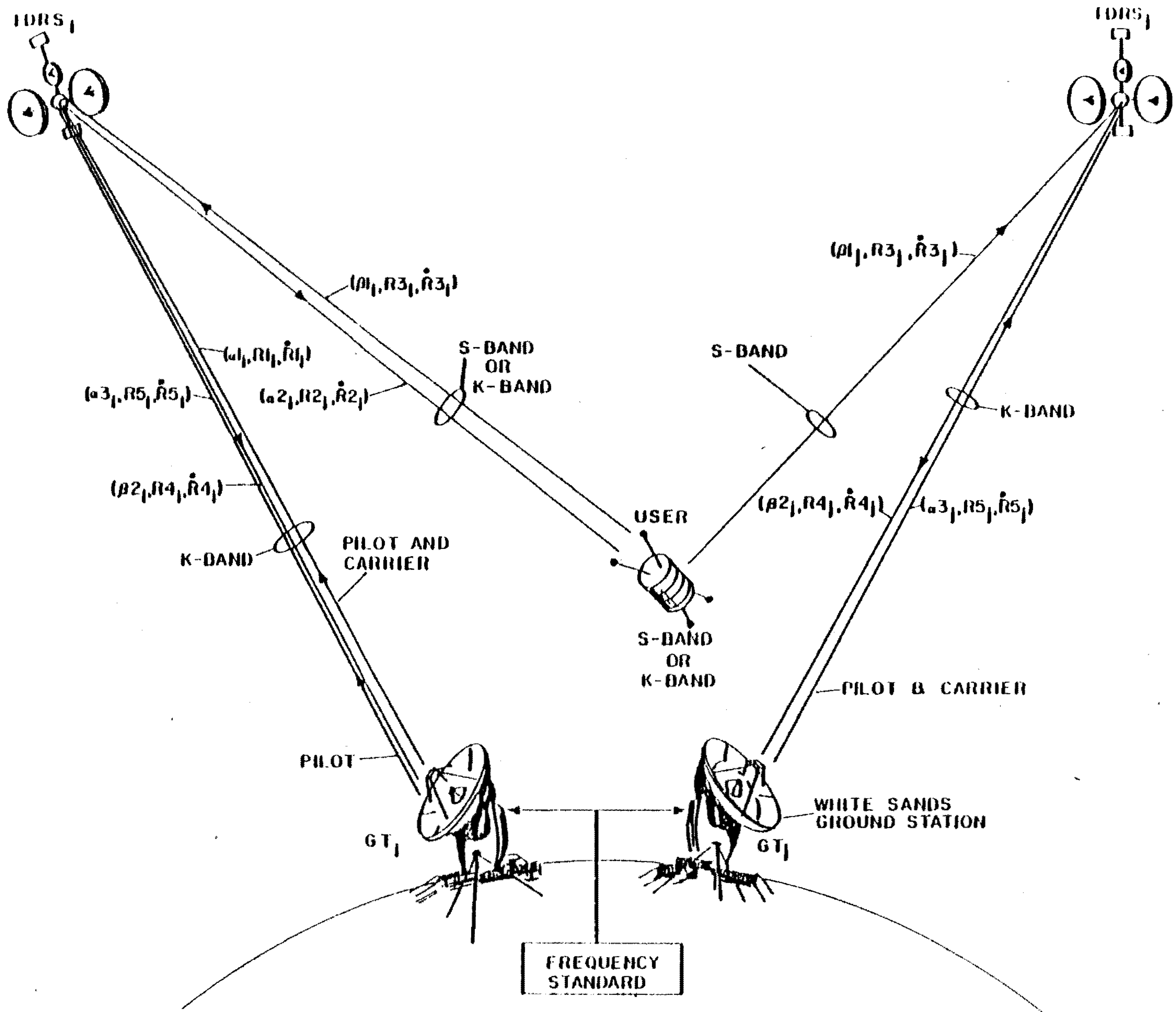


Figure 3-1. Closed-loop Tracking Configuration

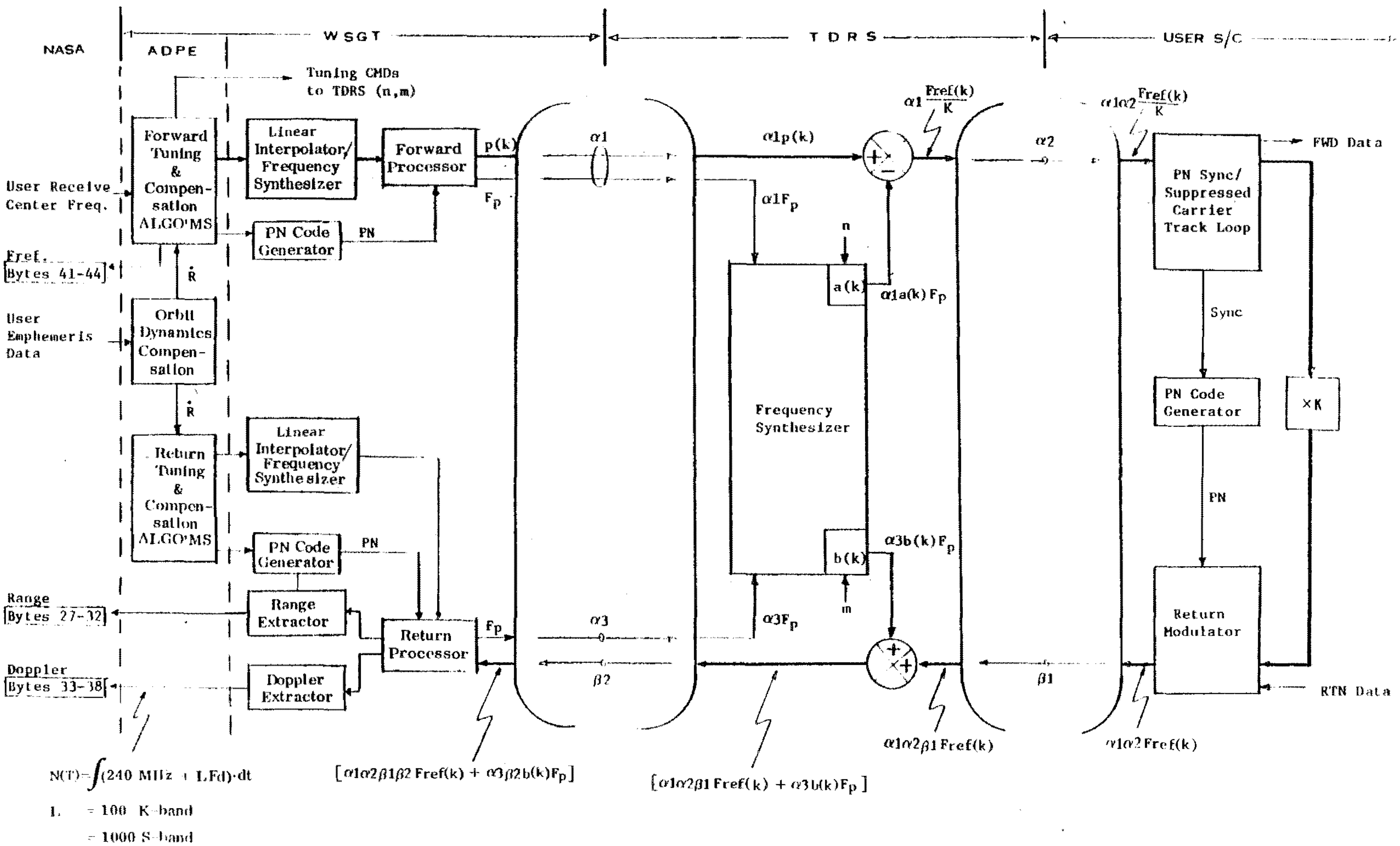


Figure 3-2. Closed-loop Signal Generation and Processing

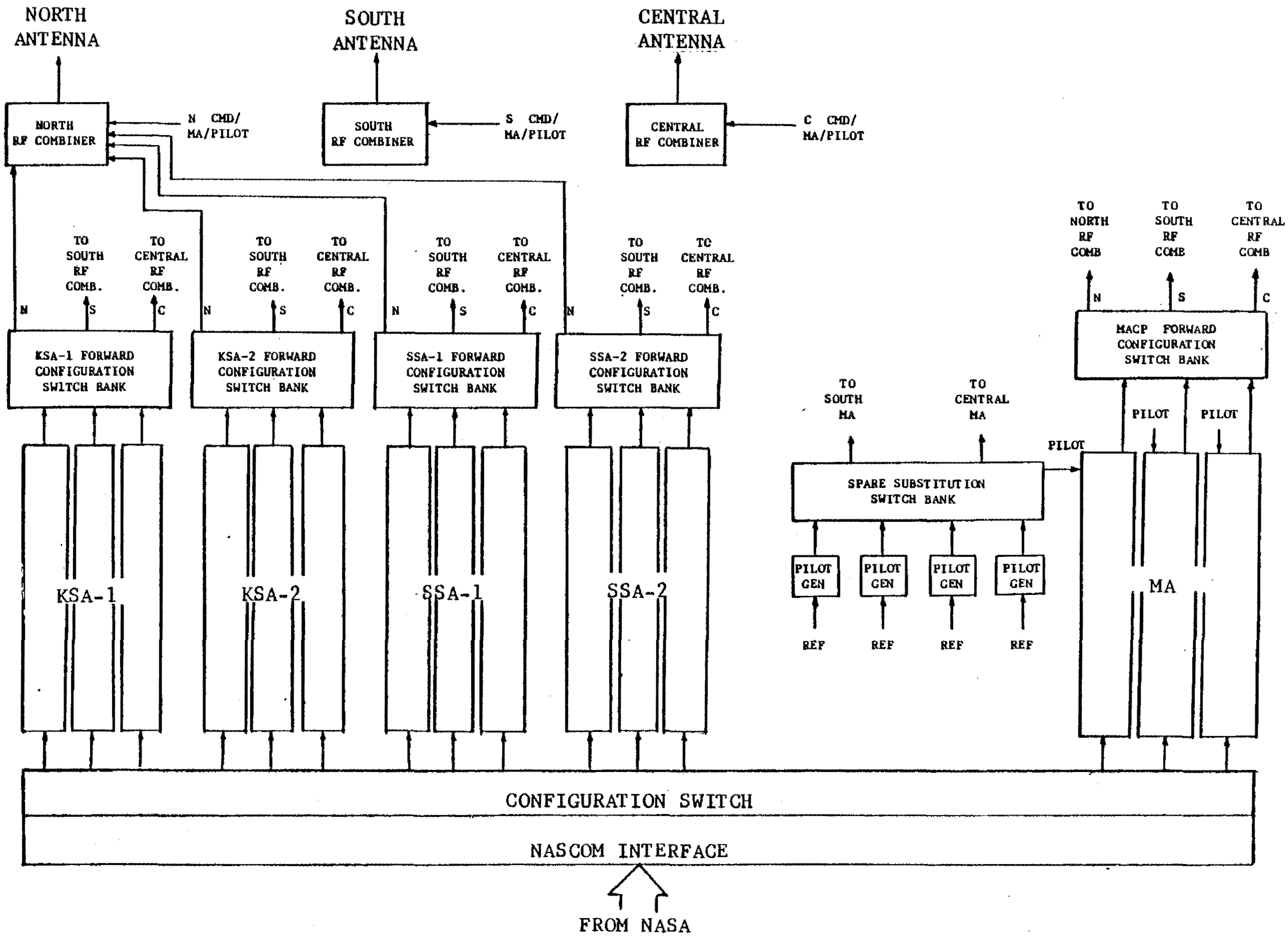


Figure 3-3. Configuration Switching for Uplink Services

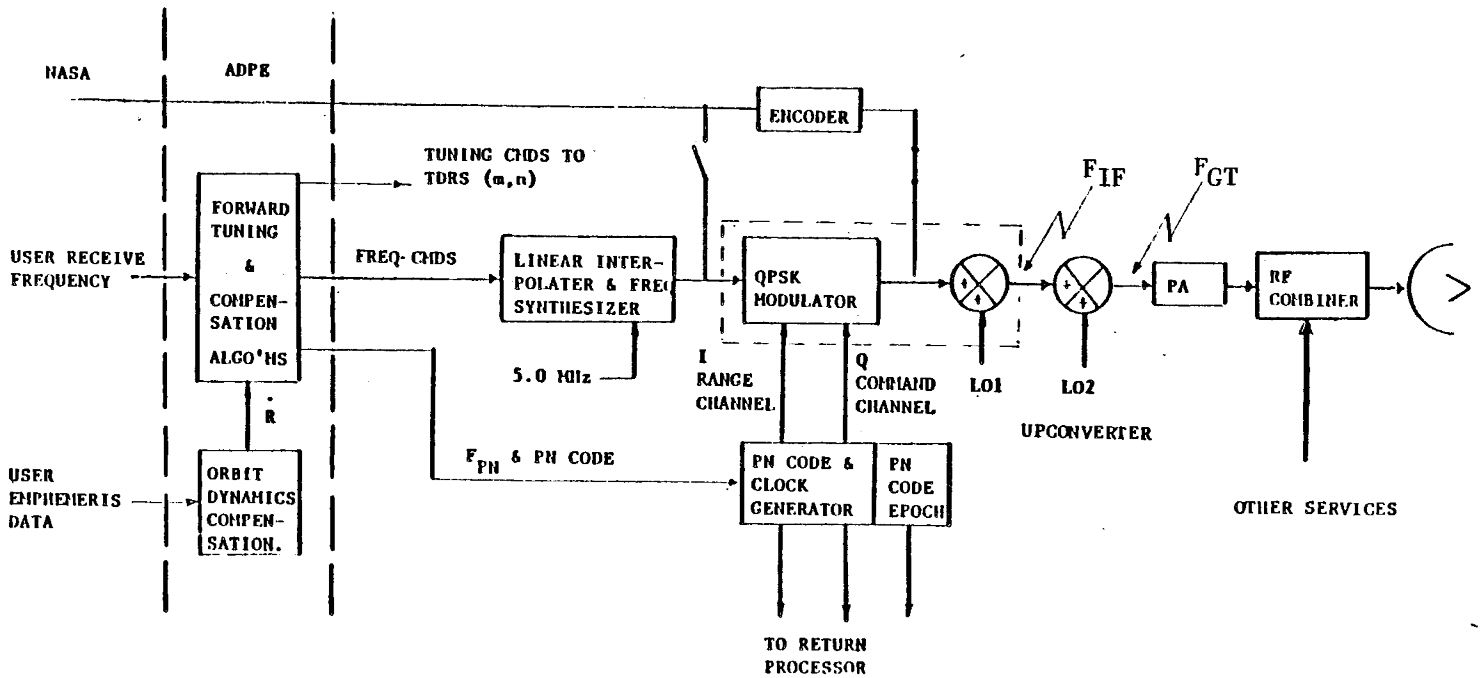


Figure 3-4. Uplink Signal Generation

The frequency synthesizer generates an IF F_o from a 5-MHz input reference signal. Between the ADPE defined points F_o, $F_o + \Delta F_1$, and $F_o + \Delta F_1 + \Delta F_2$, the linear interpolator performs linear interpolation and generates a linear ramp of high resolution frequency commands to update the frequency synthesizer output. The phase of the IF carrier is continuous during the interpolation process. The Doppler compensation profiles are presented in figure 3-5.

3.2.2.5 The forward modulator consists of a PN generator and a QPSK modulator. The PN generator receives the user spacecraft unique PN code assignment and PN clock from the ADPE and generates two synchronous PN sequences: a short (command) code and a long (ranging) code. The clock frequency is related to the user spacecraft transmit frequency (Fref) and is given by $\frac{31}{96M}$ Fref (M = 240 for MA and SSA or 1600 for KSA). The resolution of the PN clock frequency is 0.01 Hz. The clock frequency can also be Doppler compensated during the user acquisition process (reference 10).

3.2.2.6 For the internal modulation mode, the QPSK modulator receives the IF carrier from the frequency synthesizer and the two synchronous PN sequences from the PN generator. A command channel is formed by Biphase Shift Key (BPSK) modulating the IF carrier (0 and 180 degrees) with either the modulo-2 sum of the input data and the short PN code or, in the case of high data bit rate, with the input data. A separate range channel is formed by BPSK (±90 degrees) modulating a delayed IF carrier with the long PN code. The QPSK modulator combines the range and command channels to form a spread spectrum QPSK signal. For the external modulation mode, the IF carrier is modulated externally, which bypasses the forward modulator.

3.2.2.7 The modulated signal is frequency translated within the forward modulator, converted to K-band frequency by the upconvertor, power amplified, and then input to the K-band RF combiner via the forward configuration switch. The RF combiner combines all uplink services P(k), uplink pilot F_p, and TDRS command to form a composite uplink signal. P(k) consists of KSA-1, KSA-2, SSA-1, SSA-2, and MA (for k = 1, 2,..., 5, respectively). The composite uplink signal is transmitted to a TDRS via the 18-meter K-band antenna.

3.2.2.8 The uplink pilot, F_p, generated from a 5-MHz cesium standard at WSGT, is combined with the uplink MA signal in the MA upconvertor. F_p is transmitted continuously to the TDRS at a fixed frequency of 15,150 MHz and is used to generate the forward and return coherent frequency translation and return telemetry carrier on board the TDRS transponder. The TDRS command signal, generated from the TTC equipment at WSGT, is transmitted to the TDRS at a nominal center frequency of 14,785.9625 MHz. The TDRS command signal is used for spacecraft maneuver and control, such as momentum dumping, antenna pointing, SSA forward and return frequency tuning, polarization selection, etc. (Reference 6.)

3.2.2.9 After the user spacecraft is acquired, Doppler compensation can be terminated at NASA request when closed-loop Doppler measurement is required. The linear interpolator and frequency synthesizer will change smoothly from a compensated mode to a measurement mode within 9 seconds to minimize the probability of user loss of lock. The synthesizer output will linearly change to a constant value such that the nominal forward frequency from the TDRS to a user spacecraft becomes an exact multiple of 221 Hz for S-band and 146.9 Hz for K-band (reference 10). The linear interpolator and frequency synthesizer can also provide fine frequency tuning for the forward signal. The allocated frequency tuning ranges are: ±0.700 MHz for KSA, ±0.250 MHz for SSA, and ±0.092 MHz for MA. (The uplink frequency allocations at WSGT are summarized in figure 3-6 and table 3-4.)

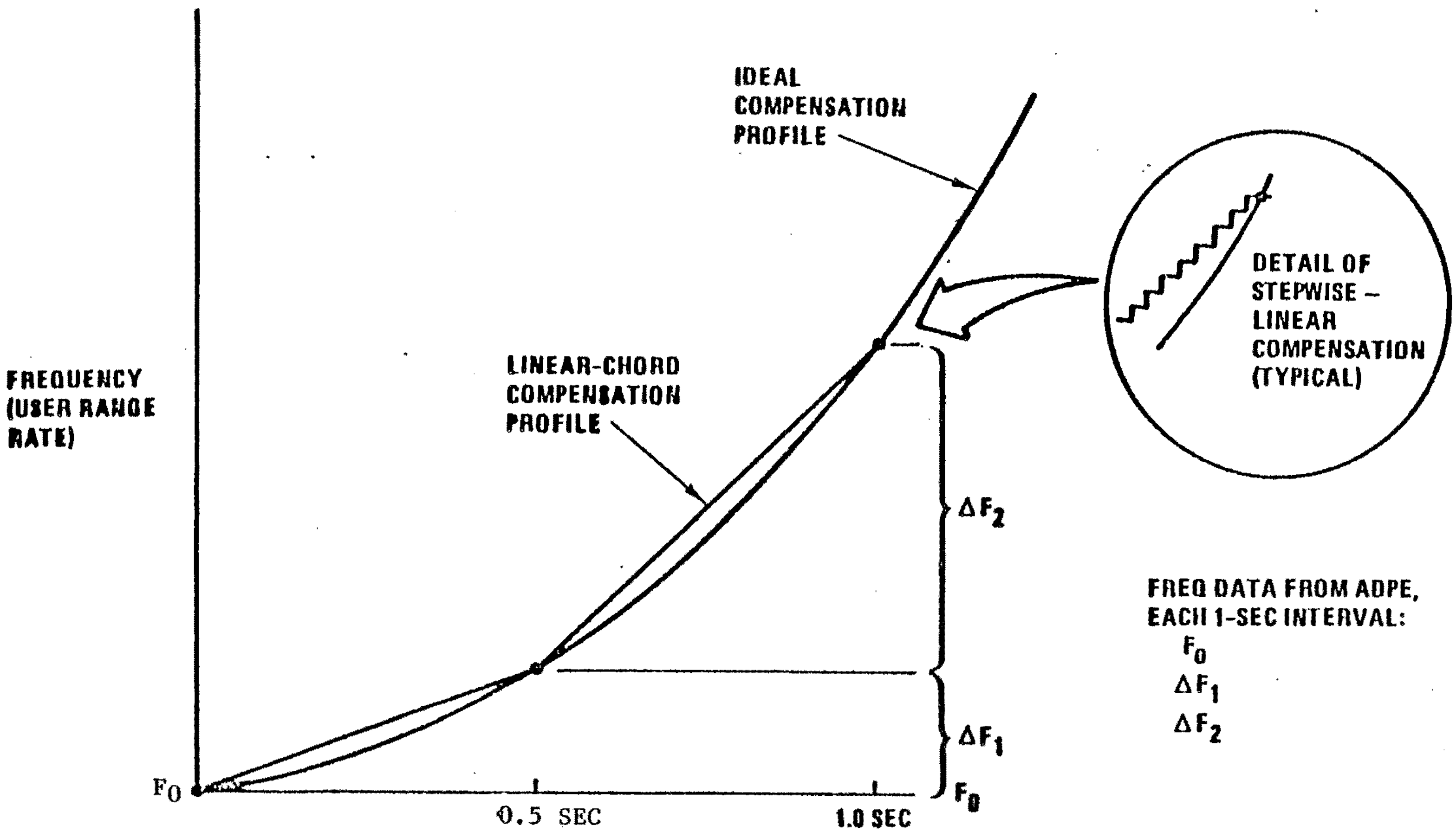


Figure 3-5. Doppler Compensation Profiles

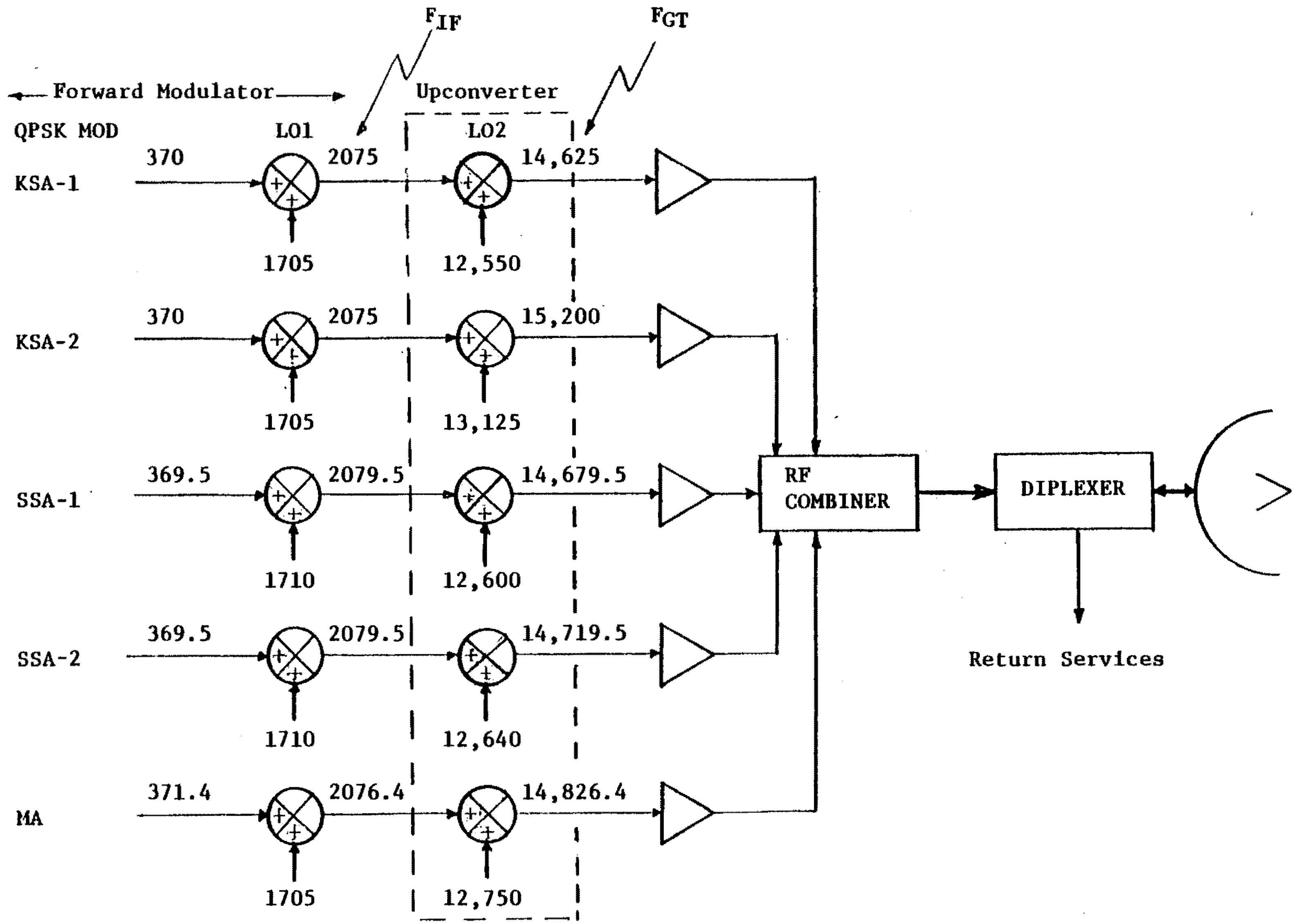


Figure 3-6. WSGT Uplink Carrier Frequency Allocations

Table 3-4. WSGT Uplink Frequency Allocations (reference 4)

Parameters (See figure 3-6 for nomenclature)	Service (MHz)				
	KSA-1	KSA-2	SSA-1	SSA-2	MA
QPSK modulator output	370.0 ± 1.270	370 ± 1.270	369.5 ± 0.340	369.5 ± 0.340	371.4 ± 0.185
F_{L01} (first local oscillator)	1705.0	1705.0	1710.0	1710.0	1705.0
F_{IF} (intermediate frequency)	2075.0 ± 1.270	2075 ± 1.270	2079.5 ± 0.340	2079.5 ± 0.340	2076.4 ± 0.185
F_{L02} (second local oscillator)	12,550.0	13,125.0	12,600.0	12,640.0	12,750.0
F_{GT} (nominal center frequency transmitted)	14,625.0 ± 1.270	15,200.0 ± 1.270	14,679.5 ± 0.340	14,719.5 ± 0.340	14,826.4 ± 0.185
	±0.700 tuning ±0.570 compensation		±0.250 tuning ±0.090 compensation		±0.092 tuning ±0.093 compensation

3.2.3 FORWARD SIGNAL VIA THE TDRS

3.2.3.1 The composite uplink signal transmitted from WSGT to the TDRS is received via the 2-meter K-band SGL antenna. After isolation by a diplexer, the uplink signal is subsequently downconverted to an IF by a K-band downconvertor. The IF signal is fed to the forward processor which demultiplexes, bandpass filters, amplifies, and independently levels the forward link services and extracts the IF pilot and command carrier. The Doppler shifted IF pilot is input to the master frequency generator as the reference signal to generate the required coherent forward translation frequencies (refer to section 2.2). Figure 3-7 shows the forward signal via the TDRS.

3.2.3.2 The MA signal is coherently translated to the nominal 2106.4-MHz S-band frequency within the forward processor. The forward MA signal is routed to redundant driver amplifiers in the MA transmitter. The driver amplifier output signal is power split by a 12-way power divider which supplies the drive signal for 12 phase shifter/ power amplifier channels. The phase shifters are adjusted by ground command to steer the forward channel array beam. Each power amplifier output is coupled through a diplexer to one of 12 transmit/receive elements in the 30-element MA antenna array. Any 8 of the 12 element channels provide sufficient power to satisfy system EIRP requirements. The MA antenna array is a physically passive system; the forward beam is formed and steered electronically without any antenna motion. The forward MA signal is left-hand circular polarized.

3.2.3.3 The downconverted KSA signals are coherently translated to 13,775.0-MHz nominal center frequency by the forward processor. The KSA forward signal is amplified by a K-band TWTA, and then is routed through a polarization selection switch to one of the 4.9-meter SA antennas for transmission. The forward KSA signal can have either RHCP or LHCP, selectable via ground command.

3.2.3.4 The downconverted SSA signals are coherently translated to the S-band forward frequencies via the forward processor. Any forward frequency in the 2030.435- to 2113.315-MHz band can be selected for each SSA channel. Frequency tuning for the SSA channels is accomplished by a combination of ground controlled spacecraft channel tuning and fine tuning of the ground terminal transmitted uplink frequency. The spacecraft forward S-band channel is tuned over the applicable S-band frequency range by the forward SSAFS in discrete 0.5-MHz increments. The 221/240 relationship between the forward and return SSA services is achieved by digitally changing the uplink frequency by 19/240 of the SSA transmit frequency whenever the SSAFS is tuned. This process substantially simplifies the spacecraft frequency synthesizer. (SSA frequency tuning and translation are shown in figure 3-8.) The SSA forward signal is routed to an S-band TWTA for amplification, then through an S-band diplexer and polarization selection switch, and is fed to the 4.9-meter SA antenna for transmission. The forward SSA signal can have either RHCP or LHCP, selectable via group command.

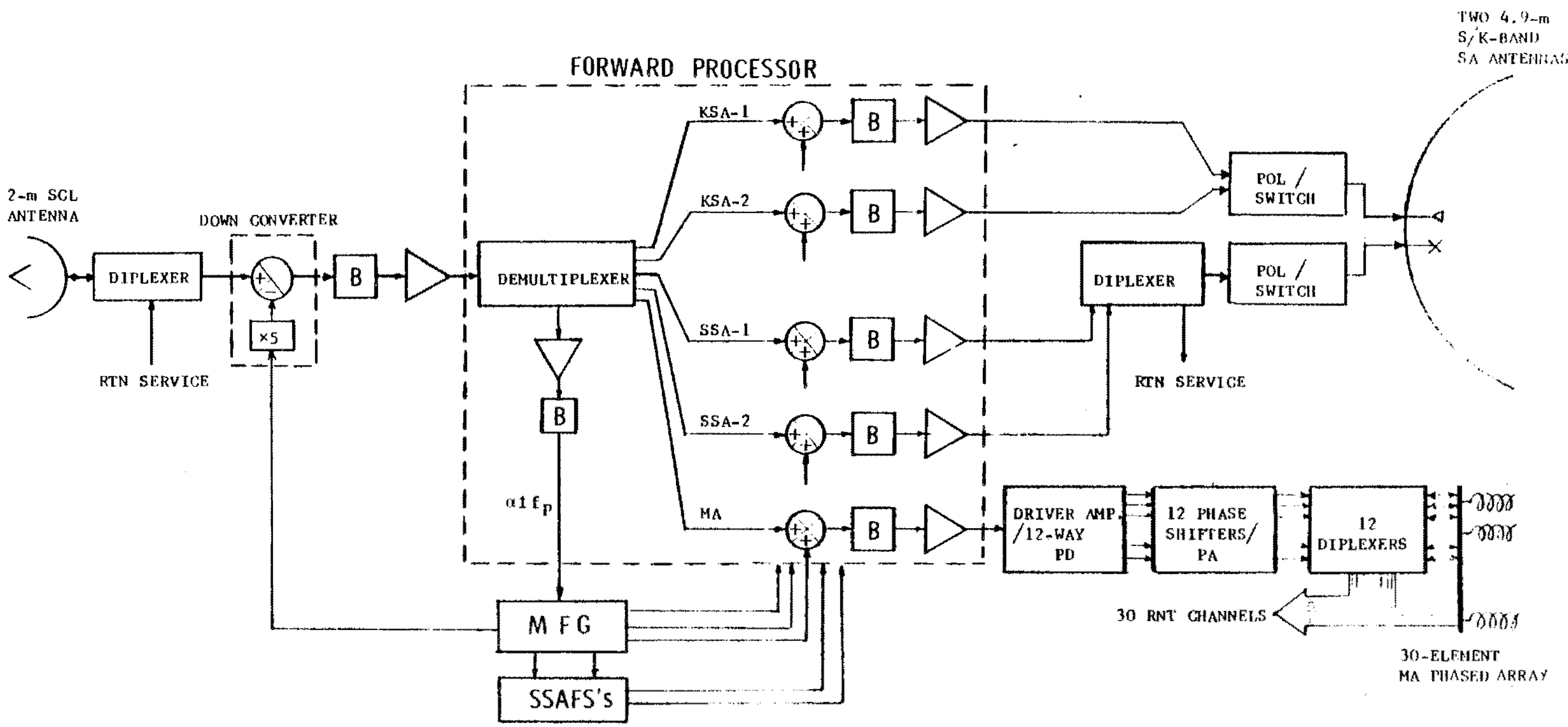
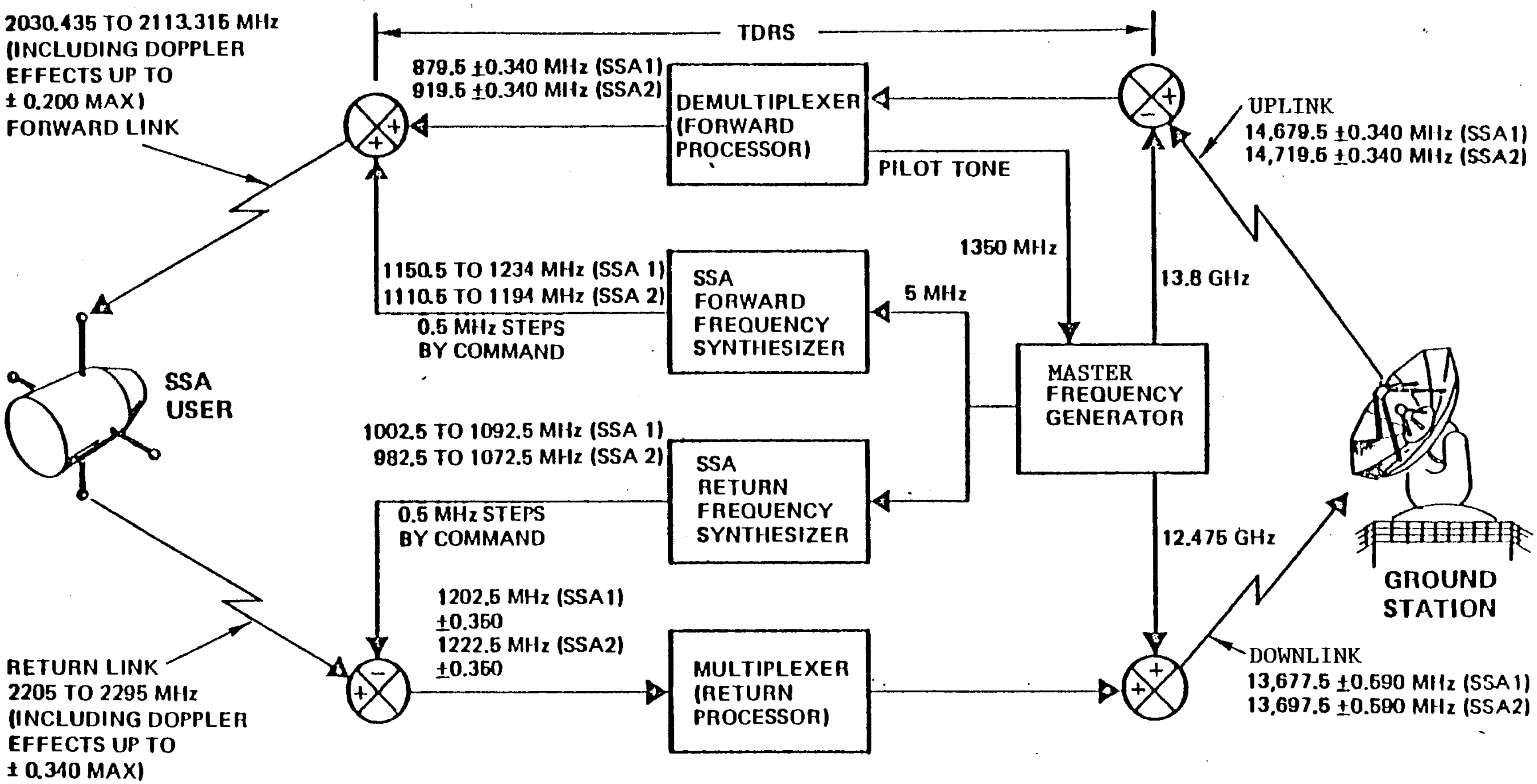


Figure 3-7. Forward Signal Via the TDRS



NOTES

- SPACECRAFT SYNTHESIZER TUNES IN 0.5 MHz INCREMENTS VIA GROUND COMMANDS (TT&C)
- 221/240 USER FREQUENCY RATIO ACCOMPLISHED BY GROUND TERMINAL TUNING
- THE FORWARD LINK SSA FREQUENCY IS AN EXACT INTEGER MULTIPLE OF 221 Hz DURING TRACKING

Figure 3-8. SSA Frequency Tuning and Translation

3.2.3.5 Let $(TDRS)_i$ be the i^{th} Tracking and Data Relay Satellite on the forward link and

$P(k)$ = the uplink carriers with k=1, 2, . . . , 5, corresponding to KSA-1, KSA-2, SSA-1, SSA-2, and MA

F_p = the zero-Doppler uplink pilot frequency = 15,150 MHz

$\alpha 1_i$ = Doppler factor of the uplink signal due to relative motion between WSGT and $(TDRS)_i$

$a(k)F_p$ = effective forward frequency translation on board the $(TDRS)_i$

Then, the forward frequency via the $(TDRS)_i$ to user spacecraft can be calculated as follows:

$$\alpha 1_i \, P(k) + \alpha 1_i \, a(k)F_p = \alpha 1_i \, [P(k) + a(k)\, F_p]$$
$$= \alpha 1_i \, Fref/K$$

Where:

$Fref/K \equiv P(k) + a(k)F_p$ is the TDRS transmit center frequency

Fref = user spacecraft transmit center frequency

K = user spacecraft turnaround ratio

(Figure 3-9 gives a schematic representation of the forward frequency translation via the TDRS. The calculation of the associated parameters are given in section 2.2 and are summarized in table 3-5.)

3.2.4 SIGNAL PROCESSING BY THE USER TRANSPONDER

3.2.4.1 General. The user transponder provides the remaining telecommunication links between the orbiting user spacecraft and WSGT via the TDRS. The two types of user spacecraft, MA and SA, differ only in their transponder channel assignment and data rate. The user transponder provides the following services:

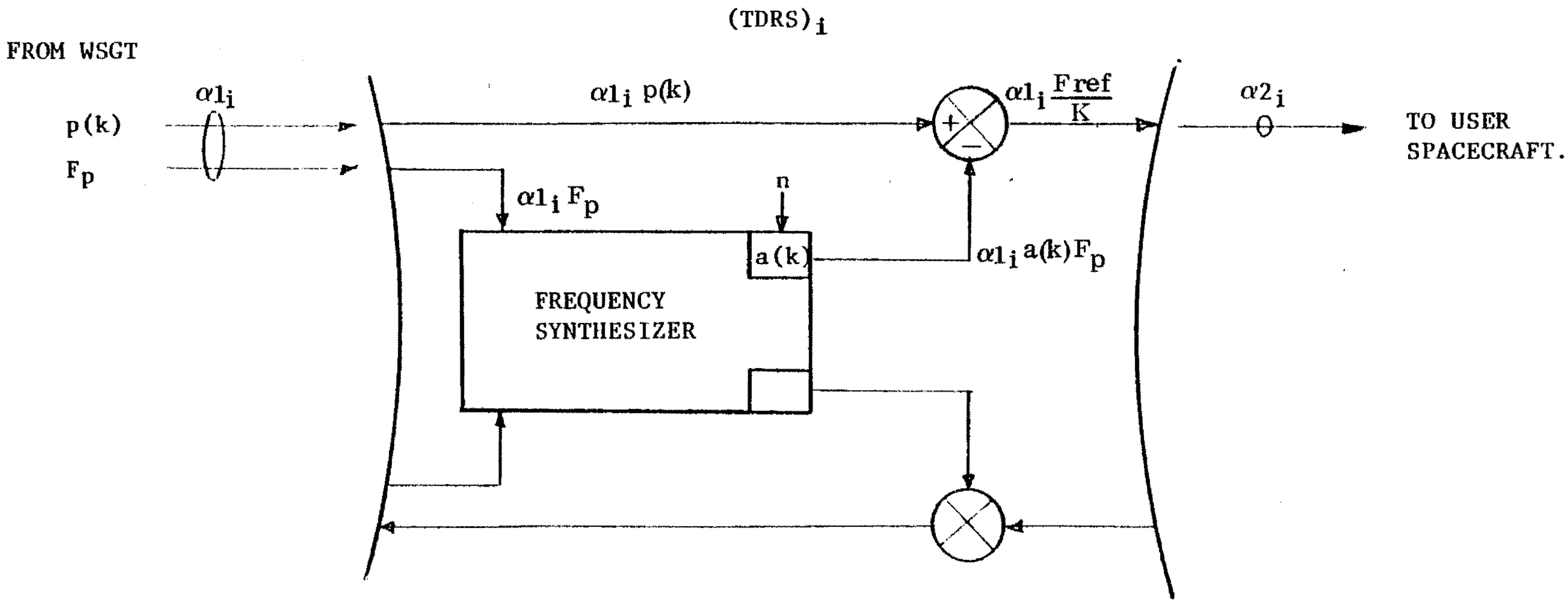
a. Receive, search, and acquire the forward link PN code and carrier.

b. Extract the forward command messages.

c. Transmit one or two independent return link data channels.

d. Provide coherent (closed-loop) or noncoherent (open-loop) tracking return signal.

The signal processing by the user transponder is schematically shown in figure 3-10 (reference 11).



$\frac{Fref}{K} = p(k) - a(k)F_p$: TDRS TRANSMIT CENTER FREQUENCY

$a(k)F_p$: THE EFFECTIVE FORWARD FREQUENCY TRANSLATION

Figure 3-9. Schematic Representation of the Forward Frequency Translation Via the TDRS

Table 3-5. Forward Frequency Translation Via the TDRS

Service / Parameters	KSA-1	KSA-2	SSA-1	SSA-2	MA
P (k)	14,625.0	15,200.0	14,679.5	14,719.5	14,826.4
$a(k)F_p$	850.0	1425.0	From 12,566.0 to 12,649.5 in 0.5-MHz steps	From 12,606.0 to 12,689.5 in 0.5-MHz steps	12,720.0
$Fref/K = P(k) - a(k)F_p$	13,775.0	13,775.0	2030.435 to 2113.315	2030.435 to 2113.315	2106.4

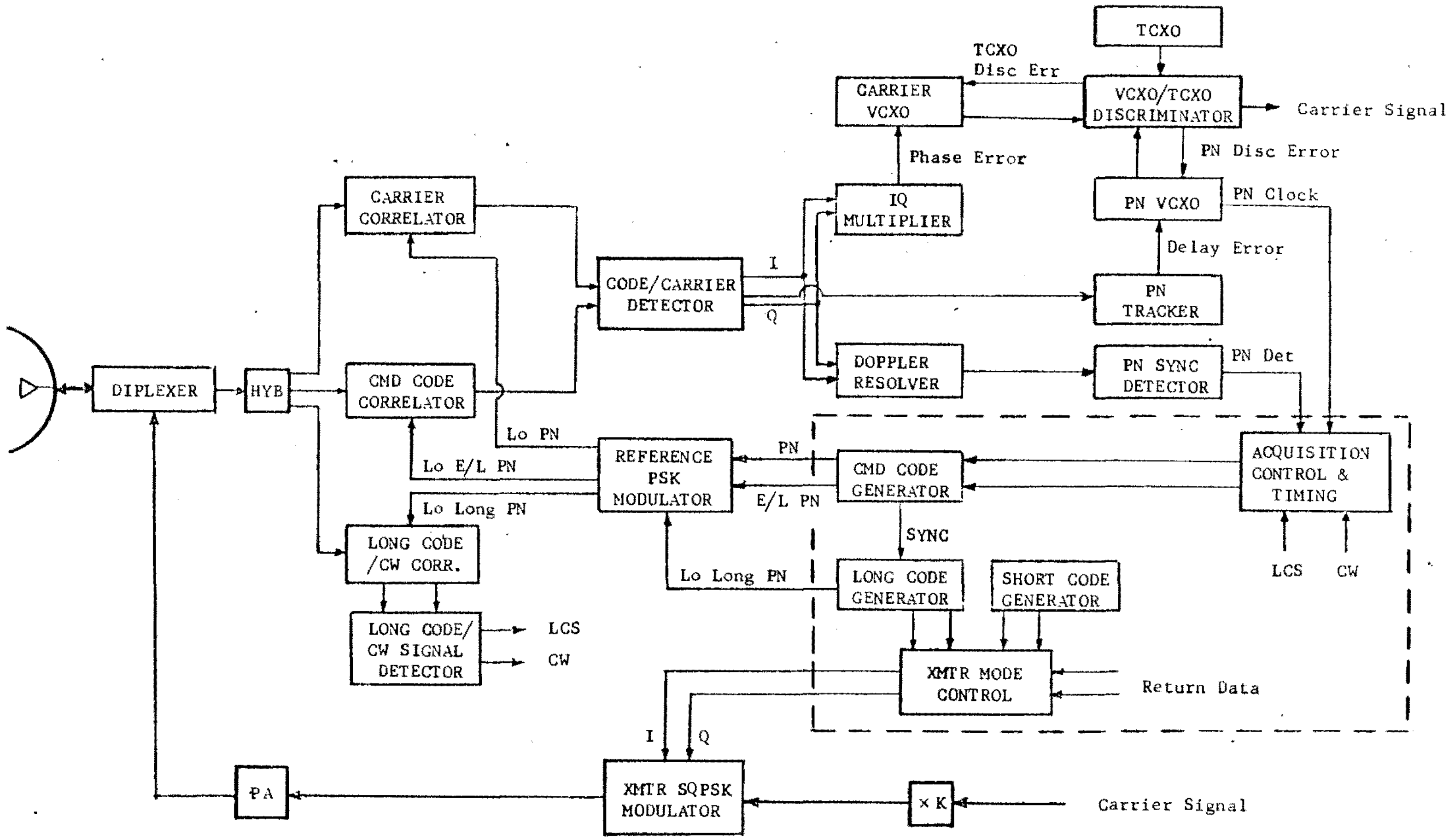


Figure 3-10. Signal Processing by the User Transponder

3.2.4.2 Receiver. The received signal is split into three paths: one for the carrier tracking channel, one for the command (short) code tracking channel, and one for the range (long) code/CW signal detection. The NASA standard TDRSS user transponder can be operated in either TDRSS mode or STDN mode. The range (long) code/CW detection is used as an automatic switch to configure the operational mode of the user transponder.

a. Command code tracking: the command code tracking channel consists of a code correlator, PSK modulator, code/carrier detector, PN tracker, local PN generator, and code VCXO. In the code correlator, the input signal is correlated with an early/late (E/L) PSK modulated local reference signal. The result is detected to baseband by the command code/carrier detector and subsequently input to the PN tracker. The PN tracker derives the PN timing error to adjust the PN VCXO. The local PN generator chip rate (PN clock) is thus tuned to match that of the received PN sequence.

b. Carrier tracking: at the time the PN tracking loop is acquiring, the carrier loop is also locking up with frequency aiding from the coherently related PN clock. The I (range channel) and Q (command channel) baseband signals are filtered and multiplied in the Costas loop IQ detector module to provide a carrier phase error signal to the carrier loop filter/VCXO module. In this process the carrier VCXO is coherently tuned to the received carrier signal.

c. During the acquisition process, highly accurate carrier and PN frequencies are required. For this reason the carrier and PN VCXO's are locked to a stable Thermal-controlled Crystal Oscillator (TCXO) during acquisition. This TCXO also serves as a noncoherent source for the transmitter.

d. Command code PN synchronization is accomplished by the Doppler resolver and PN sync detector modules. The Doppler resolver contains several baseband parallel filters to cover the initial acquisition frequency uncertainty. Each filter output is tested by a sequential detector contained in the PN sync detector. After the command code is acquired, the range (long) code acquisition is accomplished by searching over 256 chip positions.

3.2.4.3 Transmitter

a. The transmitter can be configured to operate in either coherent (closed-loop) mode or noncoherent (open-loop) mode. In the coherent mode, the receiver is locked to the received signal, and the receiver VCXO normally supplies the transmit carrier signal through an RF switch. In the noncoherent mode, the highly stable TCXO reference, at approximately the same receiver rest frequency as the VCXO, drives the transmitter. The carrier is subsequently modulated by the transmitter SQPSK modulator.

b. In the coherent mode, the TDRSS I and Q data inputs are modulo-2 added to two range (long) PN sequences which have been time synchronized to the received range code to provide the ranging function. The resulting two digital sequences modulate the two quadrature channels of the SQPSK modulator. In the noncoherent mode, either a shorter pair of PN sequences is used, or the same range code used in the coherent mode may be selected by ground command (the forward and return signal parameters are listed in tables 2-3 and 2-4, respectively).

c. The transmit carrier frequency is related to the receiver rest frequency by a turnaround ratio K (K = 240/221 for MA and SSA, and 1600/1469 for KSA). Let $\alpha 1_i$ Fref/K be the $(TDRS)_i$ transmit frequency, $\alpha 2_i$ be the Doppler factor on the forward link due to relative motion between $(TDRS)_i$ and the user spacecraft. Then the user spacecraft transmit carrier frequency is given by:

$$K (\alpha 1_i \alpha 2_i Fref/K) = \alpha 1_i \alpha 2_i Fref$$

3.2.5 RETURN SIGNAL VIA THE TDRS

3.2.5.1 The return signals transmitted from the user spacecraft to the TDRS are received, bandpass filtered, amplified, coherently translated, then multiplexed at the TDRS to form a composite downlink signal, and upconverted to K-band frequency for downlink transmission to WSGT (see figure 3-11).

3.2.5.2 The TDRS transponder uses the Doppler shifted uplink pilot frequency, $\alpha 3F_p$, at the time of reception of the return signals, to generate the required coherent return translation frequencies and return TDRS telemetry.

3.2.5.3 The return MA signals from all user spacecraft are received by the 30-element MA antenna simultaneously, and frequency translated into a 30-channel FDM within the MA receiver (refer to para 2.2.4). Each of the 30 MA channels has a different Doppler frequency due to the return frequency translations. The Doppler frequency differences contain the same Doppler signature, $\alpha 3$, of the uplink pilot and equal 7.5 ($\alpha 3$ - 1) MHz between two consecutive FDM channels.

3.2.5.4 The KSA return signals are received by the SA antenna in either left-hand or right-hand circular polarization, selectable by ground command. The KSA signals are then bandpass filtered, amplified, and frequency translated to IF. There are two downlink channels available for the KSA service: a composite channel and a dedicated channel. The dedicated channel is reserved for high data rate return service.

3.2.5.5 The SSA signals are received by the SA antenna, and are transferred through a polarization selection switch and SSA diplexer. The signals are then bandpass filtered, amplified, and frequency translated to IF by the return SSAFS (refer to para 2.2.3). The return SSAFS provides the coarse frequency tuning for a return SSA frequency range of 2205 to 2295 MHz in discrete 0.5-MHz increments. The SSAFS return frequency translation is selected via ground command to accommodate the downlink SSA frequency allocations.

3.2.5.6 The multiplexer combines the 30-channel MA signals, the two SSA signals, and either one of the two KSA signals into a single composite signal for transmission to the WSGT over one of the two downlink channels. The remaining KSA signal is bandpass filtered, amplified, and routed directly to the second (dedicated) downlink channel. Either of the two KSA signals can be selected by ground command for transmission over the dedicated channel.

3.2.5.7 The multiplexed downlink signal and the dedicated KSA signal are each translated to K-band downlink frequency by an upconvertor. The signals are bandpass filtered, amplified by a K-band TWTA, and routed to the 2-meter K-band SGL antenna for transmission. The dedicated and composite channels are required to have different polarization for channel discrimination.

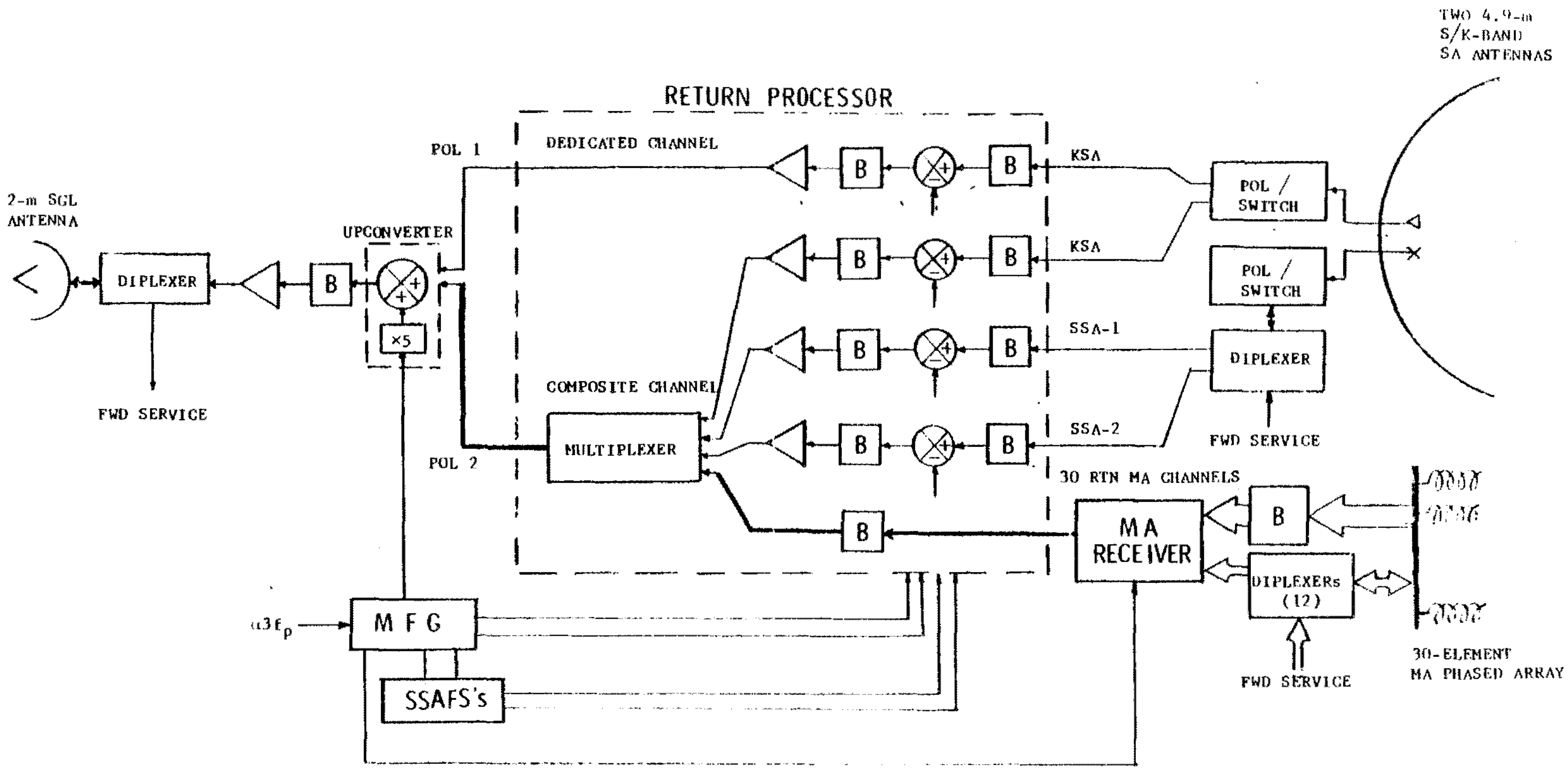


Figure 3-11. Return Signals Via the TDRS

3.2.5.8 Let $(TDRS)_j$ be the jth Tracking and Data Relay Satellite on the return link and

$\alpha 3_j$ = Doppler factor of the uplink pilot at the time of reception of the return signals

$\beta 1_j$ = Doppler factor of the return signal due to relative motion between user spacecraft and $(TDRS)_j$

$b(k)F_p$ = effective return frequency translation on board the $(TDRS)_j$ with k equals 1, 2, 3, 4, and 5 for KSA-1, KSA-2, SSA-1, SSA-2, and MA, respectively.

Then, the downlink frequency via the $(TDRS)_j$ to WSGT can be calculated as follows (see figure 3-12):

$$\alpha 1_i \, \alpha 2_i \, \beta 1_j \, Fref + \alpha 3_j \, b(k) F_p$$

The calculation of the return link parameters are given in para 2.2 and are summarized in table 3-6.

3.2.6 CLOSED-LOOP DOPPLER FORMULAS

Let $\beta 2_j$ be the Doppler factor of the downlink signal due to the relative motion between $(TDRS)_j$ and WSGT, then the downlink frequency received by WSGT is given by:

$$\beta 2_j \left[\alpha 1_i \, \alpha 2_i \, \beta 1_j \, Fref + \alpha 3_j \, b(k) F_p\right]$$

or

$$\alpha 1_i \, \alpha 2_i \, \beta 1_j \, \beta 2_j \, Fref + \alpha 3_j \, \beta 2_j \, b(k) F_p$$

The instantaneous Doppler frequency Fd(k) is defined by:

$$Fd(k) = \alpha 1_i \, \alpha 2_i \, \beta 1_j \, \beta 2_j \, Fref + \alpha 3_j \, \beta 2_j b(k) F_p - \left[Fref + b(k) F_p\right]$$

Where:

$$\alpha 1_i \, \alpha 2_i \, \beta 1_j \, \beta 2_j = 1 - \frac{1}{c} \dot{R}L_{ij}$$

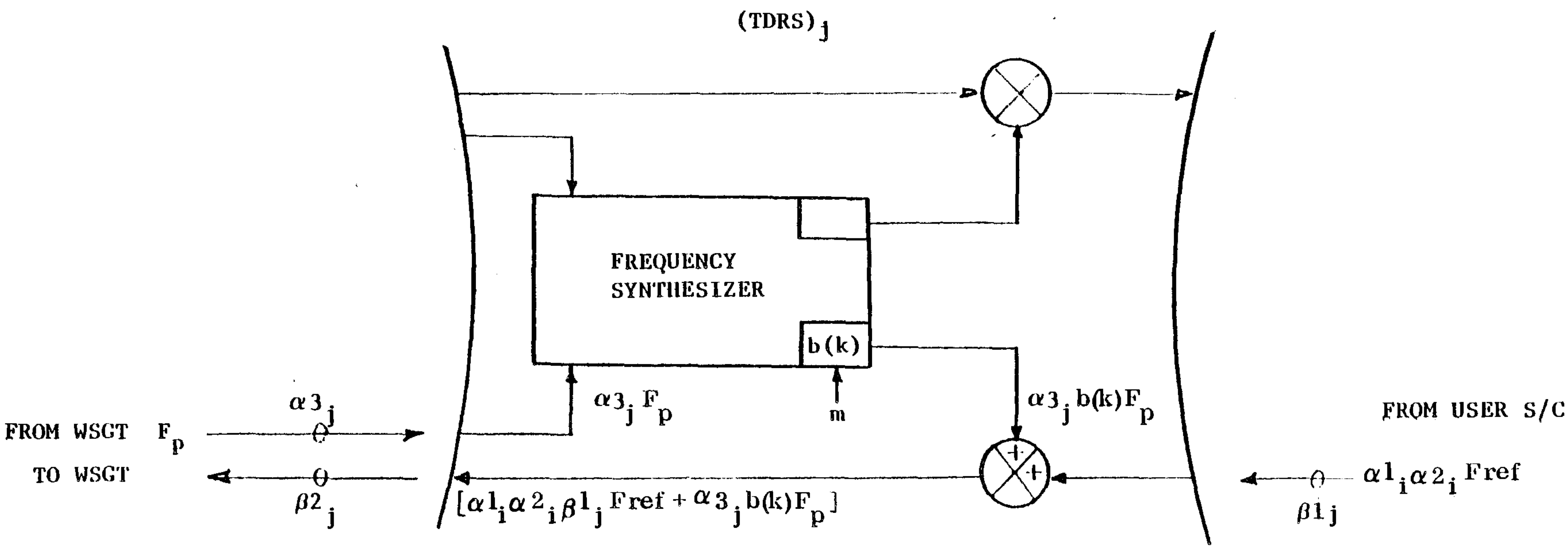
$$\alpha 3_j \, \beta 2_j = 1 - \frac{1}{c} \dot{R}s_j$$

with

$$\dot{R}L_{ij} \equiv \dot{R}1_i + \dot{R}2_i + \dot{R}3_j + \dot{R}4_j$$

$$\dot{R}s_j \equiv \dot{R}5_j + \dot{R}4_j$$

These relations are derived in appendix B.



$b(k)F_p$: THE EFFECTIVE RETURN FREQUENCY TRANSLATION

Figure 3-12. Schematic Representation of the Return Frequency Translation Via the TDRS

Table 3-6. Return Frequency Translation Via the TDRS

Parameter \ Service	KSA-1	KSA-2	SSA-1	SSA-2	MA
Fref/K	13,775.0	13,775.0	2030.435 to 2113.315	2030.435 to 2113.315	2106.4
K	1600/1469	1600/1469	240/221	240/221	240/221
Fref	15,003.4	15,003.4	2205 to 2295	2205 to 2295	2287.5
$b(k)F_p$	- 1475	- 1075	13,677.5 - Fref in 0.5-MHz steps	13,697.5 - Fref in 0.5-MHz steps	30-channel FDM: $b_1(5)F_p$ with 1 = 1, 2, . . . , 30 11,117.5, 11,125.0, 11,132.5, 11,140.0, 11,147.5 11,155.0, 11,162.5, 11,170.0, 11,177.5, 11,185.0 11,192.5, 11,200.0, 11,207.5, 11,215.0, 11,222.5 11,230.0, 11,237.5, 11,245.0, 11,252.5, 11,260.0 11,267.5, 11,275.0, 11,282.5, 11,290.0, 11,297.5 11,305.0, 11,312.5, 11,320.0, 11,327.5, 11,335.0
Fref + $b(k)F_p$	13,528.4	13,928.4	13,677.5	13,697.5	Center of FDM band 13,513.75

Substitute back into the formula for Fd(k)

$$Fd(k) = \left[1 - \frac{1}{c}\dot{R}L_{ij}\right] Fref + \left[1 - \frac{1}{c}\dot{R}s_j\right] b(k)F_p - \left[Fref + b(k)F_p\right]$$

$$= -\frac{1}{c}\dot{R}L_{ij}\ Fref - \frac{1}{c}\dot{R}s_j\ b(k)F_p$$

Note

If $i = j$ Fd(k) $\equiv$ two-way Doppler

$i \neq j$ Fd(k) $\equiv$ hybrid Doppler

It should be noted that the frequency differences in the second Doppler term of the 30-channel MA FDM signal will be subsequently removed by the MA element separator at WSGT prior to MA beam forming and signal demodulation (see figure 3-17).

3.3 OPEN-LOOP TRACKING (ONE-WAY AND DIFFERENCED ONE-WAY DOPPLER)

3.3.1 GENERAL

The TDRSS can provide one-way Doppler tracking for a user spacecraft without scheduling a forward link from WSGT to the user spacecraft. One-way Doppler tracking consists of return signal generation by the user spacecraft transponder, return frequency translation via the TDRS, and downlink signal processing at WSGT. Differenced one-way Doppler is derived by a tracking data user ADPE from two 1-way Doppler data streams via two TDRS's simultaneously. Differenced one-way Doppler is used to minimize the user spacecraft transmit frequency error or offset. Figures 3-13 and 3-14 give a simplified diagram of the open-loop tracking configuration and signal generation and processing, respectively (reference 12).

3.3.2 ONE-WAY DOPPLER

3.3.2.1 The return signal is generated by the user spacecraft transponder via an on-board TCXO. Through a return modulator, the return signal is properly modulated consistent with the selected return channel characteristics. The user spacecraft transmit frequency is approximately K times the user spacecraft receiver rest frequency, and is stable to within ± 700 Hz for S-band and ±5 kHz for K-band over any 48-hour period for the NASA standard transponder.

3.3.2.2 Let Fref be the NASA estimate of user spacecraft transmit frequency; Fref is defined in the SHO. Let $\Delta f(t)$ be the user spacecraft transmit frequency error or offset from the Fref estimate. Then the user spacecraft transmit frequency F_o can be written as:

$$F_o = \text{Fref} + \Delta f(t)$$

3.3.2.3 The return signal F_o is transmitted to the TDRS and subjected to a Doppler shift $\beta 1$. The TDRS receives, frequency translates, and relays the return signal to WSGT. The downlink frequency from TDRS to WSGT can be written as:

$$\beta 1 \, [\text{Fref} + \Delta f(t)] + \alpha 3 b(k) F_p$$

3.3.3 OPEN-LOOP DOPPLER FORMULAS

3.3.3.1 One-way Doppler. Let $\beta 1_i$ and $\beta 2_i$ be the Doppler factors on the return and downlink via the return $(\text{TDRS})_i$, respectively. Then the downlink frequency received by WSGT is given by:

$$\beta 2_i \left\{ \beta 1_i \, [\text{Fref} + \Delta f(t)] + \alpha 3_i b(k) F_p \right\}$$

or

$$\beta 1_i \, \beta 2_i \, [\text{Fref} + \Delta f(t)] + \alpha 3_i \, \beta 2_i b(k) F_p$$

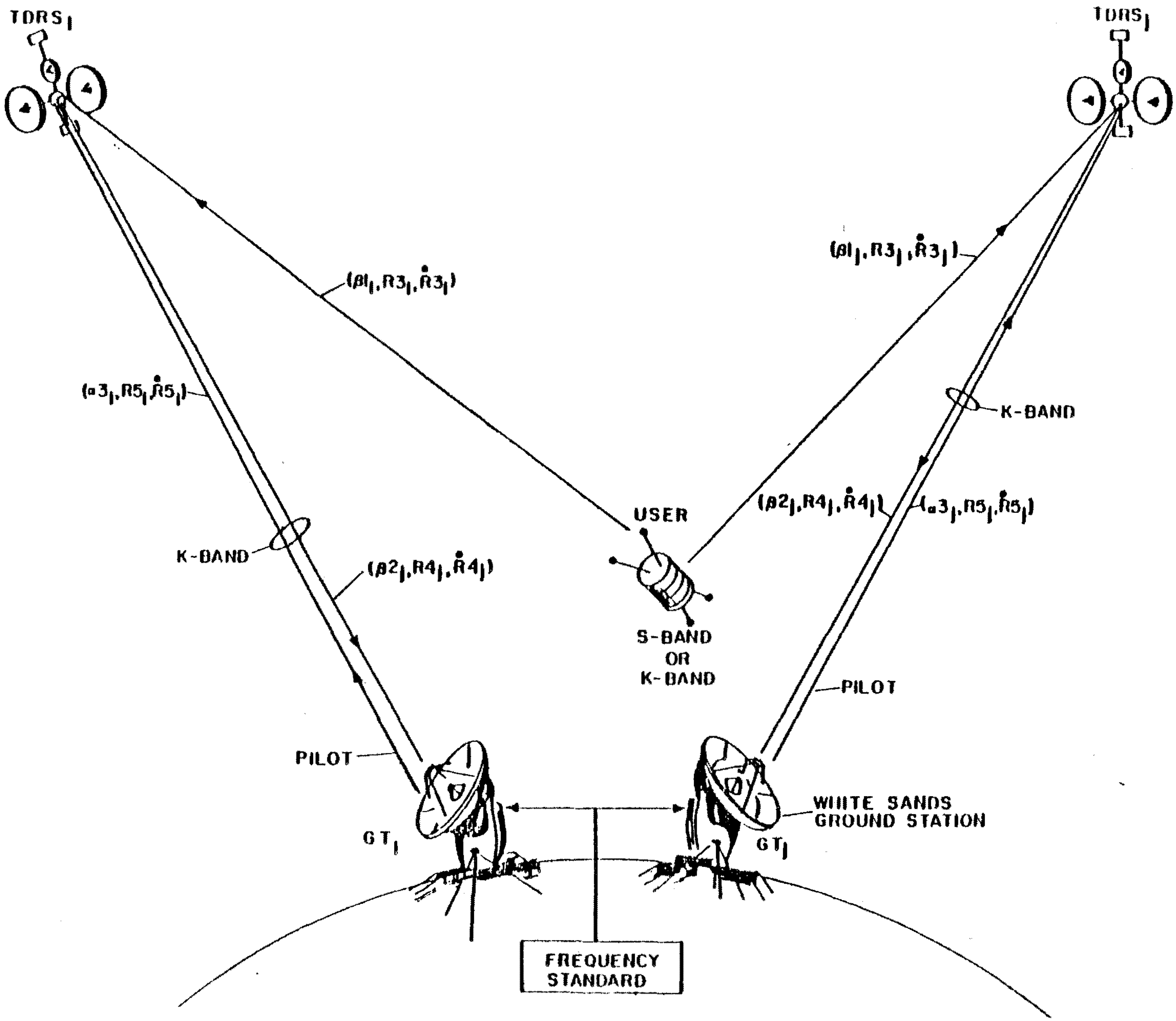


Figure 3-13. Open-loop Tracking Configuration

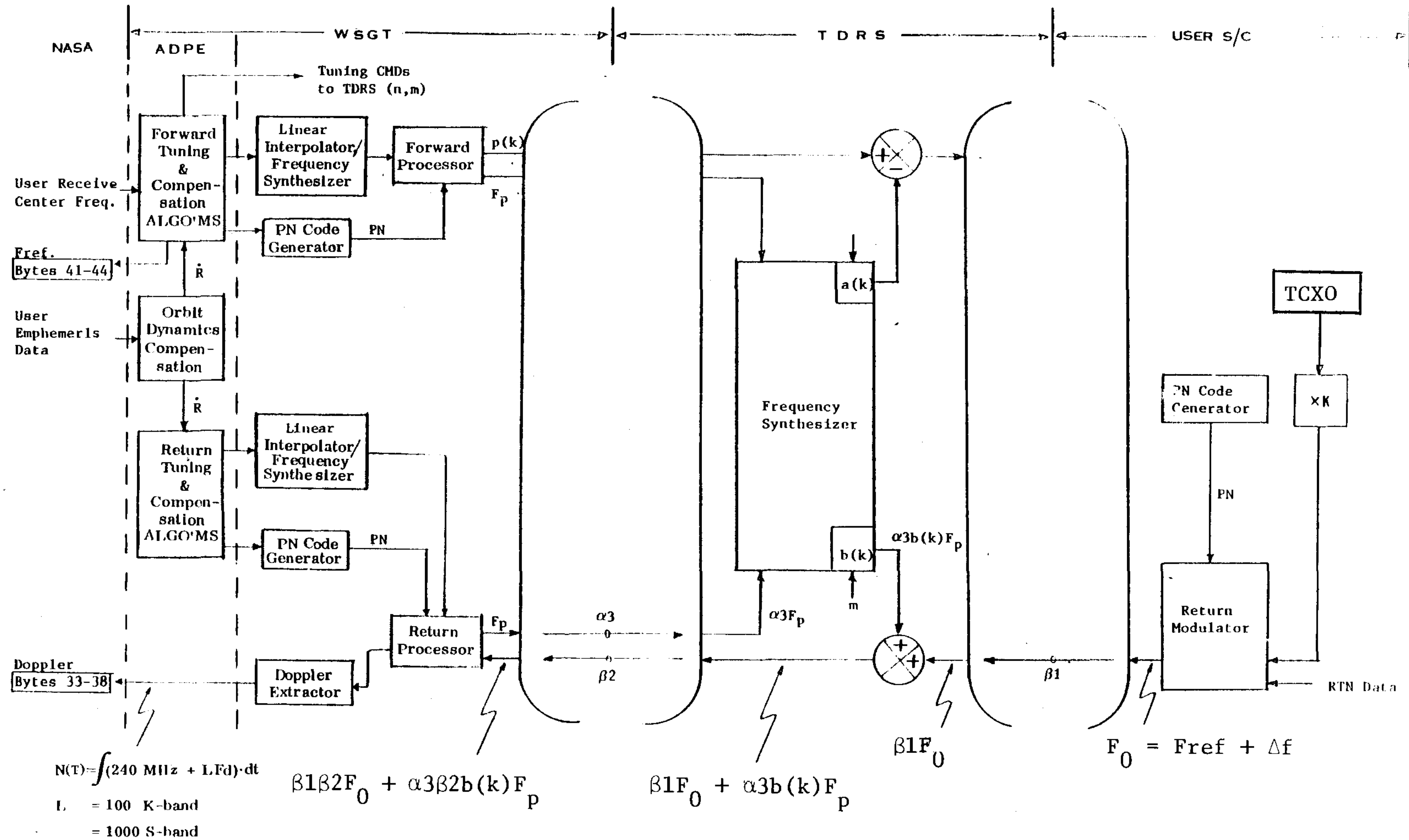


Figure 3-14. Open-loop Signal Generation and Processing

The instantaneous one-way Doppler frequency Fd(k) is defined by:

$$Fd\,(k) = \beta 1_i \beta 2_i \;[Fref + \Delta f(t)] + \alpha 3_i \beta 2_i\, b(k) F_p - [Fref + b(k) F_p]$$

Where:

$$\beta 1_i \beta 2_i = 1 - \frac{1}{c}\dot{R}L_i$$

$$\alpha 3_i \beta 2_i = 1 - \frac{1}{c}\dot{R}s_i$$

With
$$\dot{R}L_i \equiv \dot{R}3_i + \dot{R}4_i$$

$$\dot{R}s_i \equiv \dot{R}5_i + \dot{R}4_i$$

These relations are derived in Appendix B.

Substituting back into the formula for Fd(k):

$$Fd(k) = [1 - \frac{1}{c}\dot{R}L_i]\,[Fref + \Delta f(t)] + [1 - \frac{1}{c}\dot{R}s_i]\, b(k)F_p - [Fref + b(k)F_p]$$

$$= \Delta f(t) - \frac{1}{c}\dot{R}L_i\; Fref - \frac{1}{c}\dot{R}s_i\; b(k)F_p - \frac{1}{c}\dot{R}L_i \Delta f(t)$$

Where: Fref = the NASA-estimated user transmit frequency, as specified in the SHO. (Fref (k) $\simeq 2 \times 10^9$ Hz for S-band or 1.5×10^{10} Hz for K-band.

$\Delta f(t)$ = user transmit frequency offset from Fref. ($\Delta f \approx 10^3$ Hz for S-band or 10^4 Hz for K-band.)

$\frac{1}{c}\dot{R}L_i \Delta f(t)$ is in the order of 10^{-2} Hz for S-band and 10^{-1} Hz for K-band.

It is noted that the user spacecraft transmit frequency offset (Δf) contributes directly to the error of the Doppler frequency measurement. In order to minimize the effect of Δf, differenced one-way Doppler can be used.

3.3.3.2 <u>Differenced One-way Doppler</u>. For differenced one-way Doppler, the same user spacecraft transmitted signal $[Fref + \Delta f(t)]$ is received by both $(TDRS)_i$ and $(TDRS)_j$, frequency translated, and relayed independently to WSGT. Let $[Fd(k)]_i$ and $[Fd(k)]_j$ be the instantaneous one-way Dopplers via $(TDRS)_i$ and $(TDRS)_j$, respectively,

then
$$[Fd(k)]_i = \Delta f(t_i) - \frac{1}{c}\dot{R}L_i\; Fref - \frac{1}{c}\dot{R}s_i\; b(k)_i F_p - \frac{1}{c}\dot{R}L_i \Delta f(t_i)$$

$$[Fd(k)]_j = \Delta f(t_j) - \frac{1}{c}\dot{R}L_j\; Fref - \frac{1}{c}\dot{R}s_j\; b(k)_j F_p - \frac{1}{c}\dot{R}L_j \Delta f(t_j)$$

Note

$b(k)_i F_p$ and $b(k)_j F_p$ are not necessarily the same; e.g., the user spacecraft can utilize one-way SSA service via $(TDRS)_i$ and one-way MA service via $(TDRS)_j$.

Taking the difference:

$$\Delta Fd = \left[Fd(k)\right]_i - \left[Fd(k)\right]_j$$

$$= \left[\Delta f(t_i) - \frac{1}{c}\dot{R}L_i\ Fref - \frac{1}{c}\dot{R}s_i b(k)_i F_p - \frac{1}{c}\dot{R}L_i \Delta f(t_i)\right] - \left[\Delta f(t_j) - \frac{1}{c}\dot{R}L_j Fref - \frac{1}{c}\dot{R}s_j b(k)_j F_p - \frac{1}{c}\dot{R}L_j \Delta f(t_j)\right]$$

$$= \left[-\frac{1}{c}\dot{R}L_i Fref - \frac{1}{c}\dot{R}s_i b(k)_i F_p\right] - \left[-\frac{1}{c}\dot{R}L_j Fref - \frac{1}{c}\dot{R}s_j b(k)_j F_p\right] - \frac{1}{c}\dot{R}L_i \Delta f(t_i) + \frac{1}{c}\dot{R}L_j \Delta f(t_j) + \left[\Delta f(t_i) - \Delta f(t_j)\right]$$

t_i and t_j are the reception times of the return signals via $(TDRS)_i$ and $(TDRS)_j$, respectively. The term $\left[\Delta f(t_i) - \Delta f(t_j)\right]$ can be expressed as:

$$\left[\Delta f(t_i) - \Delta f(t_j)\right] = \frac{df(t)}{dt}\Delta t$$

Where: Δt is the difference between the propagation delays from the user spacecraft via $(TDRS)_i$ and $(TDRS)_j$.

$\frac{df(t)}{dt}$ is the drift rate of the user spacecraft transmit frequency. For the NASA standard transponder, the maximum drift rate is approximately ±7 Hz/sec for S-band and ±50 Hz/sec for K-band.

After rearranging terms, ΔFd can be rewritten as follows:

$$\Delta Fd = \left[-\frac{1}{c}\dot{R}L_i Fref - \frac{1}{c}\dot{R}s_i b(k)_i F_p\right] - \left[-\frac{1}{c}\dot{R}L_j Fref - \frac{1}{c}\dot{R}s_j b(k)_j F_p\right] + \epsilon_1 + \epsilon_2$$

Where: $\epsilon_1 = -\frac{1}{c}(\dot{R}L_i - \dot{R}L_j)\ \Delta f(t_j)$

= the error term due to $\Delta f(t)$

$\epsilon_2 = (1 - \frac{1}{c}\dot{R}L_i)\ \frac{df(t)}{dt}\ \Delta t$

= the error term due to $\frac{df(t)}{dt}$

3.4 DOWNLINK SIGNAL PROCESSING AT WSGT

3.4.1 GENERAL

3.4.1.1 A total of 32 return services are available at WSGT. These services are divided into five independent service groups: KSA-1, KSA-2, SSA-1, SSA-2, and MA. The MA service group consists of 20 service strings, and the SA service groups consist of 3 service strings each. Any service string in a group is capable of sparing any other service string in the same group. The received downlink signals from any one of the three 18-meter K-band antennas can be connected to any one of the service strings in a particular service group via the return configuration switch. The WSGT can receive and process up to 19 MA, 6 SSA, and 6 KSA user spacecraft return signals simultaneously (one MA service string is reserved for return link calibration). Up to two S-band and K-band Shuttle return services can be substituted for normal SSA or KSA return services, respectively. The configuration switching for the downlink services is shown in figure 3-15 (reference 8).

3.4.1.2 The downlink signals are received by the 18-meter K-band antenna, and routed through a polarization selection switch to separate the KSA dedicated and the composite signals. The composite signal including the return TDRS telemetry is further separated into different carrier signals in a power divider. The downlink signal processing at WSGT consists of service configuration switching, downconversion, channel-weighting and combining (for the 30-channel FDM MA return signals), Doppler conversion and correction, signal demodulation, and Doppler and range extraction. The return TDRS telemetry is processed by separate TTC equipment at WSGT. A schematic representation of the downlink signal processing at WSGT is shown in figure 3-16 (references 4 and 6).

3.4.2 DOWNCONVERSION

3.4.2.1 MA

a. Because of the return frequency translation on board the TDRS, each channel of the 30-channel FDM MA signal will have different frequency and Doppler. These frequency and Doppler differences must be eliminated prior to MA beam forming, signal demodulation, and Doppler extraction. The frequency and Doppler differences elimination process is performed by the MA element separator.

b. The 30-channel FDM MA signals are downconverted and frequency translated by one of the three MA element separators. The MA element separator uses the return TDRS telemetry carrier, which contains the Doppler characteristics $\alpha 3_i$, $\beta 2_i$, as the reference frequency source to generate a 30-channel frequency translation via a two-stage translation process (see figure 3-17). The 30-channel frequency translation provided by the MA element separator can be written as:

$$f_t(m,n) = f_{dwn} + f(m) + f(n)$$

$$= \left[11,250 + (1275 + 75m) + (720 + 7.5n)\right] \alpha 3_i \beta 2_i \text{ MHz}$$

where: 11,250 is the downconversion frequency
1275 + 75m is the 1st stage frequency translation
720 + 7.5n is the 2nd stage frequency translation

$m = 0,1,2$
$n = 0,1,2,\ldots,9$

The values of m and n are properly selected for each of the 30 MA channels such that a 160-MHz (nominal) signal with equal Doppler frequency is obtained for all 30 MA channels at the output of the MA element separator.

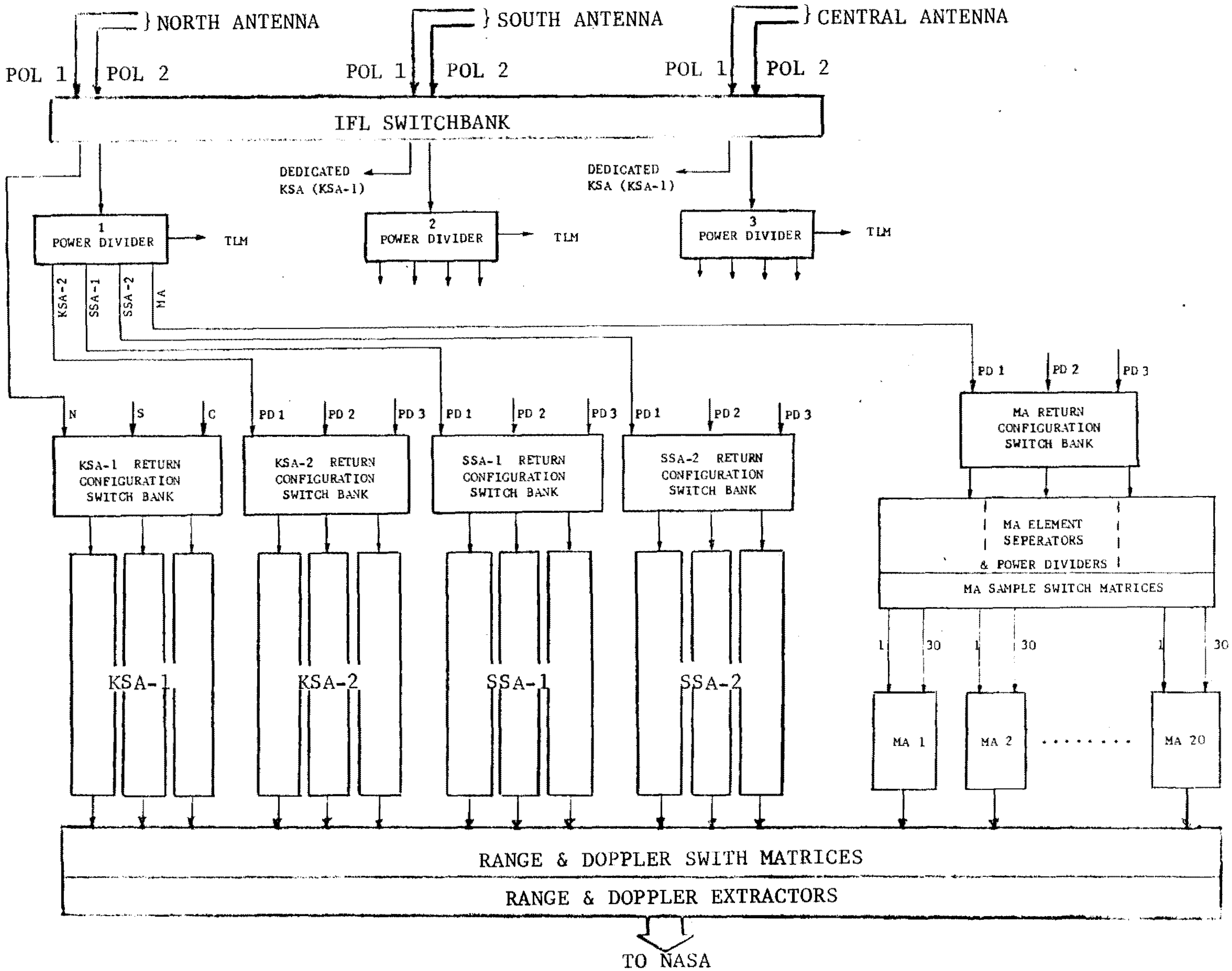


Figure 3-15. Configuration Switching for Downlink Services

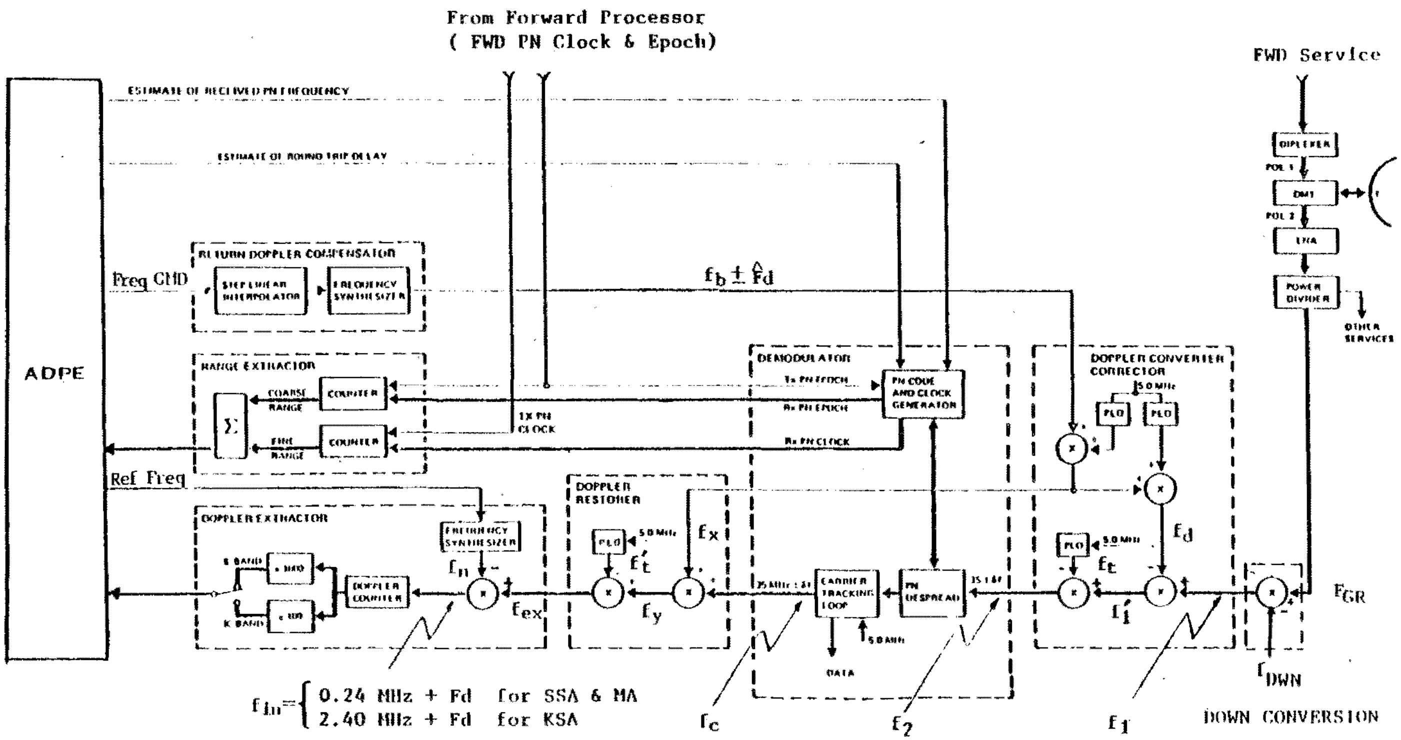


Figure 3-16. Downlink Signal Processing at WSGT

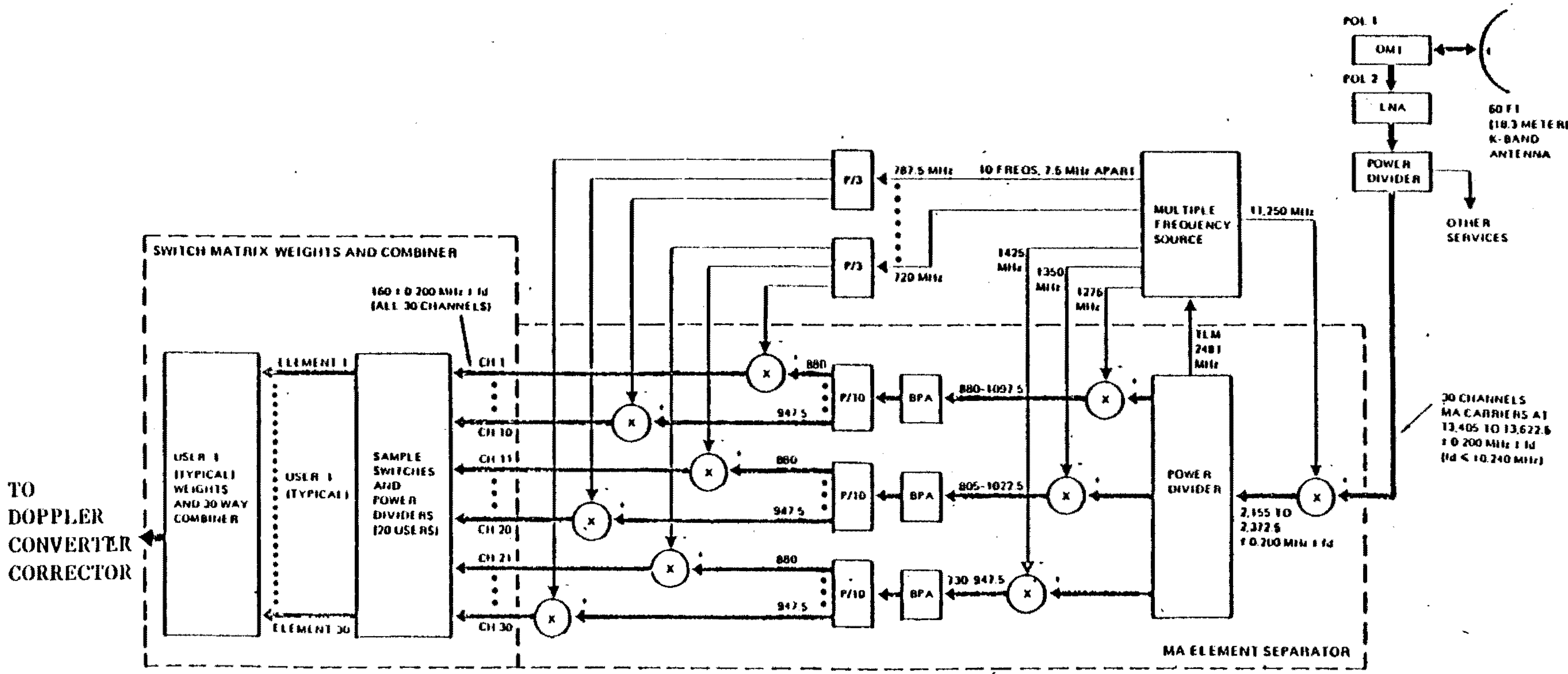


Figure 3-17. MA Element Separator

The nominal center frequency of $f_t(m,n)$ can be given as:

$$f_t(m,n) = \begin{Bmatrix} 13{,}245.0,\ 13{,}252.5, \ldots, 13{,}305.0,\ 13{,}312.5, & m = 0, & n = 0, \ldots, 9 \\ 13{,}320.0,\ 13{,}327.5, \ldots, 13{,}380.0,\ 13{,}387.5, & m = 1, & n = 0, \ldots, 9 \\ 13{,}395.0,\ 13{,}402.5, \ldots, 13{,}455.0, 13{,}462.5, & m = 2, & n = 0, \ldots, 9 \end{Bmatrix}$$

Let $f_1(l)$ with $l = 1, 2, \ldots, 30$ be the intermediate frequencies at the 30 outputs of the MA element separator and let $F_{GR}(5)_l$ with $l = 1, 2, \ldots, 30$ be the WSGT received 30-channel MA signals.
Then:

$$f_1(l) = F_{GR}(5)_l - f_t(m,n)$$

Where:

$$F_{GR}(5)_l = \alpha 1_i \alpha 2_i \beta 1_j \beta 2_j \text{ Fref} + \alpha 3_j \beta 2_j b_l(5) F_p$$

for closed-loop tracking

and

$$F_{GR}(5)_l = \beta 1_j \beta 2_j F_o + \alpha 3_j \beta 2_j b_l(5) F_p$$

for one-way Doppler tracking

$f_1(l)$ can be rewritten as:

$$f_1(l) = \begin{Bmatrix} \alpha 1_i \alpha 2_i \beta 1_j \beta 2_j \text{Fref} \\ \text{or} \\ \beta 1_j \beta 2_j F_o \end{Bmatrix} + \alpha 3_j \beta 2_j b_l(5) F_p - \alpha 3_j \beta 2_j f_t(m,n)$$

where $b_l(5)F_p$ is the effective return frequency translation of each of the 30-channel FDM MA elements:

$$\left\{b_l(5)F_p\right\} = \begin{Bmatrix} 11117.5 & 11125.0 & 11132.5 & 11140.0 & 11147.5 \\ 11155.0 & 11162.5 & 11170.0 & 11177.5 & 11185.0 \\ 11192.5 & 11200.0 & 11207.5 & 11215.0 & 11222.5 \\ 11230.0 & 11237.5 & 11245.0 & 11252.5 & 11260.0 \\ 11267.5 & 11275.0 & 11282.5 & 11290.0 & 11297.5 \\ 11305.0 & 11312.5 & 11320.0 & 11327.5 & 11335.0 \end{Bmatrix} \text{ MHz}$$

From the given values of $b_l(5)\ F_p$ and $f_t\ (m,n)$

$$\alpha 3_j \beta 2_j b_l(5) F_p - \alpha 3_j \beta 2_j f_t(m,n) = -2127.5\ \alpha 3_j \beta 2_j$$

for all 30 channels. The frequency differences on the second Doppler term of the 30-channel FDM MA signals are now removed. The 30 channel output frequencies, f_1 (independent of l), from the MA element separator are given by:

$$f_1 = \begin{Bmatrix} \alpha 1_i \alpha 2_i \beta 1_j \beta 2_j \text{Fref} - 2127.5\ \alpha 3_j\ \beta 2_j & \text{closed-loop} \\ \beta 1_j \beta 2_j F_o \quad - 2127.5\ \alpha 3_j \beta 2_j & \text{one-way} \end{Bmatrix}$$

The nominal center frequency of f_1 is equal to:

$$f_1 = \begin{cases} Fref(5) - 2127.5 = 2287.5 - 2127.5 = 160 \text{ MHz, closed-loop} \\ F_o(5) - 2127.5 = 2287.5 - 2127.5 = 160 \text{ MHz, open-loop} \end{cases}$$

c. The 30-channel f_1 IF signals from the MA element separator are input to the switch matrix weights and combiner. Each element is further separated into 20 channels by a power divider. Twenty groups of 30-element MA signals are formed, one for each of the 20 MA channel strings (see figure 3-18). The MA antenna beam forming is accomplished by adjusting the 30 inphase and 30 quadrature weights. The weights are commanded by the central computer. The weighted signals are then summed via a 30-way combiner to form the sum-channel signal and input to the Doppler convertor corrector.

3.4.2.2 SSA and KSA. The downlink SSA and KSA signals are downconverted to an intermediate frequency f_1 by ground-generated frequencies which are phase-locked to the 5-MHz cesium standard. The downconverted signals, f_1, are then input directly to the Doppler convertor corrector.

3.4.3 DOPPLER CONVERTOR CORRECTOR

The Doppler convertor corrector removes spacecraft-imposed Doppler, residual of the forward compensation plus forward frequency tuning (to within the required uncertainty limit) from the f_1 signal via a combination of return Doppler compensation and fine frequency tuning so that the demodulator input will be approximately a constant narrow-band IF of 35 MHz. The return Doppler compensator will perform Doppler compensation continuously (regardless of forward compensation activity) and functions in a similar fashion as the forward Doppler compensator. The Doppler corrected signal is then input to the demodulator.

3.4.4 DEMODULATOR

The demodulator accepts a double sideband suppressed carrier, QPSK or BPSK modulated IF signal. The demodulator coherently demodulates the sideband energy to recover a reference carrier and baseband data. Dynamic aiding to the demodulator is provided by the ADPE in the form of Doppler and Doppler rate compensation for carrier and PN spread signals plus the estimated time delay of the return PN epoch, which affords rapid collapse of the spread spectrum and carrier recovery. Baseband data output includes return PN epoch and clock signals for range data extraction.

3.4.5 DOPPLER RESTORER

The narrowband recovered carrier signal is further processed in the Doppler restorer so that the full Doppler bandwidth is restituted. To this effect, the estimated Doppler plus fine tuning, $\hat{F}d$, is added back to the IF carrier (which contains $-\hat{F}d$), rendering the full Doppler component Fd. This signal is input via the Doppler extractor switch matrix to the Doppler extractor where it is further translated by the Doppler extractor frequency synthesizer. The synthesizer is commanded by the ADPE. The translation frequency is determined based on the stored forward and return compensation and tuning information so that the Doppler counter input is 240.0 kHz $+$Fd for MA and SSA, and 2.40 MHz $+$Fd for KSA. (The downlink frequency translation at WSGT is shown in figure 3-19 and table 3-7.)

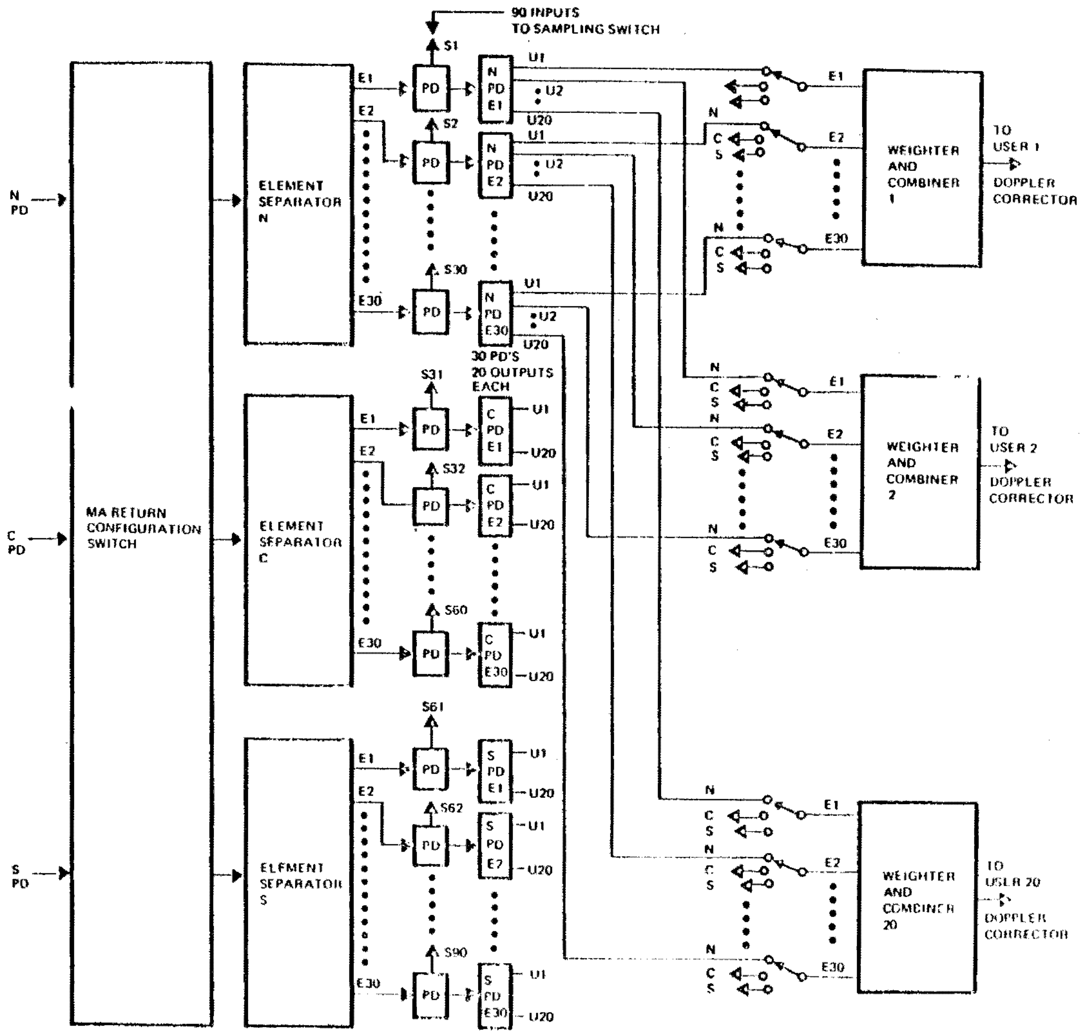


Figure 3-18. MA Switching Plan

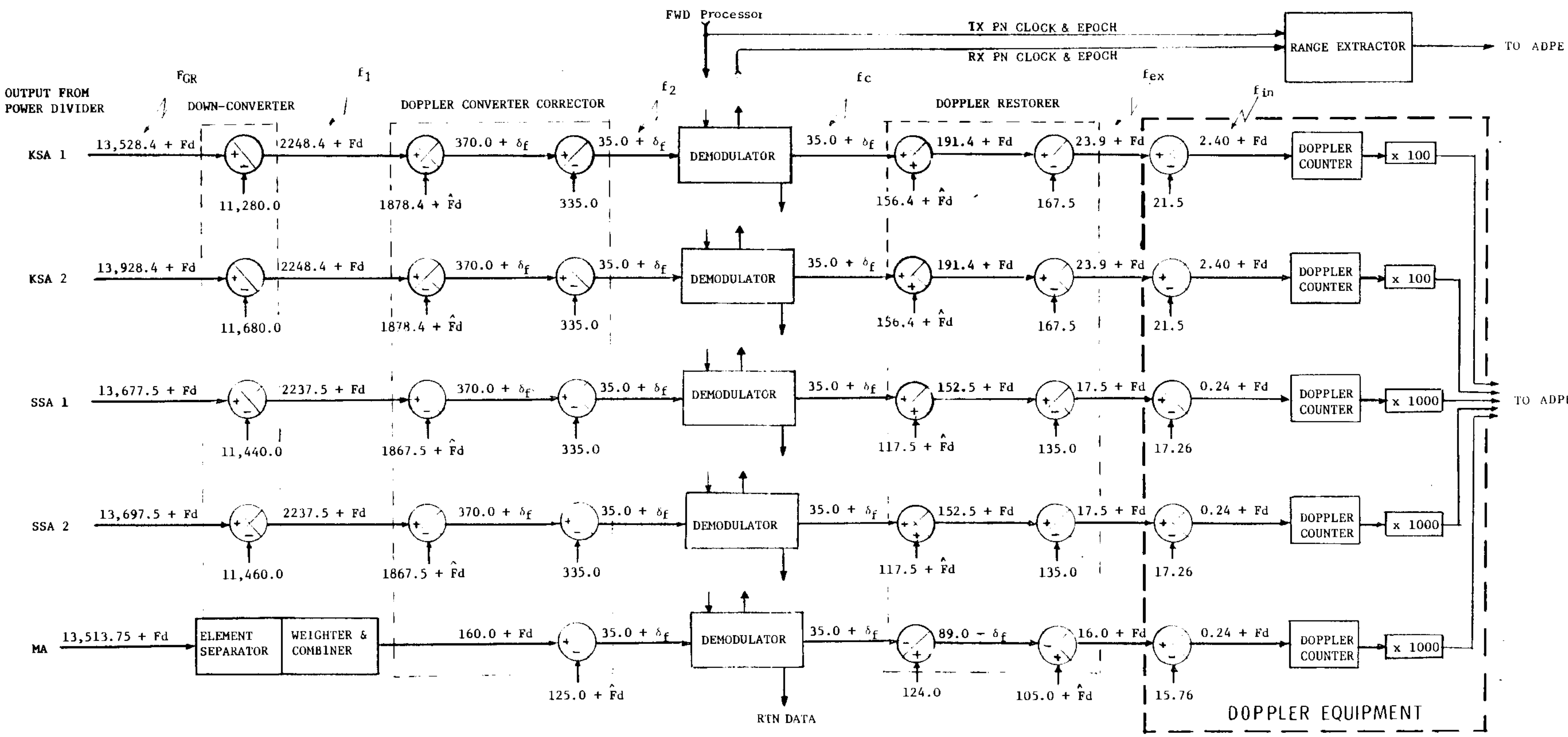


Figure 3-19. Frequency Translation at WSGT

Table 3-7. WSGT Downlink Frequency Allocations

Parameters (See figure 3-16 for nomenclature)	Services (MHz)				
	KSA-1	KSA-2	SSA-1	SSA-2	MA
F_{GR} (nominal center frequency received)	13,528.4 ± 1.410 + Fd	13,928.4 ± 1.410 + Fd	13,677.5 ± 0.350 + Fd	13,697.5 ± 0.350 + Fd	13,513.75 ± 0.200 + Fd (30-channel FDM, 7.5-MHz channel spacing)
f_{DWN} (downconversion)	11,280.0	11,680.0	11,440.0	11,460.0	(MA element separator)
f_1 (intermediate frequency)	2248.4 ± 1.410 + Fd	2248.4 ± 1.410 + Fd	2237.5 ± 0.350 + Fd	2237.5 ± 0.350 + Fd	160.0 ± 0.200 + Fd
f_d (Doppler corrections plus estimates)	1878.4 ± 1.410 + $\hat{Fd}$	1878.4 ± 1.410 + $\hat{Fd}$	1,867.5 ± 0.350 + $\hat{Fd}$	1867.5 ± 0.350 + $\hat{Fd}$	125.0 ± 0.200 + $\hat{Fd}$
f_1' (where $\delta_f = Fd - \hat{Fd}$)	370.0 + δ_f		370.0 + δ_f		35.0 + δ_f
f_t	335.0		335.0		
f_2 (demod input frequency)	35.0 + δ_f		35.0 + δ_f		35.0 + δ_f
f_c (recovered carrier with Doppler residual)	35.0 + δ_f		35.0 + δ_f		35.0 + δ_f
f_x (Doppler correction offset)	156.4 ± 1.410 + $\hat{Fd}$		117.5 ± 0.350 + $\hat{Fd}$		f_t' = 124.0
f_y (Doppler restorer)	191.4 ± 1.410 + Fd		152.5 ± 0.350 + Fd		89.0 − δ_f
f_t'	167.5		135.0		f_x = 105.0 ± 0.200 + $\hat{Fd}$
f_{ex} (Input frequency to Doppler extractor)	23.9 ± 1.410 + Fd ±0.762 tuning ±0.648 forward compensation Fd = total user Doppler ($\leq$ 1.600)		17.5 ± 0.350 + Fd ± 0.25 residual return tuning ± 0.100 forward compensation Fd = total user Doppler ($\leq$ 0.240)		16.0 ± 0.200 + Fd ± 0.100 tuning ± 0.100 forward compensation Fd = total user Doppler ($\leq$ 0.240)
f_n (frequency synthesizer input)	21.5 ± 1.410		17.26 ± 0.350		15.76 ± 0.200
f_{in} (Doppler counter input)	2.40 + Fd		0.24 + Fd		0.24 + Fd

3.5 RANGE AND DOPPLER MEASUREMENTS

3.5.1 GENERAL

3.5.1.1 The range and Doppler measurements are implemented by the WSGT range and Doppler equipment which is composed of two functional areas: range extraction and Doppler extraction. Interfaces which are common to the two functional areas are: the Common Timing and Frequency Standard (CTFS), AC power, and the Automatic Data Processing Equipment (ADPE).

3.5.1.2 The range equipment provides ranging information in the form of measured time delays between the currently received return PN chip m and the corresponding transmitted forward PN chip m at each 1-second tic; i.e., to determine how long ago the corresponding forward chip m was most recently transmitted. The range equipment consists of nine range extractors and the necessary switching equipment to establish the desired range extraction configuration.

3.5.1.3 The Doppler equipment provides range-rate information derived from the Doppler frequency shift of the received carrier sample with respect to the synthesized reference carrier sample. The Doppler equipment consists of 19 Doppler extractors (10 for one-way and 9 for two-way) plus the necessary switching equipment to establish the desired Doppler extraction configuration. (The range and Doppler equipment at WSGT are shown in figure 3-20.)

3.5.2 RANGE EXTRACTION

3.5.2.1 Range Extraction Switch Matrix. There are totals of 15 forward and 35 return inputs (forward and return PN clocks and epochs) to be configured to the nine range extractors. The desired range extraction configuration is established via the range extraction switch matrix, which is controlled by the range switch control. The range switch control receives digital command messages from the Remote Multiplex Demultiplex Unit (RMDU). The RMDU interfaces with the ADPE to identify the addresses of the forward reference (PN clock and epoch), the return service ranging input (PN clock and epoch), and the range extractor. The maximum reconfiguration time for all nine range extractors is 250 milliseconds after receipt of the range switch control command. The range extraction switch matrix is shown in figure 3-21 (reference 13).

3.5.2.2 Range Extractor

a. The range measurement consists of making precise time delay measurements between corresponding PN epoch and clock edges of signals from the forward modulator and return PN code despreader. The range extractor operates from five basic signals: nominal 3-MHz forward and return clocks, which are coherent with the transmitted (forward) and received (return) PN codes, forward and return epoch pulses which occur once per PN code sequence, and the 1-pps signal from CTFS. Range measurements are continuously made at 1-second intervals synchronously with the 1-pps time tic from CTFS. Range measurements are independent of the sample rate and are output prior to the next 1-second time tic. A functional diagram of the range extractor is given in figure 3-22 (reference 14).

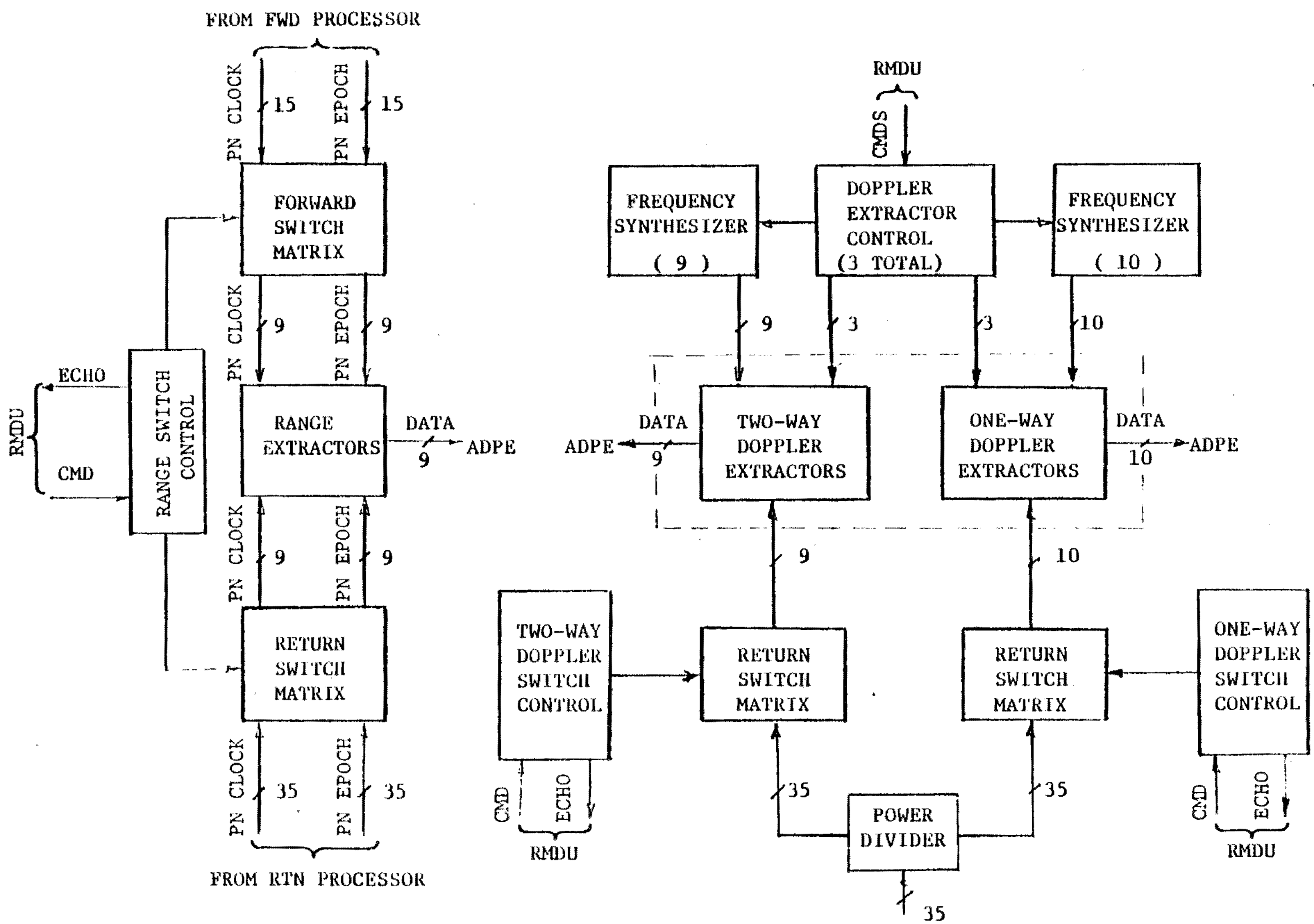


Figure 3-20. Range and Doppler Equipment

RMDU CMD DATA
(ADDRESSES OF FWD EPOCH & CLOCK,
RTN EPOCH & CLOCK AND RANGE EXTRACTOR)

FORWARD CLOCK & EPOCH SWITCH MATRIX

RANGE EXTRACTOR	MA N	MA C	MA S	SSA 1 N	SSA 1 C	SSA 1 S	SSA 2 N	SSA 2 C	SSA 2 S	KSA 1 N	KSA 1 C	KSA 1 S	KSA 2 N	KSA 2 C	KSA 2 S
1	x	x	x	x	x	x	x	x	x						
2	x	x	x	x	x	x	x	x	x						
3	x	x	x	x	x	x	x	x	x						
4	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
5	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
6	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
7	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
8	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
9	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

RETURN CLOCK & EPOCH SWITCH MATRIX

RANGE EXTRACTOR	MA 1	MA 2	MA 3	MA 4	MA 5	MA 6	MA 7	MA 8	MA 9	MA 10	MA 11	MA 12	MA 13	MA 14	MA 15	MA 16	MA 17	MA 18	MA 19	MA 20	SSA 1 N	SSA 1 C	SSA 1 S	SSA 2 N	SSA 2 C	SSA 2 S	KSA 1 N	KSA 1 C	KSA 1 S	KSA 2 N	KSA 2 C	KSA 2 S	SKSA N	SKSA C	SKSA S
1	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x															
2	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x															
3	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x															
4																					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
5																					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
6																					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
7																					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
8																					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
9																					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

X INDICATES THE ALLOWED INPUTS CONFIGURATION

Figure 3-21. Range Extraction Switch Matrix

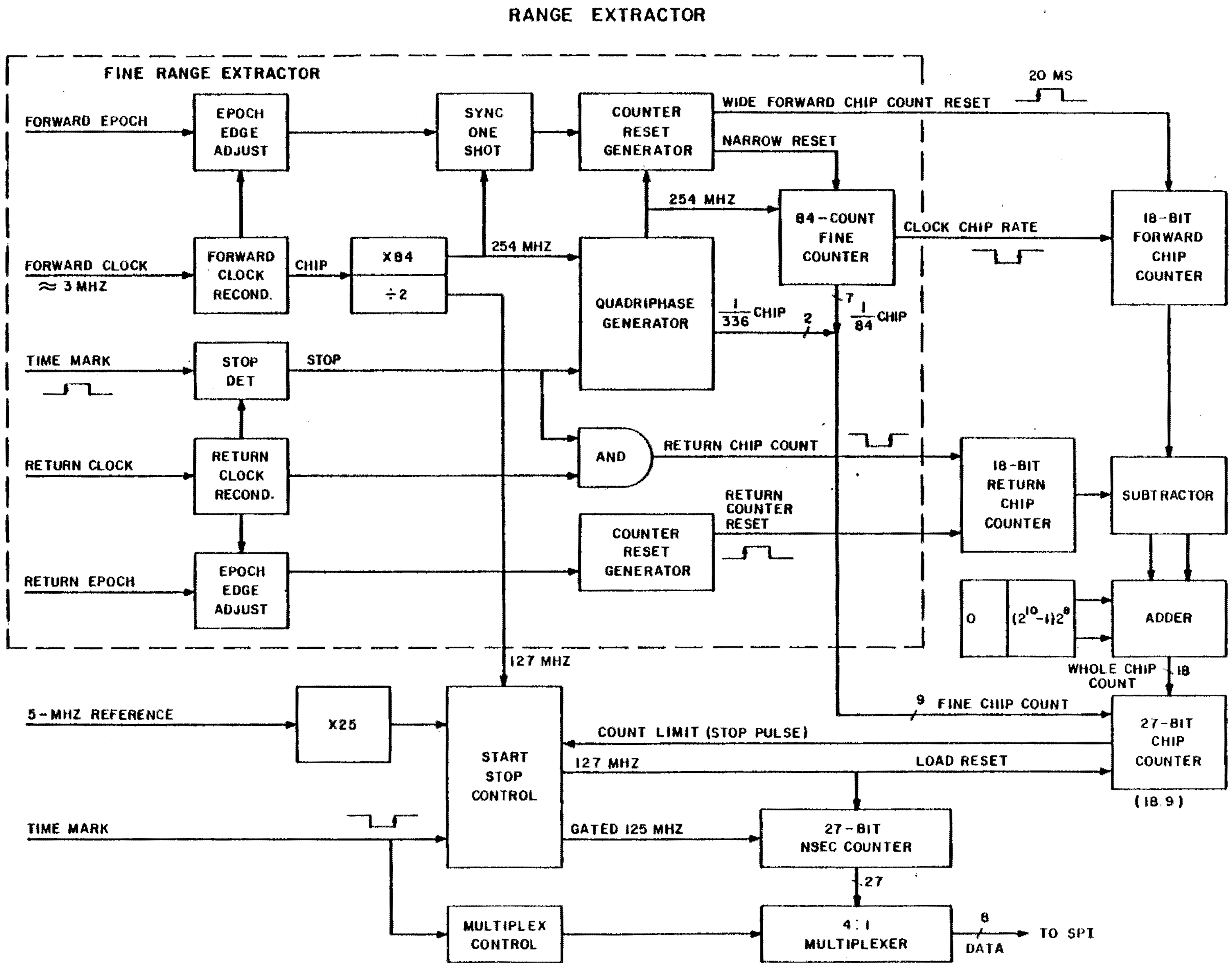


Figure 3-22. Range Extractor

b. The forward PN clock is counted by three separate chip and fraction-of-a-chip counters:

(1) The 18-bit forward chip counter counts at the forward chip rate and is recycled upon reception of each forward epoch. The 18-bit chip counter can have a maximum of $(2^{18}-1)$ counts with each cycle count corresponding to one PN chip.

(2) The 84-count fine counter of the fine range extractor counts at 84 times the forward clock rate to a maximum reading of 83. Each 84-count cycle corresponds to 1/84 chip.

(3) The quadriphase decoder of the fine range extractor counts at 336 times the forward clock rate to a maximum rading of 3. Each cycle count corresponds to 1/336 chip or 1/4 of the 84-count cycle.

c. The return PN clock is counted by an 18-bit return chip counter at the return PN chip rate. The 18-bit return chip counter is reset to zero upon reception of each return epoch.

d. Upon reception of the 1-second time tic, the forward and return 18-bit chip counters are stopped on the next positive transition of the return PN clock; this resolves the measurement to within one chip's time (see figure 3-23). Because the fine range extractor (fraction of a chip resolver) recycles at every positive transition of the forward clock, it measures the return to forward clock phase difference directly when it is asynchronously stopped with the positive edge of the return PN clock as shown in figure 3-24. The quadriphase decoder in conjunction with the 84-multiplier of the fine range extractor subdivides the forward PN clock into 336 parts; because the nominal forward clock is about 3 MHz, the time delay resolution is approximately 1.0 nsec.

e. Because the forward and return 18-bit chip counters are continuously reset by their respective PN epochs, the counters will provide the exact forward and return whole-chip counts at any given time. At the 1-second time tic, the forward and return 18-bit counters are stopped at the next positive transition of the return PN chip, and the count difference is sent to a logic decision processor. Here the count difference is analyzed and a code modulo is added if the difference is negative.

f. The 18-bit count output of the decision processor is sent to the 27-bit (18,9) chip counter where it represents the 18 MSB (most significant bits) of the measured delay, accurate to one chip. The fine range extractor output consists of seven bits of 84ths of a chip delay and two bits of 4ths of an 84th of a chip delay; these two signals effectively indicate the number of 1/336's of chip delay at the time of the 1-second time tic. The nine bits from the fine range counter, in 1/336's fractions of a chip, and the 18 bits from the whole chip counter are stored in the 27-bit (18,9) chip counter. At this point, the measurement is made in chips and will be converted to nanoseconds in the following process.

g. The conversion from chips and fractions of a chip to nanoseconds of delay time is accomplished by using a clock signal which is 1/8 the highest clock rate used to count the actual time delay. By using the forward clock as the basis for timing out the chip counter the problem of variable code repetition rate caused by forward compensation, service type, and carrier frequency is avoided.

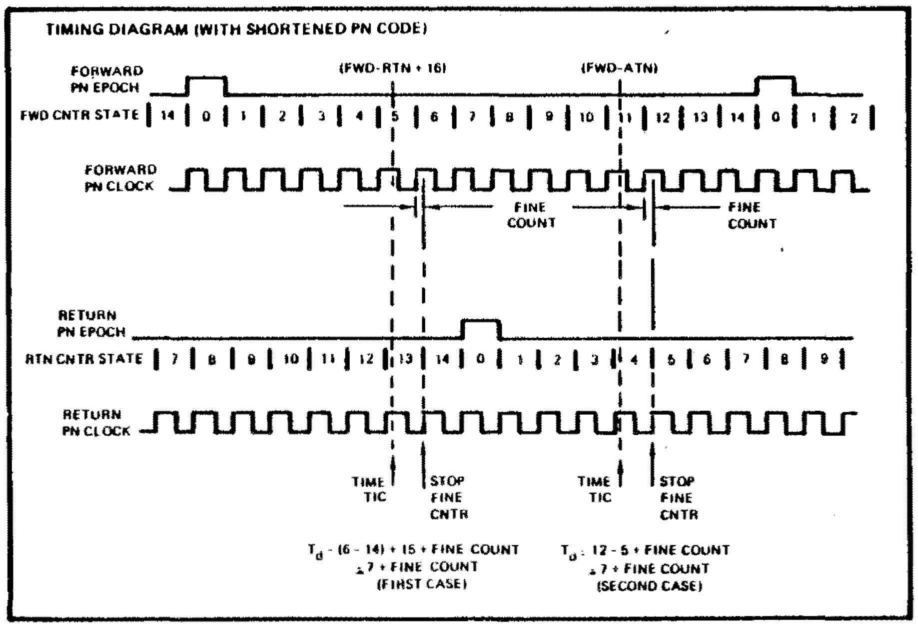


Figure 3-23. Timing

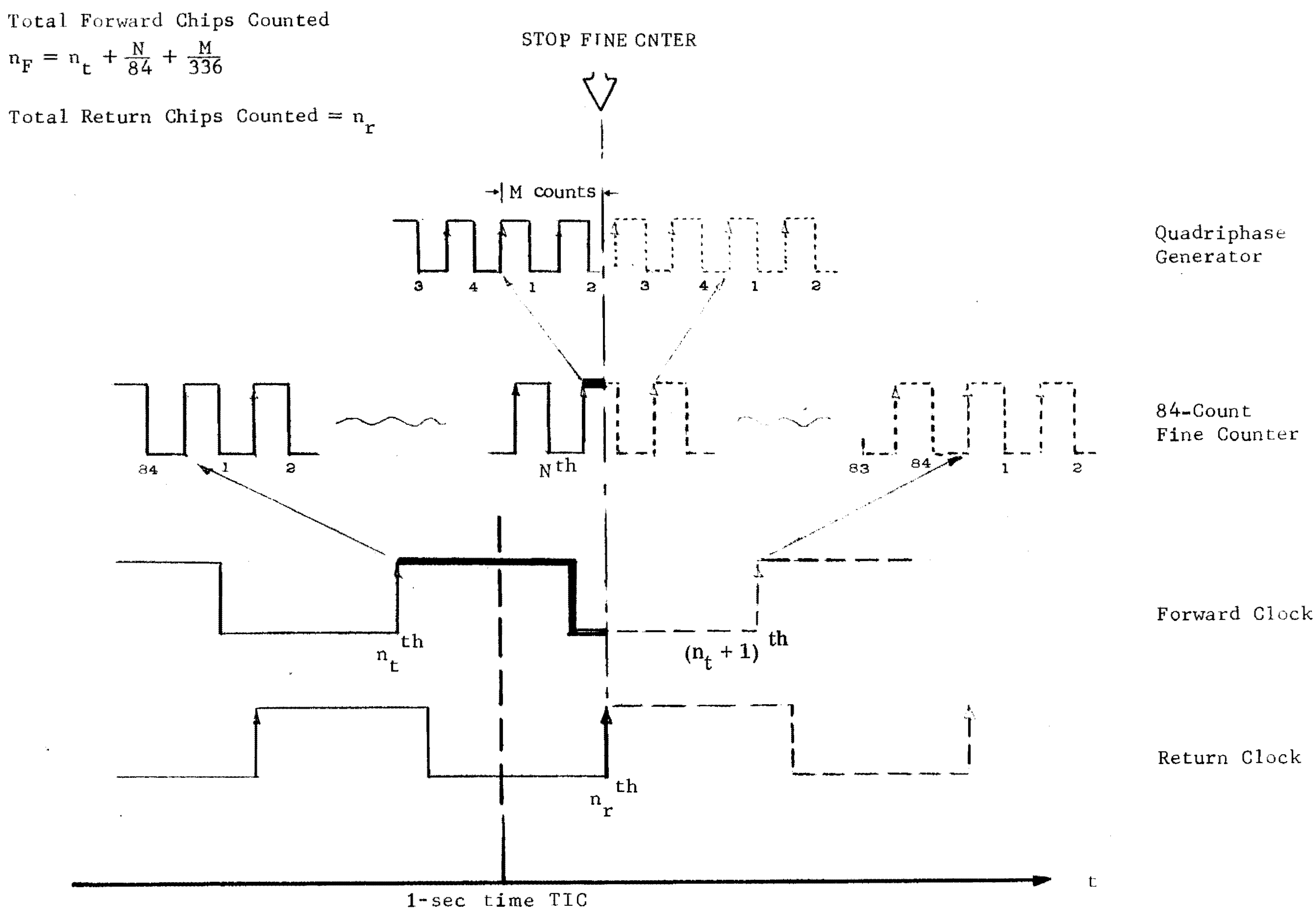


Figure 3-24. Range Extraction Timing

h. The chip to nanosecond counter measures the elapsed time that it takes to time out the chip counter as follows:

(1) The 27-bit (18, 9) chip register contains 18 MSB which correspond to $n_t - n_r$ (number of chips transmitted minus number of chips received) and 9 bits which represent F (fraction of a chip).
F can be written as

$$F = \frac{N}{84} + \frac{M}{336}$$

Where: $N = 0, 1, 2, \ldots, 83$

$M = 0, 1, 2, 3$

F can be translated to mean

$$F = \frac{4N}{336} + \frac{M}{336} = \frac{K}{336}$$

$$K = 0, 1, 2, \ldots, 335$$

This (18, 9) bit number is, therefore, a representation of

$$n_t - n_r + \frac{K}{336}$$

(2) If the nine bits are counted down to zero (equivalent to counting a chip by 1/336ths), one count is deducted from $(n_t - n_r)$, the nine bits are reset to 335, and the process is repeated until $(n_t - n_r)$ is zero, then this process is equivalent to counting down C_1 counts, or:

$$C_1 = (n_t - n_r)\ 336 + K$$

(3) Another counter, C_2, is started at the initiation of the countdown process and accumulates at the rate of exactly 125 MHz. If R_1 is the forward chip rate, the C_1 counts will be counted down at the rate of $42R_1$ by design. Consequently, the time to exhaust the C_1 counter reading (T) is

$$(n_t - n_r)\ 336 + K - 42R_1 T = 0$$

or

$$T = \frac{8(n_t - n_r) + \frac{K}{42}}{R_1} \text{ seconds}$$

But the actual desired delay time (Δt) is simply

$$\Delta t = \frac{(n_t - n_r) + \frac{K}{336}}{R_1}$$

Consequently, the relationship between T and Δt is

$$\Delta t = T/8$$

(4) If T is represented as a count C_2 of the 125-MHz counter (each count of the 125-MHz counter corresponds to 8 nanoseconds), then

$$T = C_2 \times 8 \text{ nsec}$$

$$\Delta t = \frac{C_2 \times 8}{8} \text{ nsec}$$

$$\Delta t = C_2 \text{ nsec}$$

At the maximum count $(2^{10} - 1)\, 2^8$, the time to exhaust the C_1 count (assuming a clock frequency of 3 MHz) is

$$t_m = 8\Delta t \text{ max} = \frac{8\,(2^{10} - 1)\, 2^8}{3 \times 10^6} = 0.698 \text{ second}$$

(5) The raw range measurement (Δt) is output on the next second after it is required, but is time-tagged on the second before it is output. The range is output to the ADPE as four 8-bit words and is available to NASA in bytes 27 to 32 of the data format (bytes 27 and 32 and the five leading bits of byte 28 are always zero).

3.5.3 DOPPLER EXTRACTION

3.5.3.1 Doppler Extraction Switch Matrix and Doppler Extractor Control. A total of 35 return inputs is to be configured to 19 Doppler extractors (10 one-way and 9 two-way). The desired Doppler extraction configuration is established via the Doppler extraction switch matrix, which is controlled by the Doppler switch control. The Doppler switch control receives digital command messages from the RMDU identifying the addresses of the return demodulators and Doppler extractors. The Doppler extraction equipment is controlled by three Doppler extractor controls. Each Doppler extractor control receives commands from the RMDU identifying the service selected (MA, SSA, or KSA), the one-way or two-way reference frequency, and Doppler counter reset/enable command for each Doppler extractor in service. The maximum reconfiguration time for all 19 Doppler extractors is 250 milliseconds after receipt of the RMDU control commands. The Doppler extraction switch matrix is shown in figure 3-25 (reference 13).

3.5.3.2 Doppler Extractor

a. The Doppler measurements are made at 1-second intervals (±25 nsec), independent of the sample rate, and are initiated by the 1-second time tics from CTFS. The input to the Doppler extractor is a biased Doppler signal consisting of a scaled sample of the return carrier. The biased Doppler signal frequency is counted cumulatively by a nondestruct Doppler counter to a specified accuracy of ±1 count (excluding 1-second time tic jitter of ±25 nsec). A measurement granularity of 1/1000 cycle per count for SSA and MA and 1/100 cycle per count for KSA is obtained. A functional diagram of the Doppler extractor is shown in figure 3-26 (reference 14).

b. The Doppler extractor consists of three counters: a Doppler cycle counter, a Doppler cycle length counter, and a partial Doppler cycle counter. A scaled biased Doppler signal is fed to the Doppler cycle counter which has a 50-minute (minimum) counting capacity. The cycle counter increments at every positive crossing of the input scaled biased Doppler signal and continuously

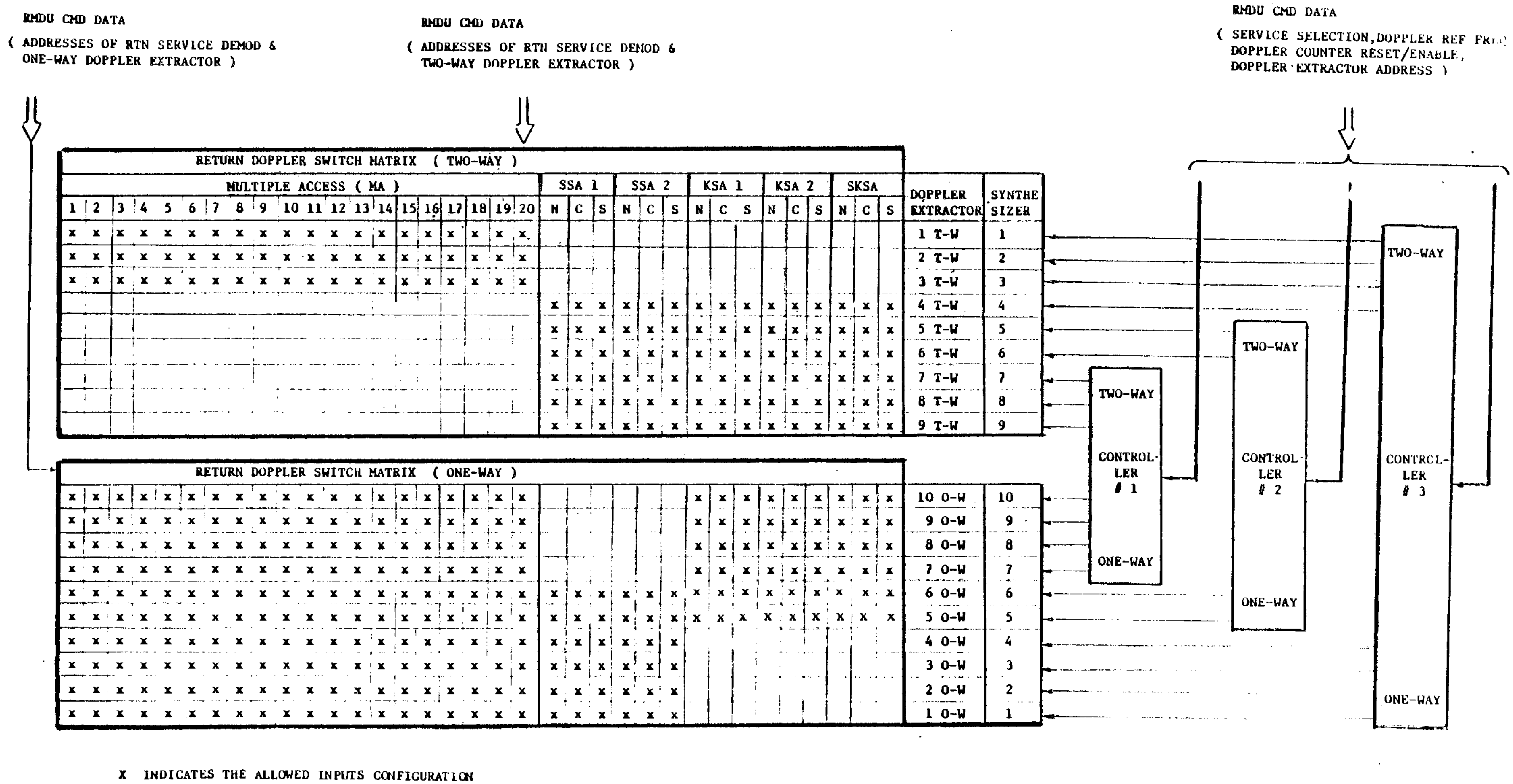


Figure 3-25. Doppler Extraction Switch Matrix

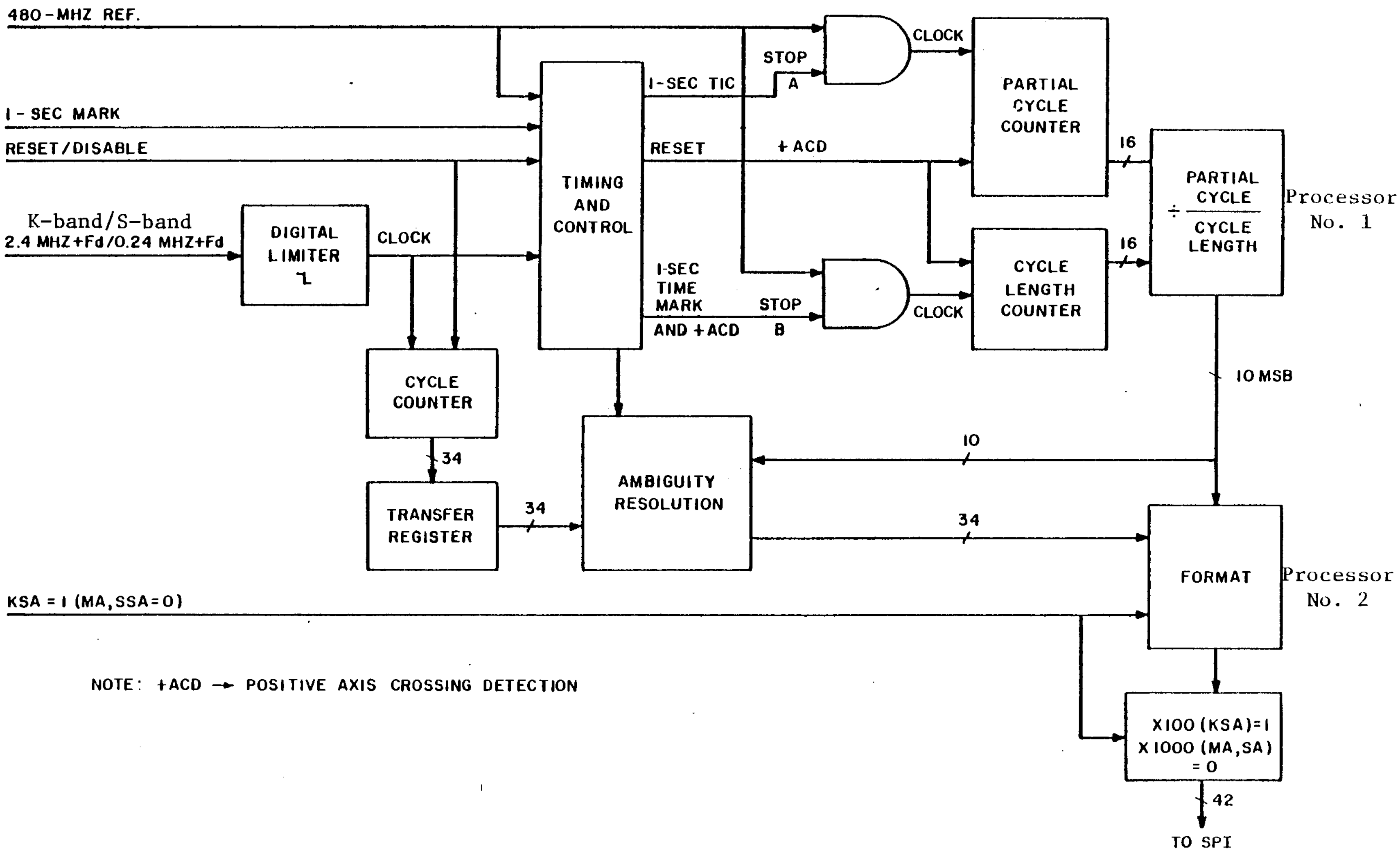


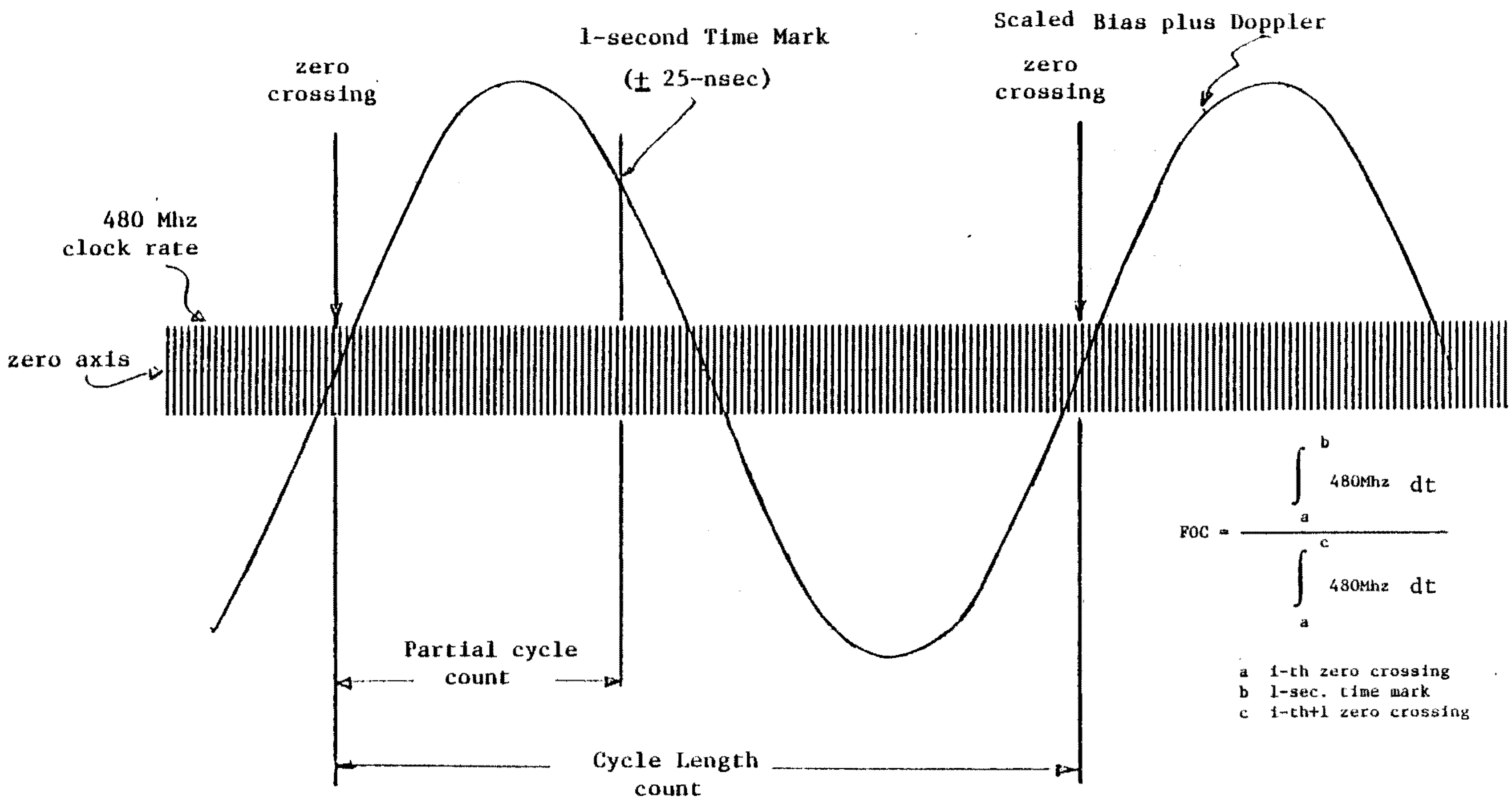
Figure 3-26. Doppler Extractor

counts integer or whole cycles independent of the 1-second time tic. At the 1-second time tic, the cycle counter is sampled and the reading is stored in the transfer register. The accuracy of the reading is to 1 Doppler cycle.

c. In the idle state, that is, between tics, the partial cycle counter and the cycle length counter increment at the 480-MHz rate; each counter starts and stops the counts at consecutive positive-going axis crossings of the scaled biased Doppler signal; each counter is reset to zero after overflowing and a new counting sequence starts. The purpose of the partial cycle and cycle length counters is to subdivide the current Doppler cycle in progress into a maximum granularity (minimum resolution) of 1/1000 cycle for SSA and MA, and 1/100 cycle for KSA.

d. At the 1-second time tic, the partial cycle counter is stopped and the cycle length counter is allowed to continue to the end of the current scaled biased Doppler cycle in progress and then is stopped. The content of the cycle length counter represents the total possible subdivisions of the current Doppler cycle in progress. The content of the partial cycle counter at the 1-second time tic represents the number of subdivisions which have occurred since the beginning of the current Doppler cycle (see figure 3-27).

e. The ratio of the contents between the partial cycle counter and the cycle length counter is computed in processor 1. The results of this processor (fine resolution) is added to the integer cycle counter reading. After ambiguity resolution, this composite reading is multiplied by 100 if KSA and 1000 if SSA or MA. Output is available to the ADPE as 42 bits and the ADPE outputs six 8-bit words to NASA using bytes 33 to 38 of the data format (six leading bits of the most significant byte 33 are always set to zero).



$$FOC = \frac{\int_a^b 480\text{Mhz}\ dt}{\int_a^c 480\text{Mhz}\ dt}$$

a i-th zero crossing
b 1-sec. time mark
c i-th+1 zero crossing

Figure 3-27. Fractional Doppler Cycle Measurement

SECTION 4. MODELING OF THE TRACKING SIGNAL PATHS

SECTION 4. MODELING OF THE TRACKING SIGNAL PATHS

4.1 BACKWARD SIGNAL TRACE

4.1.1 GENERAL

A backward signal trace in an inertial frame of reference has been chosen for both the range and the Doppler computed measurements because the range observation is time tagged at the end of the measurement (from transmission to reception of the ranging signal) and the Doppler is modeled using the range-difference method. An inertial frame of reference, defined in figure 4-1, was selected primarily because it makes unnecessary any consideration of rotational effects on the radar signal. Except as modified by atmospheric refraction, all signal paths are straight lines traversed at constant speed, c. The disadvantage incurred by the need to transform the WSGT location into inertial coordinates is offset by the fact that the satellite state vectors are supplied by the integrator in inertial coordinates and do not need to be further transformed to model the observations. (Reference 15.)

4.1.2 RANGE AND DOPPLER TIME TAGS

4.1.2.1 The range extractor and Doppler extractor measurements are made at 1-second intervals coincident with the CTFS 1-pps signal arriving at these extractors. The time tag assigned to these measurements is the time of the 1-pps that samples these measurements; the 1-pps sampling time is synchronized to the UTC, as determined and maintained by the U.S. Naval Observatory, to within ±5 microseconds. Sampling of the range and Doppler measurements is to be performed within 0 to 336 and ±25 nanoseconds, respectively, of the UTC synchronized signal (refer to para 3.1.4). Initialization and periodic calibration of time-of-day are accomplished through the use of flying clock trips, which results in the CTFS being "on-time" to an external 1-pps source within ±0.5 microseconds (references 5 and 6).

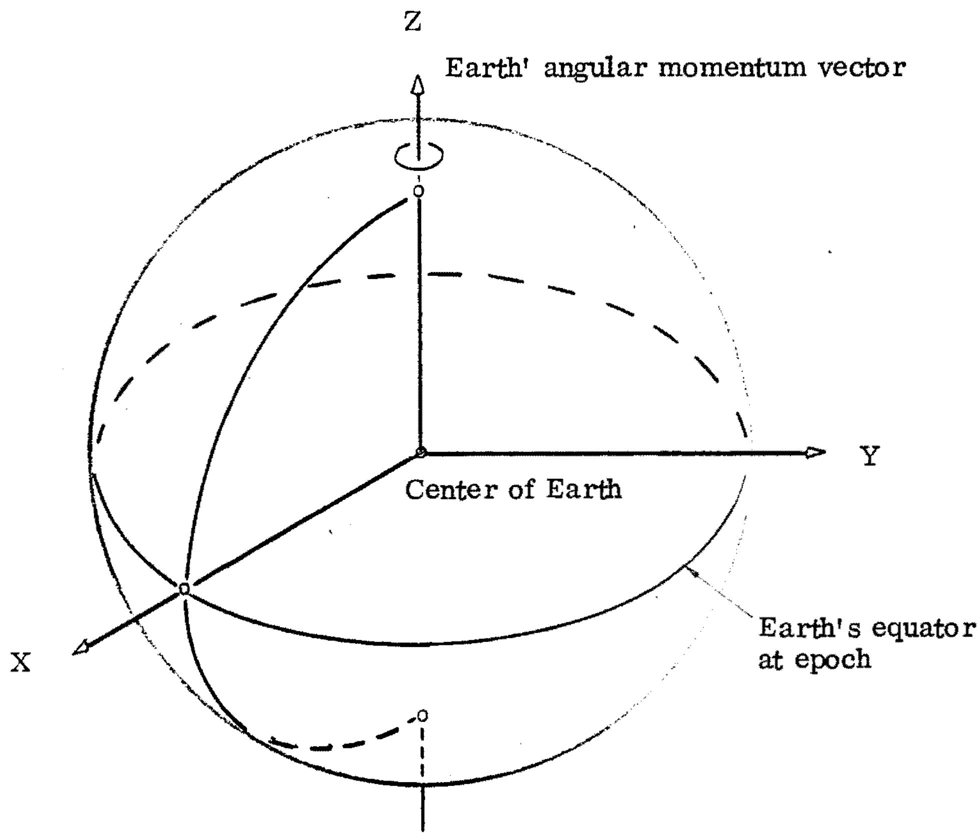
4.1.2.2 The actual time of the sampling 1-pps is modified, additionally, by the following delays (reference 16):

a. Propagation delay between the U.S. Naval Observatory and White Sands ($15 \leq t_1 \leq 20$ msec).

b. Propagation delay between the Discipline Time Frequency Standard (DTFS) and the range and Doppler extractors ($51 \leq t_2 \leq 93$ nsec).

c. Propagation delay between the range and Doppler extractor equipment racks ($7 \leq t_3 \leq 20$ nsec).

4.1.2.3 The sampling of the range extractor by the 1-pps initializes the measurement. The measurement can take as much time as one PN range chip to be completed (≈336 nsec). Further processing within the extractor, which does not compromise range accuracy, amounts to as much as 700 msec. The sampling of the Doppler extractor by the 1-pps initializes the measurement which can take as much as 100 msec to be completed due to the changing biased Doppler cycle length.



Name:	Geocentric Equatorial Inertial Cartesian Coordinate System
Origin:	The center of the earth.
Orientation:	The X-Y plane is the Earth's equator at epoch.
	The X-axis is directed towards the vernal equinox at epoch.
	The Z-axis is directed along the Earth's angular momentum vector at epoch.
	The Y-axis completes a right-handed system.
Characteristics:	Inertial, right-handed, Cartesian system.

Figure 4-1. Inertial Frame of Reference for TDRSS Observation Modeling

4.1.3 PROCEDURE FOR BACKWARD SIGNAL TRACE

4.1.3.1 Figure 4-2 shows the geometry of the signal path. A signal transmitted from WSGT at t_0 reaches the forward $(TDRS)_i$ at time t_1 and is relayed to reach the user spacecraft at time t_2. This signal is coherently turn-around with a multiplicative factor K and retransmitted by the user spacecraft and reaches the return $(TDRS)_j$ at time t_3. At this point the signal is mixed with frequencies generated from the uplink pilot (F_p) transmitted at time t_5 from WSGT. The signal is then downlinked to WSGT, arriving at time t_4. For two-way tracking, the same TDRS is used on both forward and return links; i.e., $(TDRS)_i = (TDRS)_j$. For hybrid tracking, two TDRS's are involved, one on the forward link and one on the return link; i.e., $(TDRS)_i \neq (TDRS)_j$. For open-loop tracking, no forward link is required; the signal is generated by the user spacecraft and the process starts at time t_2.

4.1.3.2 The backward signal trace begins at the WSGT receive time, t_4, which is identical to the UTC time tag T_L. The first step is to compute the WSGT location at time t_4. Next, the state vectors of the return $(TDRS)_j$ at time t_3, the user spacecraft at time t_2, the forward $(TDRS)_i$ at time t_1, and the WSGT at time t_0 are successively solved for using an iterative procedure. For open-loop tracking, the process is terminated at time t_2. The location of the WSGT at time t_5 is also determined for Doppler computation.

4.2 MODELING THE RANGE OBSERVATION

4.2.1 OBSERVED RANGE

4.2.1.1 The TDRSS range measurement is accomplished through PN code ranging technique. A $(2^{10} - 1)\ 2^8$ - chip ranging PN code with constant forward PN rate (during compensation inhibit mode) is transmitted via the range channel of the uplink signal from WSGT via the forward $(TDRS)_i$ to a user spacecraft. The user spacecraft receives and coherently demodulates the signal and regenerates the return ranging PN code (which is synchronized and coherent to the received code) and transmits it back to the return $(TDRS)_j$, where it is then relayed to WSGT. The TDRSS round-trip range measurement is the time that an RF signal takes to traverse the four-leg path from WSGT to $(TDRS)_i$, to the user spacecraft, back to $(TDRS)_j$, and then to WSGT.

4.2.1.2 The basic concept of the TDRSS range measurement is to determine how long ago a currently received return PN chip m was transmitted. This measurement process is divided into two parts: ambiguous range measurement from the range extractor, and ambiguity interval determination from path modeling.

4.2.1.3 For ambiguous range measurement, the range extractor determines, at each 1-second tic, the currently received return PN chip m by stopping the return chip counter at t_s, time of the next positive transition of the return PN clock. The time delay Tr is measured to determine how long ago the corresponding forward PN chip, m, was most recently transmitted. The TDRSS range measurement concept is illustrated in figures 4-3 and 4-4 (for a more detailed description of the range extraction process, see para 3.5.2). This measurement provides the round-trip light time minus a whole number of PN code periods or range ambiguity intervals (NA). The number of code periods is determined from an estimate of the computed round-trip light time (by path modeling) and the observed time delay Tr.

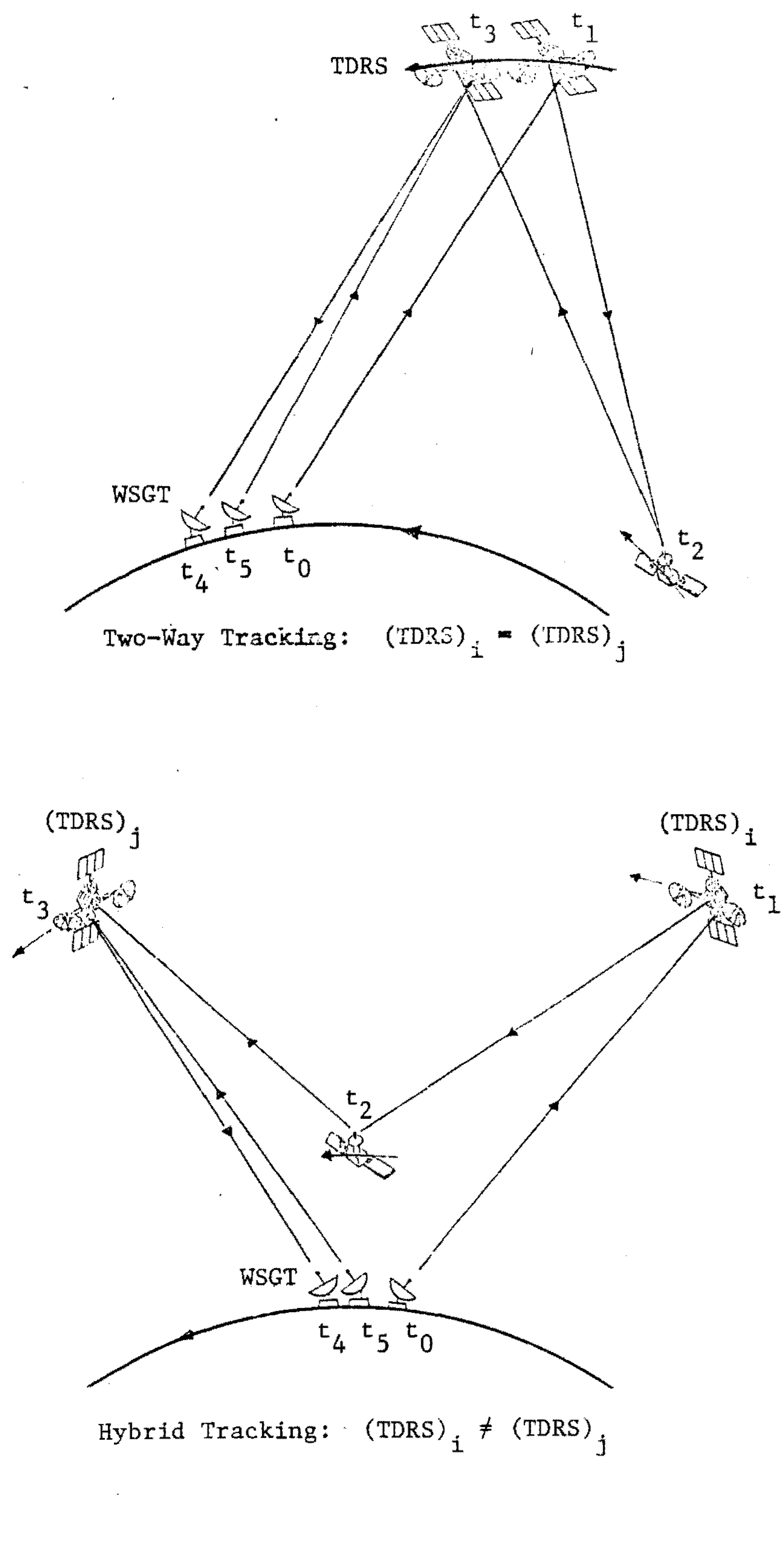
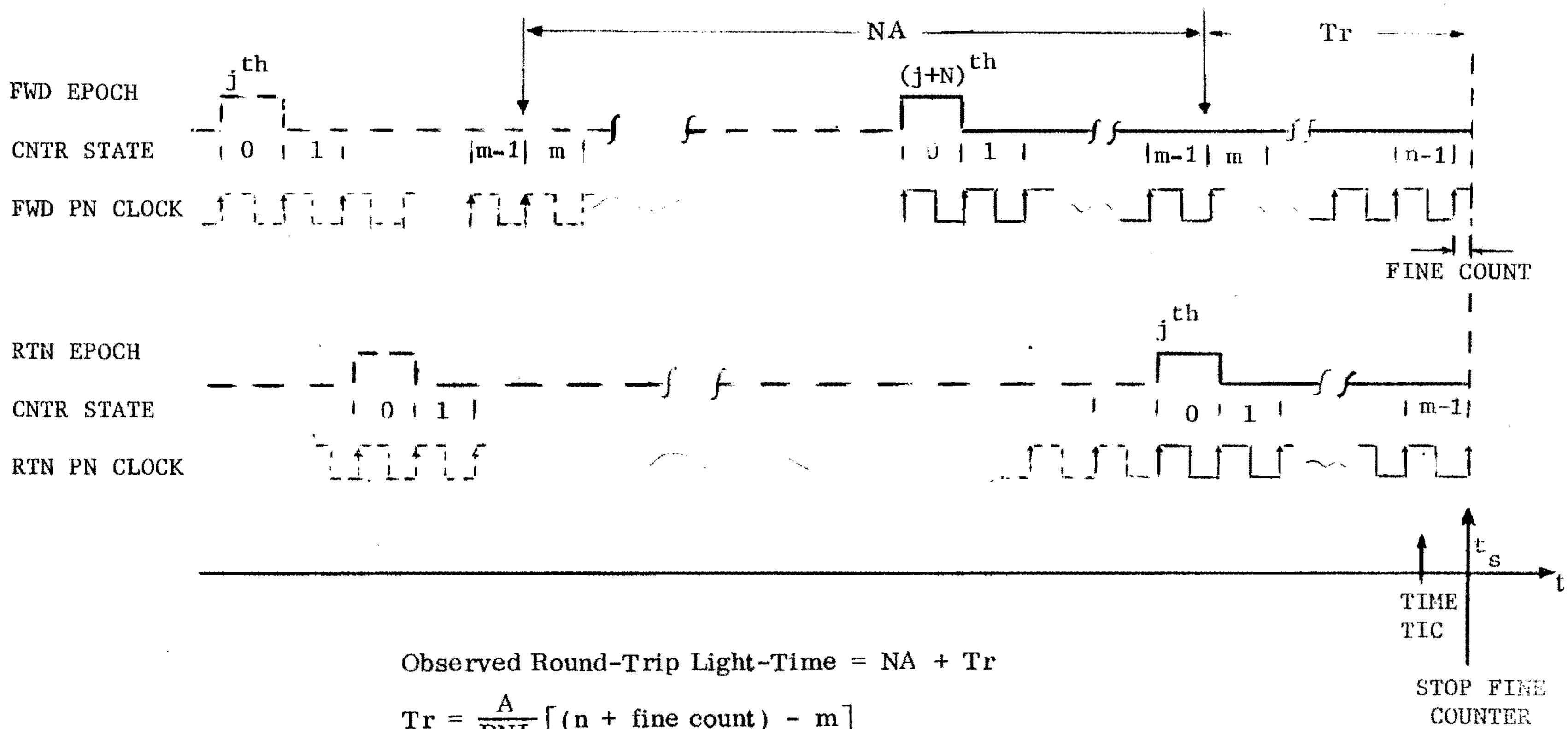


Figure 4-2. Tracking Geometry



Observed Round-Trip Light-Time = NA + Tr

$$Tr = \frac{A}{PNL}\left[(n + \text{fine count}) - m\right]$$

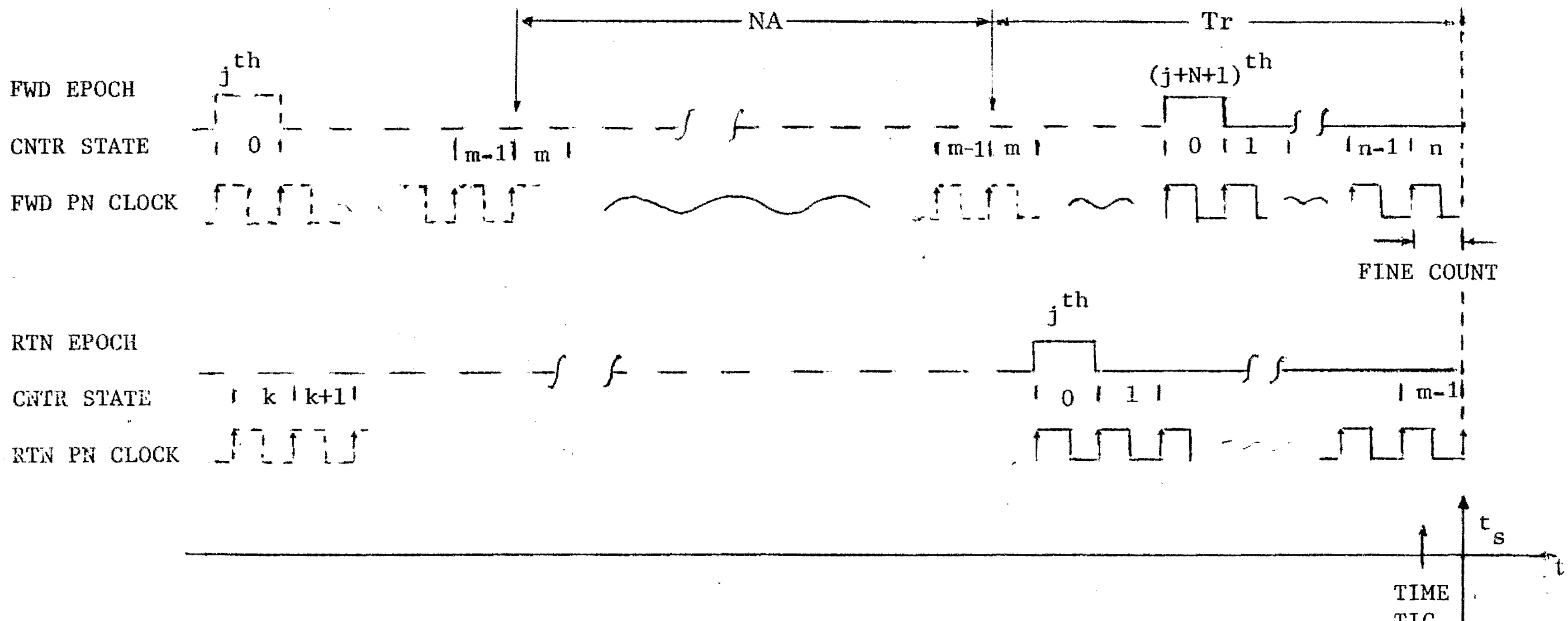
= Time delay, observed ambiguous range.
Measured by the Range Extractor.

A = Forward PN code period

PNL = PN code length

NA = Range ambiguity intervals.
N is an integer, determined from path modeling.

Figure 4-3. Range Measurement When the Return Epoch is After the Forward Epoch



Observed Round-Trip Light-Time = NA + Tr

$$Tr = \frac{A}{PNL}\left\{\left[(n + \text{fine count}) - m\right] + PNL\right\}$$

= Time delay, observed ambiguous range.
Measured by the Range Extractor.

A = Forward PN code period

PNL = PN code length

NA = Range ambiguity intervals.
N is an integer, determined from path modeling.

Figure 4-4. Range Measurement When the Return Epoch is Before the Forward Epoch

4.2.1.4 Let (n + fine count) be the reading from the forward chip counters at the stop time t_S. Then, the time delay Tr´ in unit of forward chip, is obtained as follows:

$$Tr' = (n + \text{fine count}) - m \text{ for } n > m$$

or $$= (n + \text{fine count}) - m + PNL \text{ for } n < m$$

Where: $PNL = (2^{10} - 1)\,2^{8}$ PN code length

Tr´ is a measure of how many forward chips and fractions of forward chips ago the corresponding forward PN chip m was most recently transmitted. Because the forward PN rate is constant, the constant forward PN chip period, τ, can be given by:

$$\tau = \frac{A}{PNL}$$

Where: A is the forward PN code period or range ambiguity interval.

Finally, the time delay Tr in nanoseconds can be computed as

$$Tr = \tau\left[(n + \text{fine count}) - m\right] \text{ for } n > m$$

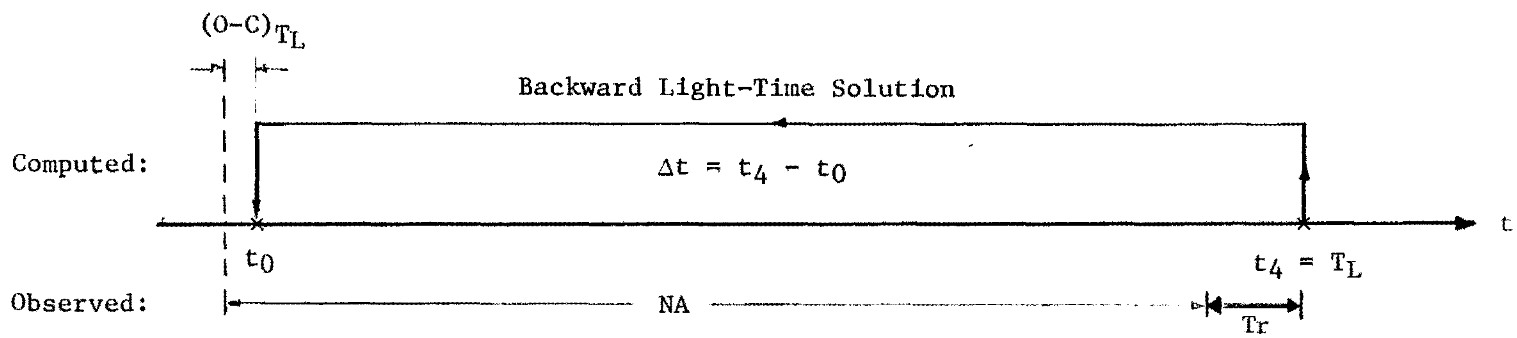
or $$= \tau\left\{\left[(n + \text{fine count}) - m\right] + PNL\right\} \text{ for } n < m$$

Note

Because the velocity of propagation is constant for all RF signals independent of frequency, the Doppler shifts of the return signal have no effect on the time delay measurement. The Doppler will modify the return PN chip period but this modification has no effect on m which is determined by the positive transition of the return PN clock; i.e., the range measurement is a function only of the position of the user spacecraft at the time of the signal turnaround, and is independent of the velocity of the user spacecraft at that point.

4.2.2 COMPUTED RANGE

The observation time tag, T_L, provided in the range data refers to the time at the end of the range measurement interval. Because the round-trip light time is longer than the PN code period, the return PN code does not correspond to the forward PN code with which it is compared, but may correspond to one transmitted an integer number of code periods earlier. The transmission time $(T_L - \delta t4 - \delta t3 - \delta t2 - \delta t1)$ is obtained by a backward signal trace using the satellites and WSGT positions starting at the time tag T_L to obtain the computed round-trip light time, $\Delta t = T_L - t_0$. The ambiguity is resolved by determining the integral number of code periods contained in the difference between the computed round-trip light time Δt and the observed time delay, Tr, such that the range O-C is minimized. Figure 4-5 shows the range observed and computed measurements.



The range ambiguity is resolved by:

$$N = \text{Round}\left[\frac{(t4\ - t0) - Tr}{A}\right]$$

The observed minus computed value:

$$(O-C)_{T_L} = (NA + Tr) - \Delta t$$

Figure 4-5. Range Observed and Computed Measurements

4.2.3 ADJUSTMENTS TO THE COMPUTED RANGE OBSERVATION

Adjustments to the computed range observation are accommodated as follows (reference 15):

a. Transponder delays which are not attributable to distance will occur in both the TDRS and user spacecraft transponders. The TDRS transponder delay will be removed by the Automatic Data Processing Equipment (ADPE) at WSGT; the user transponder delay may be added to the computed observation at the end of the light time solution. This procedure does not invalidate the light time solution itself, because during a typical 1-microsecond transponder delay, a satellite would not travel more than a few millimeters.

b. Ground station electronic delays will be accommodated by the ADPE zero-set procedures.

c. Tropospheric refraction can be provided for the WSGT TDRS links as an additional correction at the end of the light time solution, or it can be inserted into the relevant legs of the light time solution itself. For cases in which the user transponder is on the ground, additional terms are required for refraction on the user transponder legs. For a user satellite in orbit, it is suggested that observations be edited out of the solution for which the signal path between TDRS and the user passes through the atmosphere. If use of such observations is desired, an elaborate model must be developed to calculate the effect at arbitrary locations, heights, times, etc.

d. Ionospheric refraction can be handled the same way as tropospheric, except that the correction is now frequency dependent and is insignificant for K-band frequency links.

4.3 MODELING THE DOPPLER OBSERVATION

4.3.1 OBSERVED DOPPLER

4.3.1.1 The Doppler observation essentially involves the measurement of a frequency returned from the satellites to determine its Doppler shift due to the motion of the satellites, relative to WSGT and to one another. (The generation of the Doppler counter input frequency is described in detail in para 3.2.4.) The WSGT provides a biased, scaled, nondestruct, round-trip Doppler count (N) which can be sampled at 1-, 5-, 10-, 60-, or 300-second intervals.

4.3.1.2 Consider the nondestruct Doppler count over a time interval $\Delta T = T_{L+1} - T_L$. The biased Doppler count aggregated in this time interval, time tagged at T_{L+1} is:

$$\Delta n(T_{L+1}) = n(T_{L+1}) - n(T_L) = \int_0^{T_{L+1}} f_{in}(t)\,dt - \int_0^{T_L} f_{in}(t)\,dt$$

$$= \int_{T_L}^{T_{L+1}} f_{in}(t)\,dt$$

Where:

$$f_{in}(t) = \begin{cases} 240 \text{ KHz} + Fd(t), & \text{for S-band} \\ 2.4 \text{ MHz} + Fd(t), & \text{for K-band} \end{cases}$$

The Doppler count output, N(T), from WSGT to NASA is scaled by a factor J (J = 100 for K-band or 1000 for S-band). The scaled, biased Doppler count accumulated in the time interval ΔT is thus given by:

$$\Delta N(T_{L+1}) = N(T_{L+1}) - N(T_L) = J \times n(T_{L+1}) - J \times n(T_L)$$

$$= J \times \Delta n(T_{L+1})$$

$$= \int_{T_L}^{T_{L+1}} J \times f_{in}(t)\, dt$$

Where:

$$J \times f_{in}(t) = 240 \times 10^6 \text{ Hz} + JFd(t)$$

Therefore, the average observed Doppler frequency over the time interval ΔT is defined by:

$$\overline{Fd}(T_{L+1}) = \frac{\int_{T_L}^{T_{L+1}} Fd(t)\, dt}{T_{L+1} - T_L} = \frac{1}{J}\left[\frac{N(T_{L+1}) - N(T_L)}{T_{L+1} - T_L} - 240 \times 10^6\right] \text{Hz} \quad (4\text{-}2)$$

4.3.2 COMPUTED DOPPLER

4.3.2.1 The computed Doppler is modeled via the range-difference method (refer to para 3.2.6 and 3.3.3) by expressing Fd (t) in terms of the range rates $\dot{R}L_{ij}$ and $\dot{R}s_j$ and then averaging Fd (t) over the time interval. The average computed $\overline{Fd}(T_{L+1})$ is given in terms of range differences of the computed RL_{ij} and Rs_j.

4.3.2.2 The instantaneous Doppler frequency is:

$$Fd(t) = -\frac{1}{c}\, \dot{R}L_{ij}\ Fref - \frac{1}{c}\, \dot{R}s_j\ bFp.$$

Where: $\dot{R}s_j = \dot{R}5_j + \dot{R}4_j$

$$\dot{R}L_{ij} = \begin{cases} \dot{R}1_i + \dot{R}2_i + \dot{R}3_j + \dot{R}4_j & \text{for closed loop (see figure 3-1).} \\ \dot{R}3_j + \dot{R}4_j & \text{for one-way (see figure 3-13).} \end{cases}$$

Fref is the user spacecraft transmit frequency.

bFp is the nominal center frequency of the second Doppler term. (Fref and bFp are given in table 4-1).

4.3.2.3 The average Doppler frequency is obtained as follows:

$$\overline{Fd}\,(T_{L+1}) = \frac{1}{T_{L+1} - T_L} \int_{T_L}^{T_{L+1}} Fd\,(t)\ dt$$

$$= \frac{1}{T_{L+1} - T_L} \int_{T_L}^{T_{L+1}} \left(-\frac{1}{c}\,\dot{R}L_{ij}\, Fref - \frac{1}{c}\,\dot{R}s_j bFp\right)\ dt$$

$$= \frac{1}{T_{L+1} - T_L} \left[-\frac{1}{c}\, Fref\,(T_{L+1}) \int_{T_L}^{T_{L+1}} \dot{R}L_{ij} dt - \frac{1}{c}\, bFp \int_{T_L}^{T_{L+1}} \dot{R}s_j dt\right]$$

$$= -\frac{1}{c} \left[Fref\,(T_{L+1})\, \frac{\Delta RL_{ij}\,(T_{L+1})}{T_{L+1} - T_L} + bFp\, \frac{\Delta Rs_j(T_{L+1})}{T_{L+1} - T_L} \right] \qquad (4\text{-}3)$$

Where: $\Delta RL_{ij}(T_{L+1}) = RL_{ij}(T_{L+1}) - RL_{ij}\,(T_L)$

$\Delta Rs_j\,(T_{L+1}) = Rs_j\,(T_{L+1}) - Rs_j\,(T_L)$

This relation permits the computed Doppler measurements to be modeled by using a backward light time solution algorithm. For nondestruct Doppler, the time tag is at the end of the averaging interval; a backward light time solution (involving all five legs for closed-loop Doppler and three legs for one-way Doppler) anchored with receive time at the time tag T_{L+1} will provide values for both RL_{ij} and Rs_j at the end of the interval. A similar solution with receive time at time tag minus ΔT gives RL_{ij} and Rs_j at the beginning of the interval. At the start of Doppler measurements, the first calculation of RL_{ij} and Rs_j are required for initialization. Thereafter, only RL_{ij} and Rs_j at time tag T_{L+1} are required along with retrieval of the previously computed RL_{ij} and Rs_j (at time T_L). RL_{ij} is also the same value used to compute range. Hence, for each range and Doppler pair at T_{L+1}, only RL_{ij} and Rs_j are required to compute both range and Doppler. (Note that the preceding discussion is not applicable to data sampled at arbitrary time intervals.)

Table 4-1. The Second Doppler Term and the User Spacecraft Transmit Frequency

Service	Fref (MHz)	bF_p (MHz)	Comments
KSA-1	15003.4	-1475	For KSA and SSA the bF_p is the effective return frequency translation via the TDRS
KSA-2	15003.4	-1075	
SSA-1	2205 to 2295	(13677.5 - Fref) in 0.5-MHz steps	
SSA-2	2205 to 2295	(13697.5 - Fref) in 0.5-MHz steps	
MA	2287.5	-2127.5	For MA the bF_p is the resultant frequency translation due to the return TDRS and the MA Element Separator at WSGT

Note

All frequencies shown are nominal center frequencies in MHz.

4.4 RANGE AND DOPPLER COMPUTED MEASUREMENT ALGORITHMS

4.4.1 A SUMMARY OF THE OBSERVED MEASUREMENTS

4.4.1.1 The raw range data (DTr) output from the range extractor is given in units of 1/256 nanosecond (because the range measurement quantization is 1 nanosec, the last eight bits should always be zero). The conversion of DTr to range engineering units proceeeds as follows (reference 17):

a. Convert DTr to ambiguous time delay, Tr, time tagged at T_L

$$Tr(T_L) = DTr(T_L) \times 2^{-8} \times 10^{-9} \text{ seconds}$$

b. Convert $Tr(T_L)$ to observed ambiguous one-way range, $Ra(T_L)$

$$Ra(T_L) = \frac{1}{2} c\, Tr(T_L) \text{ meters}$$

4.4.1.2 The raw Doppler data output from the Doppler extractor consists of nondestruct Doppler count (N). The conversion from N to average Doppler frequency is given by

$$\overline{F}d(T_{L+1}) = \frac{1}{J}\left(\frac{N(T_{L+1}) - N(T_L)}{T_{L+1} - T_L} - 240 \times 10^6\right) \text{ Hz}$$

Where: J = 1000 for S-band links; J = 100 for K-band links — derived from byte 52 of the data format

4.4.2 COMPUTATION OF RANGE AND DOPPLER MEASUREMENTS

4.4.2.1 General. In the succeeding paragraphs, algorithms for calculating the computed measurements of the range and Doppler observations are given. (The algorithms presented were extracted from reference 17).

4.4.2.2 Range Segments Computation. The range segments are used in the computation of total range and Doppler in all possible TDRS-user configurations and are obtained as follows (see figure 4-6 for signal path definitions):

a. Downlink. Compute iteratively the downlink from the jth TDRS (TD_j) to the jth antenna at WSGT (GT_j) propagation distance $R4_j$ and propagation delay $\delta t4_j$ at T_L. Initially let $\delta t4_j(T_1) = 0.133$ second and $R4_j(T_1)_0 = 40,000$ km, and iterate the following equations:

$$[R4_j(T_L)]_k = \left| \overline{X}\, TD_j\,[T_L - \delta t4_j(T_L)] - \overline{X}\, GT_j(T_L) \right|$$

$$\delta t4_j(T_L) = \frac{[R4_j(T_L)]_k}{c}$$

until

$$\left| [R4_j(T_L)]_k - [R4_j(T_L)]_{k-1} \right| \leq 0.1 \text{ meter}$$

Where: k = 1, 2, 3, ... iteration number

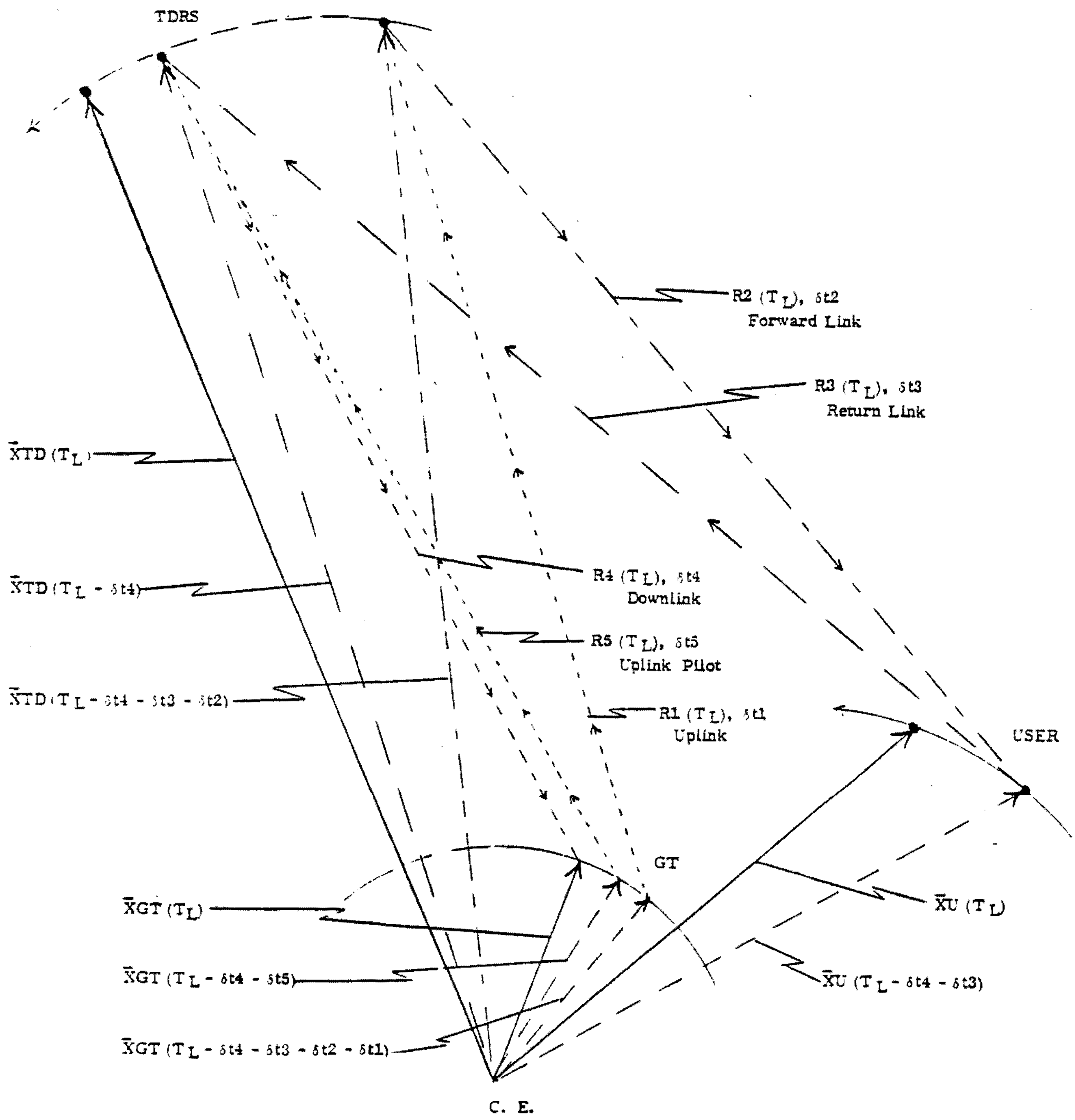


Figure 4-6. Range Segment and Propagation Delay

b. Return Link. Compute iteratively the user spacecraft (U) return link to the jth TDRS (TD_j) propagation distance $R3_j$ and the propagation delay $\delta t3_j$ at T_L. Initially let $\delta t3_j(T_L) = 0.133$ second and $R3j(T_L)_0 = 40,000$ km, and iterate the following equations:

$$[R3_j(T_L)]_k = \left| \bar{X}U[T_L - \delta t4_j(T_L) - \delta t3_j T_L)] - \bar{X}TD_j [T_L - \delta t4_j(T_L)] \right|$$

$$\delta t3j(T_L) = \frac{[R3_j(T_L)]_k}{c}$$

until

$$\left| [R3_j(T_L)]_k - [R3_j(T_L)]_{k-1} \right| \leq 0.1 \text{ meter}$$

Where: k = 1, 2, 3, ... iteration number

Note

If only one-way Doppler is to be computed, set $R2_{ij}(T_L) = 0$ and $R1_{ij}(T_L) = 0$, and proceed to step e; otherwise, proceed with step c.

c. Forward Link. Compute iteratively the ith TDRS (TD_i) forward link to user spacecraft (U) propagation distance $R2_{ij}$ and propagation delay $\delta t2_{ij}$ at T_L. Initially let $\delta t2_{ij}(T_L) = 0.133$ second and $R2_{ij}(T_L)_0 = 40,000$ km, and iterate the following equations:

$$[R2_{ij}(T_L)]_k = \left| XTD_i [T_L - \delta t4_j(T_L) - \delta t3_j(T_L) - \delta t2_{ij}(T_L)] - XU[T_L - \delta t4_j(T_L) - \delta t3_j(T_L)] \right|$$

$$\delta t2_{ij}(T_L) = \frac{[R2_{ij}(T_L)]_k}{c}$$

until

$$\left| [R2_{ij}(T_L)]_k - [R2_{ij}(T_L)]_{k-1} \right| \leq 0.1 \text{ meter}$$

Where: k = 1, 2, 3,... iteration number

d. Uplink. Compute iteratively the ith antenna at WSGT (GT_i) to the ith TDRS (TD_i) uplink propagation distance $R1_{ij}$ and propagation time delay $\delta t1_{ij}$ at T_L. Initially let $\delta t1ij\,(T_L) = 0.133$ second and $R1ij(T_L)_0 = 40{,}000$ km, and iterate the following equations:

$$[R1_{ij}(T_L)]_k = \left| \bar{X}GT_i[T_L - \delta t4_j(T_L) - \delta t3_j(T_L) - \delta t2_{ij}(T_L) - \delta t1_{ij}(T_L)] - \bar{X}TD_i[T_L - \delta t4_j(T_L) - \delta t3_j(T_L) - \delta t2_{ij}(T_L)] \right|$$

$$t1_{ij}(T_L) = \frac{[R1_{ij}(T_L)]_k}{c}$$

until

$$\left| [R1_{ij}(T_L)]_k - [R1_{ij}(T_L)]_{k-1} \right| \leq 0.1 \text{ meter}$$

Where: k = 1, 2, 3, ... iteration number

Note

If Doppler computation is required, perform step e; otherwise, proceed to step f.

e. Uplink Pilot. Compute iteratively the jth antenna at WSGT (GT_j) to the jth TDRS (TD_j) uplink pilot propagation distance R5j and propagation delay $\delta t5_j$ at T_L. Initially let $\delta t5_j\,(T_L) = 0.133$ second and $R5_j(T_L)_0 = 40{,}000$ km, and iterate the following equations:

$$[R5_j(T_L)]_k = \left| \bar{X}GT_j\,[T_L - \delta t4_j(T_L) - \delta t5_j(T_L)] - \bar{X}TD_j\,[T_L - \delta t4_j(T_L)] \right|$$

$$t5_j(T_L) = \frac{[R5_j(T_L)]_k}{c}$$

until

$$\left| [R5_j(T_L)]_k - [R5_j(T_L)]_{k-1} \right| \leq 0.1 \text{ meter}$$

Where: k = 1, 2, 3, ... iteration number

Note

For two-way track, the receive antenna may be different from the antenna transmitting the pilot tone.

f. Long Trip Range. Using steps a, b, c, and d, compute the long range RL_{ij} from the ith ground terminal (GT_i) to the user (U) satellite and back to the jth ground terminal (GT_j) at T_L as follows:

$$RL_{ij}(T_L) = [R1_{ij}(T_L) + R2_{ij}(T_L) + R3_j(T_L) + R4_j(T_L)]$$

Where: i = forward link path.

j = return link path.

Note

For two-way computation i = j; for hybrid range computation $i \neq j$.

4.4.2.3 Range Computation. The number of ambiguity intervals can now be computed as follows:

a. Compute the one-way range as follows:

$$R_{ij}(T_L) = \frac{1}{2} RL_{ij}(T_L)$$

b. Compute the ambiguity interval A (T_L) from

$$A(T_L) = \frac{PNL}{PNR(T_L)} \text{ seconds}$$

Where: $PNL = (2^{10} - 1)\, 2^8$ code chips.

$PNR(T_L) = \frac{31}{96M}$ Fref (T_L) code chips per second (code rate).

M = 240 for S-band service.

M = 1600 for K-band service.

c. Compute the one-way range ambiguity interval Ramb at T_L as:

$$Ramb(T_L) = \frac{1}{2} c\, A(T_L) \text{ meters}$$

Note

On S-band links Ramb varies as a function of Fref, which is a function of time since Ramb can differ for each tracking pass. The interval varies from about 13,261,861 meters at the lower end of the Fref band (2200 MHz) to 12,685,258 meters at the higher end (2300 MHz), at approximately 5.8 meters/kHz. On KSA links, Ramb is about 12,964,214 meters and varies about 1 meter/kHz. A typical user spacecraft will have 5 to 7 ambiguity intervals; therefore, the total variation will be approximately 40 m/kHz at S-band and 7 m/kHz at K-band.

d. Determine the number of code periods "n" from an estimate of the computed one-way range $R_{ij}(T_L)$ and the observed ambiguous one-way range Ra (T_L) (estimate must be better than 1/2 Ramb or approximately 6300 km) as follows:

$$n\,(T_L) = \text{Round}\left|\frac{R_{ij}(T_L) - Ra(T_L)}{\text{Ramb}\,(T_L)}\right|$$

Note

"Round" means round off to closest integer value.

e. Correct the observed ambiguous one-way range at T_L for ambiguity as follows:

$$R(T_L) = Ra\,(T_L) + n\,(T_L)\ \text{Ramb}\,(T_L)\ \text{meters}$$

4.4.2.4 Doppler Computation. The range segments computed at T_L are saved to be used in the computation of Doppler at T_{L+1} (except for the first computation). Then proceed as follows:

a. Compute the short range $Rs_j(T_L)$ and $Rs_j(T_{L+1})$ as:

$$Rs_j\,(T_L) = R4_j\,(T_L) + R5_j\,(T_L)$$

$$Rs_j\,(T_{L+1}) = R4_j\,(T_{L+1}) + R5_j\,(T_{L+1})$$

b. Compute ΔRL_{ij} and ΔRs_j as follows:

$$\Delta RL_{ij}\,(T_{L+1}) = RL_{ij}\,(T_{L+1}) - RL_{ij}\,(T_L)$$

$$\Delta Rs_j\,(T_{L+1}) = Rs_j\,(T_{L+1}) - Rs_j\,(T_L)$$

c. Compute the average Doppler frequency over the interval from T_L to T_{L+1} as:

$$\left[\overline{F}d_{ij}\,(T_{L+1})\right]_c = -\frac{1}{c}\left[\text{Fref}\,(T_{L+1})\ \frac{\Delta RL_{ij}\,(T_{L+1})}{T_{L+1} - T_L} + bFp_j\ \frac{\Delta Rs_j\,(T_{L+1})}{T_{L+1} - T_L}\right]\ \text{Hz}$$

Where:

$$bFp_j = 10^6\text{Hz}\begin{Bmatrix} -1475.0\ \text{MHz} & \text{KSA-1} \\ -1075.0\ \text{MHz} & \text{KSA-2} \\ \frac{1}{2}\ \text{Round}\ 2\cdot\left[13677.5 - \text{Fref}\,(T_{L+1})\ \text{MHz}\right] & \text{SSA-1} \\ \frac{1}{2}\ \text{Round}\ 2\cdot\left[13697.5 - \text{Fref}\,(T_{L+1})\ \text{MHz}\right] & \text{SSA-2} \\ -2127.5\ \text{MHz} & \text{MA} \end{Bmatrix}\ \text{Downlink channel}$$

Note

a. "Round" means round off to closest integer in MHz; the downlink channel is obtained from information in bytes 52 and 55 of the data format.

b. For SSA-1 and SSA-2, the bF_p, as determined from this algorithm, may contain a ±0.5 MHz error. A detailed discussion is given in appendix C.

4.4.2.5 Schematic Summary. A schematic summary of the algorithms is presented in figure 4-7. In addition to providing a convenient summary, the interfaces required with associated orbit determination software are also indicated.

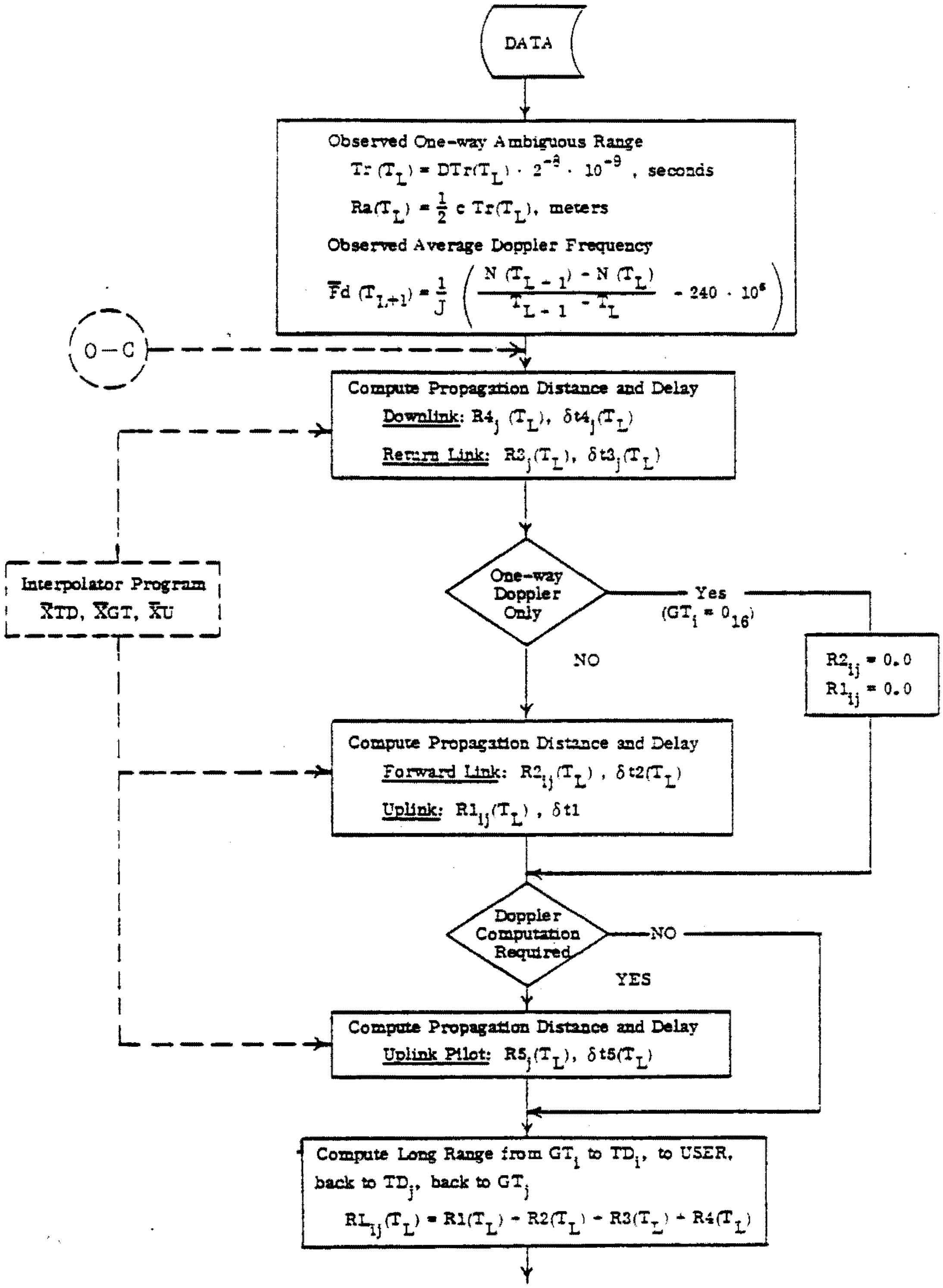


Figure 4-7. TDRSS Observed and Computed Measurement Algorithms

Observed Unambiguous One-way Range

1. Compute one-way range

$$R_{ij}(T_L) = \frac{1}{2} RL_{ij}(T_L)$$

2. Compute ambiguity interval (code period)

$$A\ (T_L) = \frac{PNL}{PNR\ (T_L)} \quad \text{seconds}$$

$PNL = (2^{10} - 1)\ 2^{8}$ code chips (long code for ranging)

$PNR\ (T_L) = \frac{31}{96M}\ Fref\ (T_L)$ code chips per second

$M = 240$ for S-band service; 1600 for K-band service

3. Compute the one-way range ambiguity interval

$$Ramb\ (T_L) = \frac{1}{2}\ c\ A\ (T_L)$$

4. Compute integer number of ambiguity intervals

$$n\ (T_L) = \text{Round}\ \frac{R_{ij}\ (T_L) - Ra\ (T_L)}{Ramb\ (T_L)}$$

5. Correct the observed ambiguous one-way range

$$R\ (T_L) = Ra\ (T_L) + n\ (T_L)\ Ramb\ (T_L)$$

Computed Average Doppler Frequency

1. Compute the short range

$$Rs_j\ (T_L) = R4_j\ (T_L) + R5_j\ (T_L)$$

$$Rs_j\ (T_{L+1}) = R4_j\ (T_{L+1}) + R5_j\ (T_{L+1})$$

2. Compute long and short range increments

$$\Delta RL_{ij}\ (T_{L+1}) = RL_{ij}\ (T_{L+1}) - RL_{ij}\ (T_L)$$

$$\Delta Rs_j\ (T_{L+1}) = Rs_j\ (T_{L+1}) - Rs_j\ (T_L)$$

3. Compute the average Doppler frequency over the interval from T_L to T_{L+1} as:

$$\bar{F}d_{ij}\ (T_L, T_{L+1}) = -\frac{1}{c}\left[Fref\ (T_{L+1})\ \frac{\Delta RL_{ij}\ (T_{L+1})}{T_{L+1} - T_L} + bFp_j\ \frac{\Delta Rs_j\ (T_{L+1})}{T_{L+1} - T_L}\right]\ \text{Hz}$$

(O—C)

Observed	Computed
$\bar{F}d\ (T_{L+1})$	$\bar{F}d_{ij}\ (T_L, T_{L+1})$
$R\ (T_L)$	$R_{ij}\ (T_L)$

Figure 4-7. TDRSS Observed and Computed Measurement Algorithms (cont)

SECTION 5. TDRS ANGULAR OBSERVED AND COMPUTED MEASUREMENT ALGORITHMS

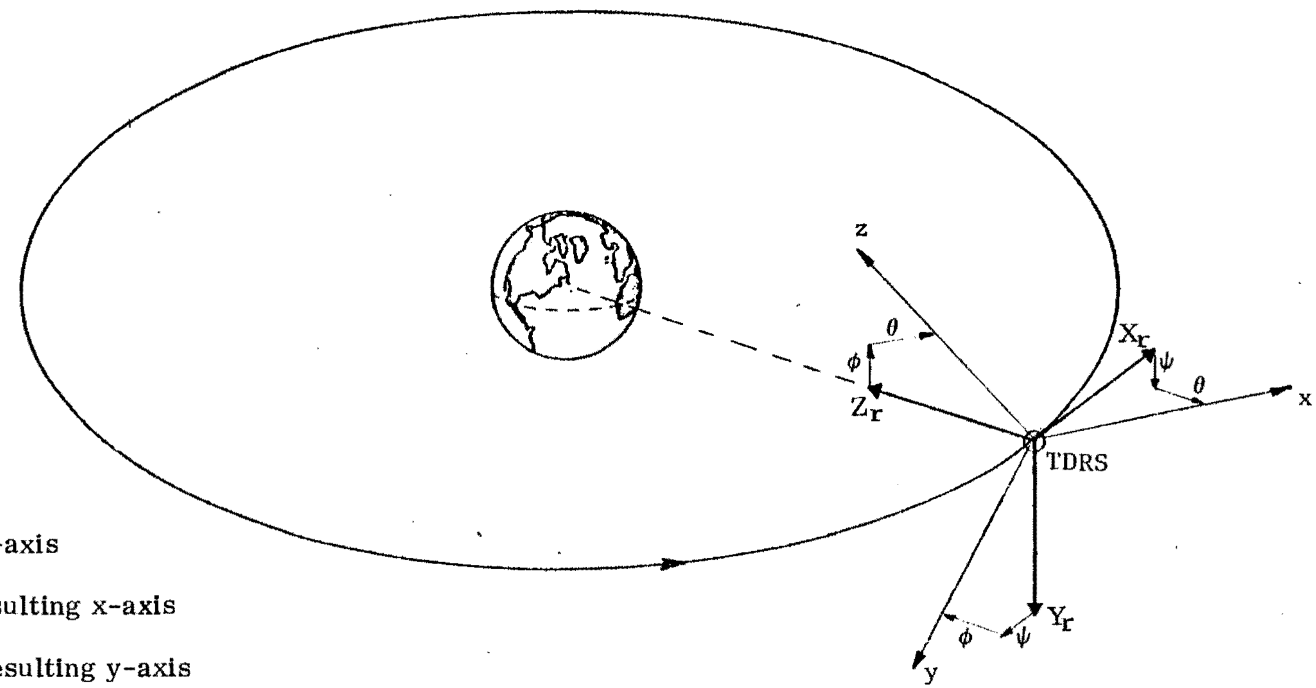
SECTION 5. TDRS ANGULAR OBSERVED AND COMPUTED MEASUREMENT ALGORITHMS

5.1 COORDINATE SYSTEMS

5.1.1 Two coordinate systems are involved in the TDRS angular measurements: the NASA defined Attitude Reference Coordinate System $(X_r, Y_r, Z_r)_{AR}$ and the TDRS Body Coordinate System $(x, y, z)_{BC}$. Both systems have their common origin located at the center of mass of the TDRS. The Attitude Reference Coordinate System has the Z_r axis in the orbital plane pointed toward nadir, the X_r-axis in the orbital plane is pointed in the general direction of the TDRS orbital motion, and the Y_r axis completes the right-handed orthogonal set as shown in figure 5-1. The TDRS Body Coordinate System has the z-axis along the spacecraft longitude center line and pointed toward Earth, the y-axis is parallel to the solar array rotational axis and pointed toward the SGL antenna side of the TDRS, and the x-axis completes the right-handed orthogonal set as shown in figure 5-2.

5.1.2 The Attitude Reference Coordinate Systems $(X_r, Y_r, Z_r)_{AR}$ is used to define the orientation of the TDRS. The orientation parameters are the Euler angles: yaw (ψ), roll (ϕ), and pitch (θ). The Euler angles transform the NASA defined Attitude Reference Coordinate System to the TDRS Body Coordinate System according to the following order of rotations: yaw, roll, and pitch (see figure 5-1).

5.1.3 The TDRS Body Coordinate System is used to define the TDRS antenna or RF beam pointing. The RF beam pointing parameters are given as RF beam azimuth (ϕ_{rf}) and RF beam elevation (ϕ_{rf}). The azimuth angle, ϕ_{rf}, is defined as a right-handed rotation about the y-axis of the TDRS Body Coordinate System; the elevation angle, ϕ_{rf}, is defined as a right-handed rotation about the resultant x axis as shown in figure 5-2. For the SA antennas, the pointing error due to the off-center locations of the rotation axes is insignificant relative to the required RF beam pointing accuracy, and can be neglected in pointing angle computations.

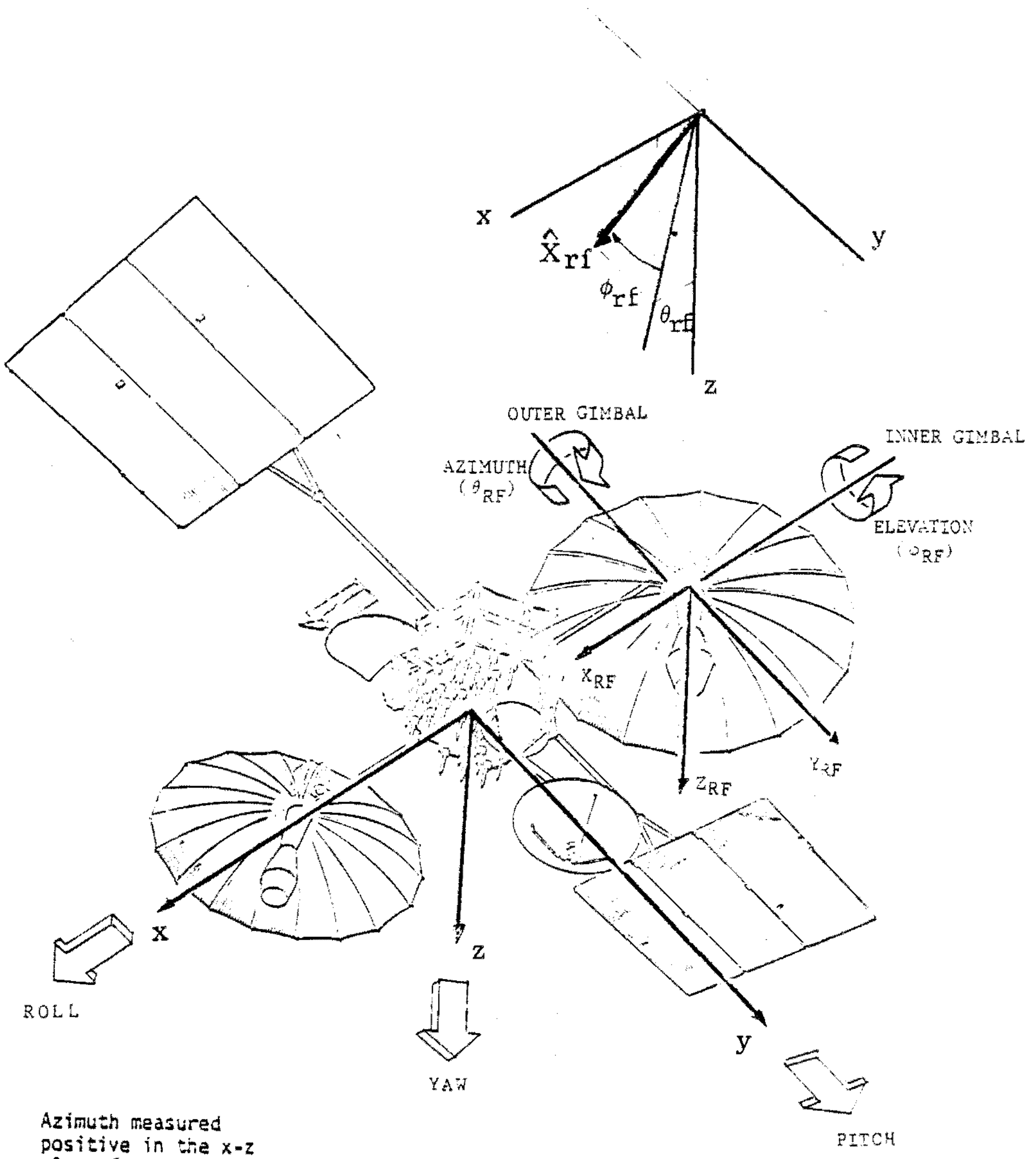


Ψ = yaw about Z_r-axis

ϕ = roll about resulting x-axis

θ = pitch about resulting y-axis

Figure 5-1. Attitude Reference Coordinates (X_r, Y_r, Z_r) and Spacecraft Body Coordinates (x, y, z).



Azimuth measured positive in the x-z plane from the z axis toward positive x axis

Elevation measured positive from the x-z plane toward negative y axis

Figure 5-2. TDRS Body and RF Beam Coordinate Systems

5.2 TDRS ANGULAR MEASUREMENT

5.2.1 GENERAL

5.2.1.1 TDRS angular measurement consists of TDRS orientation (ψ, ϕ, θ) and TDRS RF beam pointing (θ_{rf}, ϕ_{rf}). The orientation parameters are determined by the WSGT TTC subsystem. RF beam pointing for the SA and MA antennas is determined by the WSGT antenna pointing software subsystem (reference 18).

5.2.1.2 The SA antennas are pointed by two-axis ground-commanded gimbal drives in discrete steps of 0.0075 degree. The SA antenna pointing software subsystem can generate up to 35 stepping commands per 1.024 seconds during antenna slewing, or 6 stepping commands per 1.024 seconds during tracking, which corresponds to a 0.2563 deg/sec maximum slew rate, or a 0.0439 deg/sec maximum angular tracking rate, respectively. The SA antenna is open-loop pointed for S-band and autotrack pointed for K-band. The SA antenna pointing accuracy is 0.43 degree for S-band and 0.22 degree for K-band. The forward MA beam is controlled by 12 phase-shifters in the MA transmitter. The settings of the phase-shifters are adjusted by ground command to electronically steer the forward beam. MA beam pointing is updated at the rate of once every 20 seconds to maintain the pointing accuracy of 2 degrees.

5.2.2 TDRS ORIENTATION

The TDRS orientation parameters (ψ, ϕ, θ) are derived from near real-time return TDRS Attitude Control Subsystem (ACS) telemetry data. The values of ψ, ϕ, and θ are determined by the TDRS attitude determination software subsystem and then are output to the TDRS antenna pointing task once every second. ψ, ϕ, and θ are used to construct the coordinates transformation matrix between the NASA-defined Attitude Reference Coordinate System and the TDRS Body Coordinate System. (It should be noted that the TDRS orientation $[\psi, \phi, \theta]$ has no computed values.) The required accuracy of the TDRS orientation parameters is ±0.1 degree for pitch and roll, and ±0.25 degree for yaw (reference 18).

5.2.3 TDRS ANTENNA POINTING ANGLES

5.2.3.1 For MA and SSA open-loop pointing, the TDRS antenna or RF beam pointing angles (θ_{rf}, ϕ_{rf}) are derived from the observed TDRS orientation parameters (ψ, ϕ, θ) and predicted TDRS-to-user look angles. A profile of the predicted TDRS-to-user look angles is tabulated at the rate of one set per 30 seconds (for a stable orbit user). The predicted look angles are computed in the Attitude Reference Coordinate System based on the stored TDRS and user spacecraft ephemerides. From the predicted look angles profile, the TDRS RF beam pointing angles (θ_{rf}, ϕ_{rf}) are derived by a simple coordinate transformation, using the near real-time TDRS orientation parameters (ψ, ϕ, θ). For KSA autotrack pointing, the SA antenna pointing commands are derived from a closed-loop feedback algorithm which monitors the return autotrack error signal. The RF beam pointing angles (θ_{rf}, ϕ_{rf}), the TDRS orientation parameters (ψ, ϕ, θ), and the Doppler and/or range data are collected, time-tagged, and output to NASA at most once every second (reference 18).

5.2.3.2 The updated user spacecraft state vectors, based on the current Doppler and/or range tracking data, are used to derive the actual TDRS-to-user pointing angles. The RF beam pointing error is given as the spatial angular separation between the predicted and actual RF beam pointing vectors. The TDRS angular measurement and the RF beam pointing error are used as monitoring parameters only and have no direct effect on the orbit determination of the user spacecraft. For the succeeding discussion, predicted and actual RF beam pointing are defined as the observed and computed values, respectively.

5.3 RAW OBSERVATION DATA REDUCTION ALGORITHMS

Note

The following observed and computed TDRS angular measurement algorithms were extracted from reference 19.

5.3.1 TDRS ORIENTATION ANGLES (ψ, ϕ, θ)

Each of the angles ψ, ϕ, and θ is represented by a two-byte, 16-bit binary digit in the 75-byte TDRS tracking data transmission format as follows (refer to section 6):

ψ = yaw (bytes 57 and 58)
ϕ = roll (bytes 59 and 60)
θ = pitch (bytes 61 and 62)

MSB → LSB

8	. . .	1	8	. . .	1
Byte x			Byte x + 1		

In the equivalent binary bit string representation, each two-byte entity can be represented as follows:

MSB → LSB

a_{16}	a_{15}	. . .	a_3	a_2	a_1

a_i = 0 or 1. $i = 1, 2, \ldots, 16$.

The Most Significant Bit (MSB) and the Least Significant Bit (LSB) in the equivalent binary bit string representation are $180.\bar{0}$ degrees and $360.\bar{0} \times 2^{-16}$ degrees, respectively.

Let S_{16} be the decimal conversion of the 16-bit binary digit. Then the observed TDRS orientation angle corresponding to S_{16} can be given by:

$$\alpha = k_{or}(S_{16} + \tfrac{1}{2})$$

Where:

$$\tfrac{1}{2} = \text{the truncation factor}$$

$$k = 360.0 \times 2^{-16} \text{ degree}$$

$$= 0.005\ 493\ 164\ 063 \text{ degree}$$

5.3.2 TDRS RF BEAM POINTING ANGLES (θ_{rf}, ϕ_{rf})

Each of the angles θ_{rf} and ϕ_{rf} will be represented by a three-byte, 24-bit binary digit in the 75-byte TDRS tracking data transmission format as follows (refer to section 6):

θ_{rf} = azimuth (bytes 63-65)
ϕ_{rf} = elevation (bytes 66-68)

MSB → LSB

8	. . .	1	8	. . .	1	8	. . .	1
Byte x			Byte x + 1			Byte x + 2		

In the equivalent binary bit string representation, each three-byte entity can be represented as follows:

	MSB					LSB
a_{24}	a_{23}	a_{22}	. . .	a_3	a_2	a_1

Where:

a_{24} is used as the "sign" bit

$a_i = 0$ or 1

$i = 1, 2, \ldots, 24.$

In this binary bit string representation, MSB is placed above bit a_{23} (rather than above bit a_{24}) because bit a_{24} is directly related to the sign of the corresponding angle and assumes a role distinctly different from that of bits a_1 through a_{23}.

The MSB and LSB in the equivalent binary bit string representation are $90.\bar{0} \times 2^{-1}$ degrees and $90.\bar{0} \times 2^{-23}$ degrees, respectively. Let S_{23} be the decimal conversion of the 23-bit binary digit and let $\hat{\alpha}$ be defined by

$$\hat{\alpha} = k_{rf} \left(S_{23} + \frac{1}{2}\right)$$

Where:

$\frac{1}{2}$ = the truncation factor

$$k_{rf} = 90.\bar{0} \times 2^{-23} \text{ degree}$$

$$= 0.000\ 010\ 728\ 836 \text{ degree}$$

Then the corresponding predicted or observed RF beam pointing angle α is determined as follows:

If $a_{24} = 0$, then $\alpha = \hat{\alpha}$

If $a_{24} = 1$, then $\alpha = \hat{\alpha} - 90°$

5.3.3 TDRS RF BEAM POINTING RELATIVE TO THE NASA DEFINED ATTITUDE REFERENCE COORDINATE SYSTEM

From the RF beam pointing angles (θ_{rf}, ϕ_{rf}), the coordinates of the RF beam pointing vector $\hat{X}_{rf}$ relative to the TDRS Body Coordinate System can be given as follows (see figure 5-2):

$$\hat{X}_{rf} = \begin{pmatrix} x_{rf} \\ y_{rf} \\ z_{rf} \end{pmatrix}_{BC} = \begin{pmatrix} \sin\theta_{rf} \cos\phi_{rf} \\ -\sin\phi_{rf} \\ \cos\theta_{rf} \cos\phi_{rf} \end{pmatrix}_{BC}$$

Where:

x_{rf}, y_{rf}, and z_{rf} are the coordinates of the pointing vector $\hat{X}_{rf}$ in the TDRS Body Coordinate System.

A coordinate transformation, derived from the TDRS orientation (ψ, ϕ, θ), can be applied to obtain the coordinates of $\hat{X}_{rf}$ relative to the Attitude Reference Coordinate System. Let $\hat{R}_z(\psi)$, $\hat{R}_x(\phi)$, and $\hat{R}_y(\theta)$ be the yaw, roll, and pitch rotation matrices, respectively. Then

$$\hat{R}_y(\theta) = \begin{pmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{pmatrix}$$

$$\hat{R}_x(\phi) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{pmatrix}$$

$$\hat{R}_z(\psi) = \begin{pmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

and

$$\hat{X}_{rf} = \begin{pmatrix} a \\ b \\ c \end{pmatrix}_{AR} = \left[R_y(\theta) R_x(\phi) R_z(\psi) \right]^{-1} \begin{pmatrix} x_{rf} \\ y_{rf} \\ z_{rf} \end{pmatrix}_{BC}$$

$$= \hat{R}^{-1} (\theta, \phi, \psi) \begin{pmatrix} x_{rf} \\ y_{rf} \\ z_{rf} \end{pmatrix}_{BC}$$

Where: a, b, and c are the direction cosines of $\hat{X}_{rf}$ in the Attitude Reference Coordinate System.

From the orthogonality property of the rotation matrix

$$\hat{R}^{-1}(\theta, \phi, \psi) = R^{T}(\theta, \phi, \psi).$$

Therefore,

$$R^{-1}(\theta, \phi, \psi) = \left[\hat{R}_{y}(\theta)\hat{R}_{x}(\phi)\hat{R}_{z}(\psi)\right]^{T}$$

$$= \begin{pmatrix} \cos\theta\cos\psi - \sin\theta\sin\phi\sin\psi & -\cos\phi\sin\psi & \sin\theta\cos\psi + \cos\theta\sin\phi\sin\psi \\ \cos\theta\sin\psi + \sin\theta\sin\phi\cos\psi & \cos\phi\cos\psi & \sin\theta\sin\psi - \cos\theta\sin\phi\cos\psi \\ -\sin\theta\cos\phi & \sin\phi & \cos\theta\cos\phi \end{pmatrix}$$

The observed direction cosines a, b, and c of the RF beam pointing vector X_{rf} relative to the NASA-defined Attitude Reference Coordinate System can be given as follows:

$$\begin{aligned} a = {} & (\cos\theta\cos\psi - \sin\theta\sin\phi\sin\psi)\ \sin\theta_{rf}\cos\phi_{rf} + \\ & (\cos\phi\sin\psi)\ \sin\phi_{rf} + \\ & (\sin\theta\cos\psi + \cos\theta\sin\phi\sin\psi)\ \cos\theta_{rf}\cos\phi_{rf} \end{aligned}$$

$$\begin{aligned} b = {} & (\cos\theta\sin\psi + \sin\theta\sin\phi\cos\psi)\ \sin\theta_{rf}\cos\phi_{rf} - \\ & (\cos\phi\cos\psi)\ \sin\phi_{rf} + \\ & (\sin\theta\sin\psi - \cos\theta\sin\phi\cos\psi)\ \cos\theta_{rf}\cos\phi_{rf} \end{aligned}$$

$$\begin{aligned} c = {} & -(\sin\theta\cos\phi)\ \sin\theta_{rf}\cos\phi_{rf} - \\ & (\sin\phi)\ \sin\phi_{rf} + \\ & (\cos\theta\cos\phi)\ \cos\theta_{rf}\cos\phi_{rf} \end{aligned}$$

5.4 COMPUTED TDRS ANGULAR MEASUREMENT ALGORITHMS

5.4.1 GENERAL

5.4.1.1 From the current TDRSS tracking data and the TDRS ephemeris, the state vectors of TDRS and user spacecraft are generated from the backward lighttime solution (refer to the discussion in section 4). The state vectors are referenced to the Geocentric True Equator and Equinox of Date Cartesian (GEEC) coordinate system. The backward lighttime solution is used as a matter of convenience and is not required for TDRS angular measurement accuracy. The TDRS state vectors are used to construct the NASA defined Attitude Reference Coordinate System and the transformation matrix between $(X, Y, Z)_{GEEC}$ and $(X_r, Y_r, Z_r)_{AR}$.

5.4.1.2 Let $\hat{u}$ and $\hat{v}$ be the TDRS position and velocity unit vectors, respectively, corresponding to the downlink. Then

$$\hat{u} = \frac{\bar{X}TD(t_3)}{|\bar{X}TD(t_3)|} = \begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix}_{GEEC}$$

$$\hat{v} = \frac{\bar{V}TD(t_3)}{|\bar{V}TD(t_3)|} = \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix}_{GEEC}$$

Where:

$\bar{X}TD(t_3)$ and $\bar{V}TD(t_3)$ are the TDRS position and velocity vectors corresponding to the downlink, respectively (see figure 4-2).

$t_3 = t_4 - \frac{R4}{c}$, TDRS time at the downlink

t_4 = time tag of the raw data frame

R4 = downlink propagation distance from TDRS to WSGT

c = velocity of light.

Let $\hat{I}_r$, $\hat{J}_r$, and $\hat{K}_r$ be the basis vectors of the NASA defined Attitude Reference Coordinates X_r, Y_r, and Z_r, respectively. $\hat{I}_r$, $\hat{J}_r$, and $\hat{K}_r$ can be constructed in the GEEC Coordinate System as follows:

<u>Z_r-axis</u>

$$\hat{K}_r = -\hat{u} = \begin{pmatrix} -u_x \\ -u_y \\ -u_z \end{pmatrix}_{GEEC}$$

<u>Y_r-axis</u>

$$\hat{J}_r = \frac{\hat{K}_r \times \hat{v}}{|\hat{K}_r \times \hat{v}|}$$

Where:

$$|\hat{K}_r \times \hat{v}| = \sin(\hat{K}_r, \hat{v})$$
$$= \sqrt{1-\cos^2(\hat{K}_r, \hat{v})}$$
$$= \sqrt{1-(\hat{K}_r \cdot \hat{v})^2}$$
$$= \sqrt{1-(u_x v_x + u_y v_y + u_z v_z)^2}$$
$$\equiv A$$

or,

$$\hat{J}_r = \begin{pmatrix} J_{rx} \\ J_{ry} \\ J_{rz} \end{pmatrix} = \frac{1}{A} \begin{pmatrix} u_z v_y - u_y v_z \\ u_x v_z - u_z v_x \\ u_y v_x - u_x v_y \end{pmatrix}_{GEEC}$$

<u>X_r-axis</u>

$$\hat{I}_r = \hat{J}_r \times \hat{K}_r$$

or,

$$\hat{I}_r = \begin{pmatrix} I_{rx} \\ I_{ry} \\ I_{rz} \end{pmatrix} = \begin{pmatrix} J_{rz} u_y - J_{ry} u_z \\ J_{rx} u_z - J_{rz} u_x \\ J_{ry} u_x - J_{rx} u_y \end{pmatrix}_{GEEC}$$

With the derived set of basis vectors $(\hat{I}_r, \hat{J}_r, \hat{K}_r)$, the transformation from the Attitude Reference Coordinate System to the GEEC Coordinate System can be written as

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{GEEC} = \begin{pmatrix} I_{rx} & J_{rx} & K_{rx} \\ I_{ry} & J_{ry} & K_{ry} \\ I_{rz} & J_{rz} & K_{rz} \end{pmatrix} \begin{pmatrix} X_r \\ Y_r \\ Z_r \end{pmatrix}_{AR}$$

or inversely

$$\begin{pmatrix} X_r \\ Y_r \\ Z_r \end{pmatrix}_{AR} = \begin{pmatrix} I_{rx} & I_{ry} & I_{rz} \\ J_{rx} & J_{ry} & J_{rz} \\ K_{rx} & K_{ry} & K_{rz} \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{GEEC}$$

$$\equiv \hat{\mathbb{R}} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{GEEC}$$

Where $\hat{\mathbb{R}}$ is the transformation matrix from $(X, Y, Z)_{GEEC}$ to $(X_r, Y_r, Z_r)_{AR}$.

5.4.2 COMPUTED TDRS RF BEAM POINTING

5.4.2.1 Let $\bar{X}U(t_2)$ be the updated position vector of the user spacecraft corresponding to the return link (see figure 4-2). Then from the TDRS and user orbital geometry, as shown in figure 5-3, the TDRS-to-user pointing vector can be given by

$$(\hat{X}_{rf})_c = \begin{pmatrix} X_{rf} \\ Y_{rf} \\ Z_{rf} \end{pmatrix}_{GEEC} = \frac{\bar{X}U(t_2) - \bar{X}TD(t_3)}{|\bar{X}U(t_2) - \bar{X}TD(t_3)|}$$

Where: $(\hat{X}_{rf})_c$ = the actual or computed pointing vector

$t_2 = t_3 - \frac{R3}{c} = t_4 - \frac{R3 + R4}{c}$, user time at the return link

R3 = the return link propagation distance from user spacecraft to TDRS.

Apply the transformation matrix $\hat{\mathbb{R}}$ to obtain the components of the unit pointing vector $(\hat{X}_{rf})_c$ relative to the NASA defined Attitude Reference Coordinates System.

$$(\hat{X}_{rf})_c = \begin{pmatrix} A \\ B \\ C \end{pmatrix}_{AR} = \hat{\mathbb{R}} \begin{pmatrix} X_{rf} \\ Y_{rf} \\ Z_{rf} \end{pmatrix}_{GEEC}$$

Where A, B, and C are the computed direction cosines of the TDRS-to-user unit pointing vector in the Attitude Reference Coordinate System.

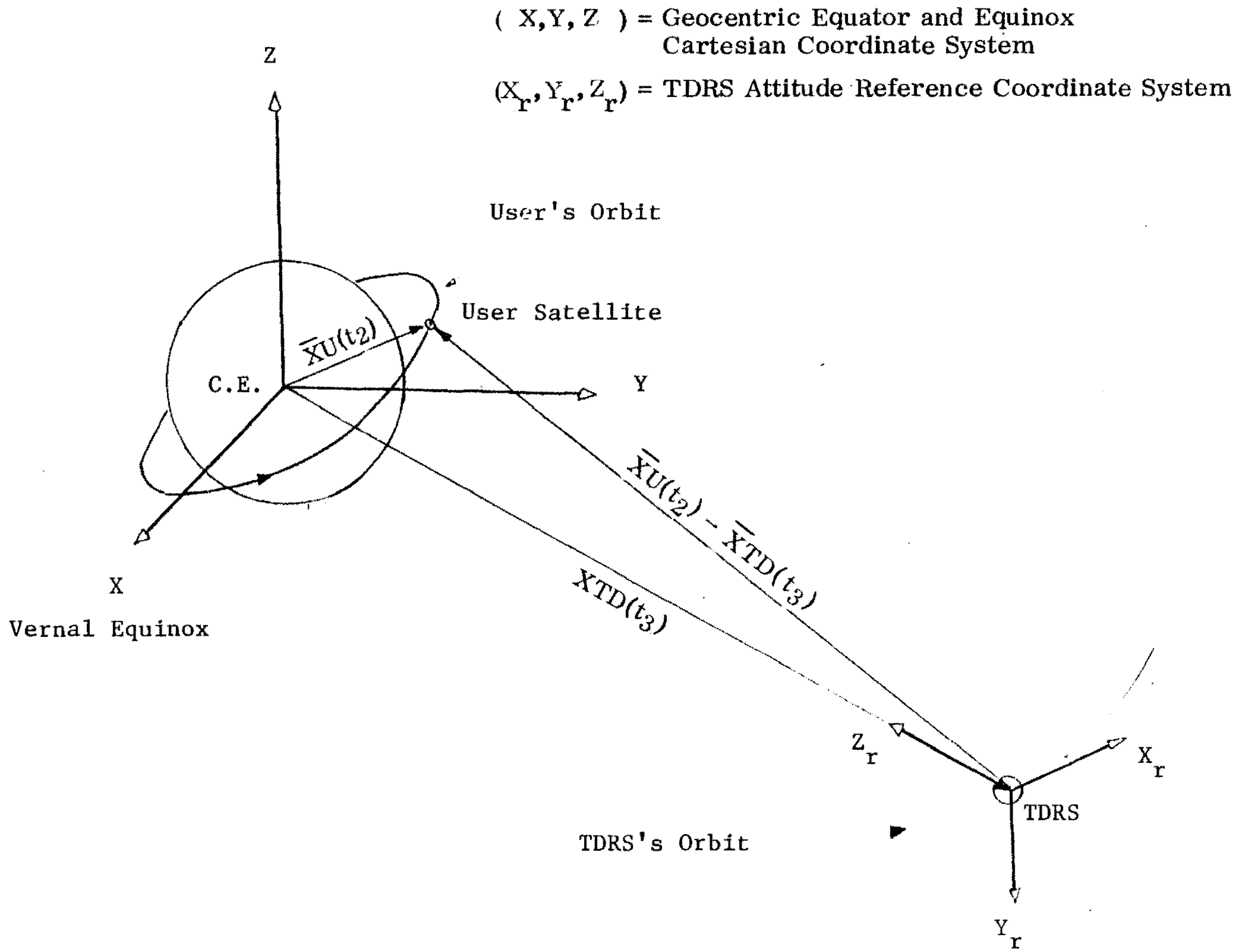


Figure 5-3. TDRS and User Orbital Geometry

5.4.2.2 Finally, the rotation matrix $\hat{R}_y(\theta)\hat{R}_x(\phi)\hat{R}_z(\psi)$, derived from the observed TDRS orientation parameters (ψ, ϕ, θ), is used to obtain the components of $(X_{rf})_c$ in the TDRS Body Coordinate System.

$$(\hat{X}_{rf})_c = \begin{pmatrix} x_{rfc} \\ y_{rfc} \\ z_{rfc} \end{pmatrix}_{BC} = \hat{R}_y(\theta)\hat{R}_x(\phi)\hat{R}_z(\psi)\begin{pmatrix} A \\ B \\ C \end{pmatrix}_{AR}$$

The computed values of the RF beam angles are

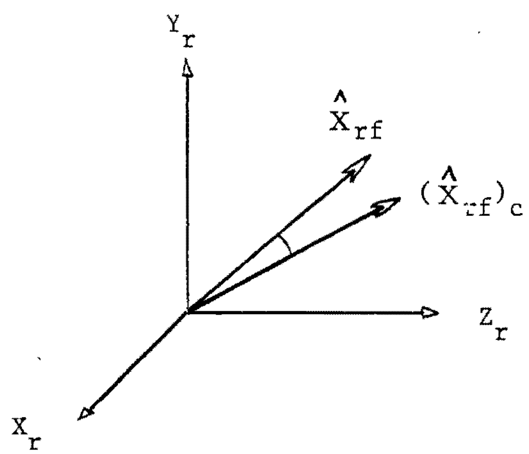
$$\theta_{rfc} = \text{Arctan}\,(x_{rfc}/z_{rfc})$$

$$\phi_{rfc} = \text{Arctan}\,(-y_{rfc})$$

It should be noted that the observed TDRS orientation parameters (ψ, ϕ, θ) are used to derive the observed and computed TDRS RF beam pointing angles; therefore, the measurement errors in ψ, ϕ, and θ are inherently imbedded in both (θ_{rf}, ϕ_{rf}) and $(\theta_{rfc}, \phi_{rfc})$.

5.5 THE RF BEAM POINTING OBSERVED MINUS COMPUTED VALUE

The observed minus computed value of the RF beam pointing, $(O-C)_{rf}$, is given by the spatial angular separation between the observed and the computed RF beam pointing vectors $\hat{X}_{rf}$ and $(\hat{X}_{rf})_c$ as follows:



$(O-C)_{rf}$ represents the total RF beam pointing error and is derived from the vector dot product of $\hat{X}_{rf}$ and $(\hat{X}_{rf})_c$ as follows:

$$(O-C)_{rf} = \text{Arccos}\left[\hat{X}_{rf} \cdot (\hat{X}_{rf})_c\right]$$

or, relative to the NASA defined Attitude Reference Coordinate System,

$$(O-C)_{rf} = \text{Arccos}\,(aA + bB + cC).$$

SECTION 6. TDRSS TRACKING DATA FORMAT

SECTION 6. TDRSS TRACKING DATA FORMAT

6.1 GENERAL

The TDRSS tracking data format is a subset of the NASA Universal Tracking Format which is used by STDN trackers with the Tracking Data Processing System (TDPS). The TDRSS tracking data will be transmitted directly from WSGT to NASA GSFC with a maximum transmission delay of 5 seconds at the TDRSS interface relative to the time of measurement. (The information presented in this section was derived from reference 20.)

6.2 FORMAT CONVENTIONS

6.2.1 The TDRSS tracking data format is a 75-byte format utilized to transmit one sample of data to NASA. Figure 6-1 and table 6-1 define the sample format and fields. Within this format data is either binary, hexadecimal, or discrete; data is contained either within single byte or within multiple byte fields. When the data is discrete, the state of a single bit or a group of bits within a byte represents a different parameter configuration. The byte conventions for the TDRSS tracking data format are shown in figure 6-2 (reference 20).

6.2.2 Within a multi-byte field, the most significant byte is transmitted first. Each byte consists of eight bits or two hexadecimal characters, with the most significant bit of each byte transmitted first. The first two bytes of each frame are carriage return and line feed.

6.3 DATA FIELD DESCRIPTION

A detailed explanation of each data field of the TDRSS tracking sample is as follows (references 20 and 21):

a. Control Characters. The content of this field (bytes 1 through 3) is fixed at the values 0D, 0A, and 01, respectively.

b. Routing Indicators. The content of this field (bytes 4 and 5) is specified by a constant 41 for each byte to indicate that the tracking data is to be routed to NASA GSFC.

c. Current Year. The content of this field (byte 6) is the two least significant digits of the current year. The LSB equals one year. This field will be obtained from the current time maintained by the computer, which is obtained initially from the ground terminal time standard.

d. Support Identification Code. The content of this field (bytes 7 and 8) is the user Support Identification Code (SIC) when TDRS is tracking orbital vehicles, or the SIC of the TDRS providing the return link service when the user is a NASA ground-based transponder. The SIC will be assigned by NASA.

e. Vehicle Identification Code. The content of this field (bytes 9 and 10) is the vehicle identification code assigned by NASA. The combination of SIC and vehicle identification code is unique for each user or TDRS.

(One 75-byte frame)

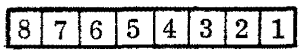
Field	Contents	Byte Numbers
Control Characters	0D 0A 01 41 41	1 2 3 4 5
Year	Y'Y'	6
SIC	II II	7 8
VID	VV VV	9 10
Seconds of Year	SS SS SS SS	11 12 13 14
μseconds of Year	μμ μμ μμ μμ	15 16 17 18
Ground Antenna Azimuth	AA AA AA AA	19 20 21 22
Ground Antenna Elevation	EE EE EE EE	23 24 25 26
Ground Antenna Range	RR RR RR RR RR RR	27 28 29 30 31 32
Ground Antenna Doppler	DD DD DD DD DD DD	33 34 35 36 37 38
AGC	00 00	39 40
Reference Frequency	ff ff ff ff	41 42 43 44
Tracker Parameters	60 tt 60 rr kk mm vv Bd Tr' t'r'	45 46 47 48 49 50 51 52 53 54
TDRSS Parameters	FR UT'	55 56
TDRS Attitude	ψψ ψψ φφ φφ θθ θθ	57 58 59 60 61 62
TDRS Beam Pointing Angles	αα αα αα εε εε εε	63 64 65 66 67 68
Spares	00 00 00 00	69 70 71 72
Control Characters	04 0F 0F	73 74 75

Note

Bytes 39, 40, 45 and 47 are shown set to values characteristic of TDRSS.

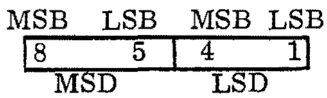
Figure 6-1. Universal Tracking Data Format (One 75-byte Frame)

Single Byte Data Fields



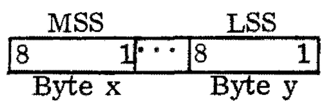
Single byte, 8 bits per byte (bit numbers shown)

Binary contents of byte

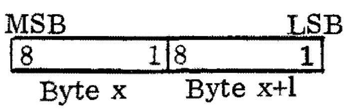


Two hexadecimal digits in byte

Multiple Byte Data Fields



Multiple byte (most significant and least significant symbols shown), y > x



Binary contents in two bytes

Figure 6-2. TDRSS Tracking Data Format Conventions

Table 6-1. TDRSS Tracking Data Format

Byte	Byte Format	Symbol and Byte Contents
1	Hexadecimal	OD_{16} } Control characters (constant)
2	Hexadecimal	OA_{16} } Control characters (constant)
3	Hexadecimal	01_{16} } Control characters (constant)
4	Hexadecimal	41_{16} } Control characters (constant)
5	Hexadecimal	41_{16} } Control characters (constant)
6	Binary	Y' = Year of century
7 and 8	Binary	I = Support Identification Code (SIC)
9 and 10	Binary	V = Vehicle Identification Code (VIC)
11 through 14	Binary	s = Time tag, seconds of year
15 through 18	Binary	μ = Time tag, microseconds of second
19 through 22	Binary	A = Return link ground antenna azimuth, LSB = $360.\overline{0} \times 2^{-32}$ deg, resolution = 0.0055 deg
23 through 26	Binary	E = Return link ground antenna elevation, LSB = $360.\overline{0} \times 2^{-32}$ deg, resolution = 0.0055 deg
27 through 32	Binary	R = Range (round trip light time), LSB = 2^{-8} nsec, resolution = 1 nsec
33 through 38	Binary	D = Doppler count, LSB = 1 count of scaled and biased Doppler signal
39 and 40	Hexadecimal	00_{16} (each byte)
41 through 44	Binary	f = Return link reference frequency (Fref), LSB 10 Hz
45	Hexadecimal	60_{16}
46	Binary	t = Forward link ground antenna ID
47	Binary	60_{16}
48	Binary	r = Return link ground antenna ID
49	Binary	k = TDRS ID's (forward and return links)
50	Binary/discrete	m = MA return link ID, TDRS tracking data only indicator, and tracking service configuration
51	Discrete	v = data validity
52	Hexadecimal	Bd = frequency band and service type
53 and 54	Hexadecimal/ discrete/binary	Tr' = tracker type, end of track, and sample rate
55	Discrete/binary	FR' = service link ID, single access TDRS/ground terminal carrier frequency ID, TDRS and RF beam orientation data validity
56	Discrete/binary	UT' = NASA ground-based TDRS tracking data transponder ID and user bit rate indicator
57 through 62	Binary	$\psi\phi\theta$ = TDRS orientation
63 through 68	Binary	$\mu\epsilon$ = TDRS RF beam orientation (ϑ_{RF}, ϵ_{RF}).
69 through 72	Hexadecimal	00_{16} (each byte), spare
73	Hexadecimal	04_{16} } control characters (constant)
74	Hexadecimal	OF_{16} } control characters (constant)
75	Hexadecimal	OF_{16} } control characters (constant)

f. Time Tag. The content of these fields is a multiple of the sample rate and is the seconds of year (bytes 11 through 14) and the microseconds of the second bytes (15 through 18). Time for seconds of the year is referenced to 00:00:00.0 January 1 of the current year. The LSB of byte 14 equals 1 second. The LSB of byte 18 equals 1 microsecond. This field is the time tag associated with the time of measurement of the range and/or Doppler data. The time of the first tracking sample transmitted in support of a scheduled tracking service is the second equal to or greater than the service start time, as scheduled by the Service Schedule Order (SHO) (which in terms of seconds of year is an integer multiple of the sampling rate). It is possible that no samples will be sent in support of a scheduled tracking service as a result. The difference between successive time tags for a given tracking service is equal to the sample rate in seconds per sample.

g. Return Link Ground Antenna Angle. The content of this field (bytes 19 through 26) is the ground antenna angles associated with the return link providing the tracking service. Azimuth is measured in the local horizontal plane, positive clockwise from north. The local horizontal plane is defined as perpendicular to the local gravitational vertical. Elevation is measured positive above local horizontal. The accuracy is 0.1 degree for each component (azimuth and elevation). The angles in both fields are represented by fractions of a circle. For both fields, the LSB equals $360.\overline{0} \times 2^{-32}$ degree and the MSB equals $180.\overline{0}$ degrees. Bytes 19 through 22 contain azimuth. Bytes 23 through 26 contain elevation.

h. Range. The content of this field (bytes 27 through 32) is the range measurement (round-trip light time) to a resolution of 1 nanosecond; the LSB equals 2^{-8} nanosecond. This field is the range masured by ground communications electronic equipment at the time specified in bytes 11 through 18, corrected for ground equipment and TDRS delays.

i. Doppler Count. The content of this field (bytes 33 through 38) is the scaled and biased Doppler counts; the LSB equals 1 cycle of the scaled biased Doppler signal ($240.\overline{0}$ MHz + 1000 fd for S-band and $240.\overline{0}$ MHz + 100 fd for K-band). This field is the Doppler measured by ground communications equipment at the time specified in bytes 11 through 18.

j. Auto Gain Control. The content of this field (bytes 39 and 40) is not applicable to TDRSS and is specified as 00 for each byte.

k. Reference Frequency. The content of this field (bytes 41 through 44) is the frequency used for Doppler extraction; the LSB equals 10 Hz, which is the required resolution of the reference frequency. For open-loop (one-way) Doppler, this field is obtained from the user transmit frequency in the return link service scheduling data in the SHO. For closed-loop (two-way or hybrid) Doppler, this field is calculated by a software algorithm that is a function of the coherent turnaround ratio and the ground transmit frequency adjusted for frequency conversions in the TDRS, when Doppler compensation is inhibited. The reference frequency is always an exact multiple of 10 Hz.

l. Transmit Antenna Size and Type. The content of this field is fixed at the value of 60_{16} to specify the 18-meter az-el antenna at WSGT.

m. Forward Link Ground Antenna ID. The content of this field (byte 46) is the TDRSS ground antenna ID associated with the TDRS which is providing the forward link for the tracking service. This field is obtained from a stored table which identifies the ID of the ground antenna supporting the TDRS providing the forward link. Ground antenna identifiers as defined by NASA are the following:

ID	Ground Antenna
0	None (for one-way tracking service)
9	North antenna
10	Central antenna
11	South antenna

n. Receive Antenna Size and Type. The content of this field (byte 47) is a constant 60_{16}.

o. Return Link Ground Antenna ID. The content of this field (byte 48) is the TDRSS ground antenna ID associated with the TDRS which is providing the return link for the tracking service. The ground antenna identifiers as defined by NASA are the following:

ID	Ground Antenna
9	North antenna
10	Central antenna
11	South antenna

p. TDRS ID's. The content of this field (byte 49) is the 4-bit identification of the TDRS providing the forward link and the 4-bit identification of the TDRS providing the return link for the tracking service. NASA has defined a unique SIC for each TDRS as follows:

TDRS-A = 1300

TDRS-B = 1301

TDRS-C = 1302

. .

. .

. .

TDRS-J = 1309

The TDRSS will perform a transformation from the SIC to a unique 4-bit code for each TDRS. The transformation is that the SIC minus 1299 equals the unique 4-bit TDRS ID as follows:

TDRS-A = 1
TDRS-B = 2
TDRS-C = 3
. .
. .
. .
TDRS-J = 10

The content of this field is as follows:

Field Location	Contents
Bits 5 through 8	Forward link TDRS ID, 0_{16} indicates that the forward link is not supporting. The LSB is bit 5.
Bits 1 through 4	Return link TDRS ID, 0_{16} is not used. The LSB is bit 1.

q. MA Return Link ID, TDRS Data Only Indication, and Tracking Service Configuration. The content of this field (byte 50) is an identification of the MA return link supporting the tracking service, an indication if TDRSS is providing tracking service to the NASA ground-based TDRS tracking data transponders that are identified in byte 56, and the configuration of the tracking service. The content of this field is defined as follows:

Field Location	Contents
Bits 4 through 8	MA return link ID: the binary ID of the RF beam forming equipment. A binary zero indicates that the MA return link is not supporting. The LSB is bit 4.
Bit 3	TDRS tracking data only indication: 0 for any ground-based tracking data (ground transponder, satellite on launch pad, or other test transponder on the ground with user SIC greater than 1309 and less than 1373); otherwise, bit 3 is set to 1.
Bits 1 and 2	Tracking service configuration

Bit 2	Bit 1	
0	1	Return link only (no forward link established to user)
1	0	Forward and return link established by this TDRS (non-hybrid)
1	1	Hybrid tracking
0	0	Spare

r. Data Validity. The content of this field (byte 51) indicates the validity of the contents of the range field (bytes 27 through 32), the Doppler count field (bytes 33 through 38), and the return link ground antenna angle fields (bytes 19 through 26). The specific validity criteria are as follows:

(1) Range data is valid if:

(a) The receiver used for the associated return service has PN lock.

(b) The range extractor used for the tracking service is up; i.e., the extractor does not have an active red alarm.

(c) The range switch matrix is up.

(d) The timing distribution amplifier for the user range equipment is up.

(e) A forward service is scheduled as indicated by a forward service flag.

(2) Two-way Doppler data is valid if:

(a) Associated receiver has indicated carrier lock at each lock sample point (once/second) throughout last tracking sample period.

(b) Forward Doppler compensation has been inhibited; i.e., the slow and hold function has been completed and the forward frequency is fixed.

(c) Doppler extractor is not exhibiting a fault indication.

(d) The Doppler RF amplifier is not exhibiting a red alarm (a red alarm must be manually set by the TOCC operator).

(e) The Doppler switch matrix is not exhibiting a fault.

(f) The Doppler extractor control unit is not exhibiting a fault.

(3) One-way Doppler data is valid if:

(a) Associated receiver has indicated carrier lock at each lock sample point (once/second) throughout last tracking sample period.

(b) Doppler extractor is not exhibiting a fault indication.

(c) Doppler RF amplifier is not exhibiting a red alarm (a red alarm must be manually set by the TOCC operator).

(d) The Doppler switch matrix is not exhibiting a fault.

(e) The Doppler extractor control unit is not exhibiting a fault.

(4) Ground antenna angles are valid if:

(a) Antenna is in autotrack mode.

(b) Antenna is not exhibiting a major fault or a control fault.

(c) Antenna measurements are on time; i.e., there was a measurement received corresponding to the 1-pps read tic.

The content of this field is as follows:

Field Location	Contents
Bits 4 through 8	0
Bit 3	Ground antenna angle validity: 1 = Valid 0 = Not valid
Bit 2	Doppler validity: 1 = Valid 0 = Not valid
Bit 1	Range validity: 1 = Valid 0 = Not valid

s. Frequency Band and Service Type. The content of this field (byte 52) is the frequency band of the forward link and/or the return link of the user being provided in the tracking service, and the type of service for which tracking service is being provided. The content of this field is as follows:

Field Location	Contents
MSD	Frequency band: 3_{16} = S-band 6_{16} = Ku-band
LSD	Service type: 1_{16} = Not used 2_{16} = Simulation service 4_{16} = Normal service

t. Tracker Type, End of Track, and Sample Rate. The content of this field (bytes 53 and 54) is the tracker type code for TDRSS, and End of Track (EOT) indication, and the rate at which the tracking data is sampled. The content of this field is defined as follows:

Field Location	Contents
Byte 53, MSD	Tracker type: 6_{16} indicates TDRSS tracking service.
Byte 53, bit 4	End of track: 1 indicates that the sample is the last to be transmitted (i.e., at the end of the scheduled service support period), otherwise a 0.

Field Location	Contents
Byte 53, bit 3	0 indicates that the data in the sample rate field is the seconds between tracking samples.
Byte 53, bit 2, through Byte 54, bit 1	Sample rate, binary seconds between tracking samples. The LSB (byte 54, bit 1) equals 1 second.

The EOT field, bit 4, is set to 1 when the time tag plus the sample time is greater than the service end time. If the tracking service is abnormally terminated, the last message sent in support of the service may not contain an EOT indicator. The sample rate is obtained from the SHO which contains a key indicating rate. This key is converted to a binary numeric field which is one of the following time periods (time period between samples): 1, 5, 10, 60, or 300 seconds.

u. Service Link ID, Single-access TDRS/Ground Terminal Carrier Frequency ID, TDRS and RF Beam Orientation Validity. The content of this field (byte 55) is the identification of the forward and/or return links providing the tracking service, an identification of the TDRS Ground Terminal (GT) carrier frequencies utilized for the SA forward and/or return links providing the tracking service, and the validity of the TDRS and RF beam orientation data provided in bytes 57 through 62 and 63 through 68. The following coordinate definition is used:

+z = Local vertical to Earth

+x = Positive roll axis (forms right-handed set with y and z)

+y = Positive pitch axis (parallel to solar array rotational axis and pointed toward SGL antenna side of spacecraft)

SA antenna link 1 is the steerable antenna on the +x axis; SA antenna link 2 is the steerable antenna on the -x axis. For forward links and for S-band return links, carrier frequency 1 is hardwired to link 1, and carrier frequency 2 is hardwired to link 2. For K-band return, link 1 may be associated with either carrier frequency, as may link 2. An SSA1 or KSA1 tracking service corresponds to link 1. An SSA2 or KSA2 tracking service corresponds to link 2.

Note

SA1 and SA2 are used to denote single-access link 1 and 2, whereas SA-1, SA-2 are used to denote single-access carrier frequency 1 and carrier frequency 2.

TDRS orientation and RF beam orientation are valid if telemetry frame synchronization has been achieved for the frame(s) containing ACS data from which TDRS orientation in the tracking sample is computed. The content of this field is defined as follows:

Field Location	Contents
Bit 8	TDRS orientation data validity (refer to bytes 57 through 62): 1 = Valid 0 = Not valid

Field Location			Contents
Bit 7			RF beam orientation data validity (refer to bytes 63 through 68): 1 = Valid 0 = Not valid
Bit 6	Bit 5	Bit 4	Forward link ID and TDRS GT carrier frequency ID
0	0	0	Forward link not supported by the TDRS providing the return link service
0	0	1	SA link 1, TDRS GT carrier frequency 1 (SA1-1)
0	1	0	Spare
0	1	1	MA
1	0	0	Spare
1	0	1	Spare
1	1	1	SA link 2, TDRS GT carrier frequency 2 (SA2-2)
1	1	1	Spare
Bit 3	Bit 2	Bit 1	Return link ID and TDRS GT carrier frequency ID
0	0	0	Spare
0	0	1	SA link 1, TDRS GT carrier frequency 1 (SA1-1)
0	1	0	SA link 2, TDRS GT carrier frequency 1 (SA2-1)
0	1	1	MA
1	0	0	Spare
1	0	1	SA link 1, TDRS GT carrier frequency 2 (SA1-2)
1	1	0	SA link 2, TDRS GT carrier frequency 2 (SA2-2)
1	1	1	Spare

v. NASA Ground-based TDRS Tracking Data Transponder ID and User Bit Rate Indicator. The content of this field (byte 56) is the identification of the NASA ground-based tracking data transponder which NASA will utilize to obtain TDRS tracking data, and an indicator to designate the telemetry bit rate group of the user for which the return link service is being provided. When support is to a ground-based transponder, the TDRSS will perform a transformation from the ground-based transponder SIC to a unique code for this field. Otherwise, this ID field is set to 0. The content of this field is defined as follows:

Field Location		Contents
Bit 8	Bit 7	User Bit Rate (BR)
0	0	5000 bps < BR
0	1	1000 bps < BR ≤ 5000 bps
1	0	500 bps < BR ≤ 1000 bps
1	1	BR ≤ 500 bps
Bits 1 through 6		Ground-based TDRS tracking data transponder ID. This field is zero when user SIC is less than or equal to 1309, or greater than or equal to 1373. This field is 1 through 63 when the user SIC is greater than 1309 and less than 1373. The value to be inserted in the field is computed by subtracting 1309 from the user SIC (reference 22).

The user bit rate is obtained from the SHO for the associated return services. For dual channel users, the bit rate of the I channel is used. The rate is checked to determine in which range it falls in order to determine the field bit configuration.

w. TDRS Orientation. The content of this field (bytes 57 through 62) is the orientation of the corrected local TDRS coordinate system relative to the NASA defined attitude reference coordinate system for the TDRS providing the return link for the tracking service.

Field Location	Contents
Bytes 57 and 58	Yaw (ψ)
Bytes 59 and 60	Roll (ϕ)
Bytes 61 and 62	Pitch (θ)

For each angle, the MSB is $180.\bar{0}$ degrees, the LSB is $360.\bar{0}$ degrees x 2^{-16}, and accuracy is 0.1 degree in pitch and roll and 0.25 degree in yaw.

x. TDRS RF Beam Orientation. The content of this field (bytes 63 through 68) is the orientation of the RF beam for the return link providing the tracking service. The orientation is relative to the TDRS body coordinate system. Bytes 63 through 65 contain the azimuth, and bytes 66 through 68 contain the elevation. The LSB of both is $90.\bar{0}$ degrees x 2^{-23}, the range is ±90 degrees, and negative values are expressed in ones complement form. The accuracy of the data is 0.5 degree for SA service and 2 degrees for MA service.

y. Spare. The content of this field (bytes 69 through 72) is specified by 00.

z. Control Characters. The content of this field (bytes 73 through 75) is fixed at 04, 0F, and 0F.

6.4 TRACKING DATA SAMPLE INSERTION INTO 4800-BIT DATA BLOCKS

6.4.1 The 4800-bit data block structure used for the tracking data interface is shown in figure 6-3. The 4800-bit data block is segmented into the following five distinct fields (reference 20):

a. Network control header (bytes 1 through 6)

b. TDRSS header (bytes 7 through 12)

c. Time field (bytes 13 through 18)

d. Data field (bytes 19 through 596)

e. Error control field (bytes 597 through 600)

6.4.2 The network control header is used to identify the start and the type of message of each 4800-bit data block. The TDRSS header is used to identify the message ID, message size, number and sequence of blocks in a multiblock message. The time field and the error control field are set to the logical 1 state for all tracking messages. The general structure of the 4800-bit data block is shown in figure 6-4.

6.4.3 Each tracking data message consists of a maximum of 15 standard NASA TDRSS 4800-bit data blocks; each block contains from one to seven tracking data samples. The number of samples per data field is a function of the number of supporting TDRSS tracking services. Multiple tracking data sets for different user spacecraft can be contained in the same block and are packed contiguously. The portion of the data field between the last bit of the last tracking data sample and the first bit of the error control field are filled by a fixed hexadecimal character $C9_{16}$. Figure 6-5 shows the tracking data message transmission format.

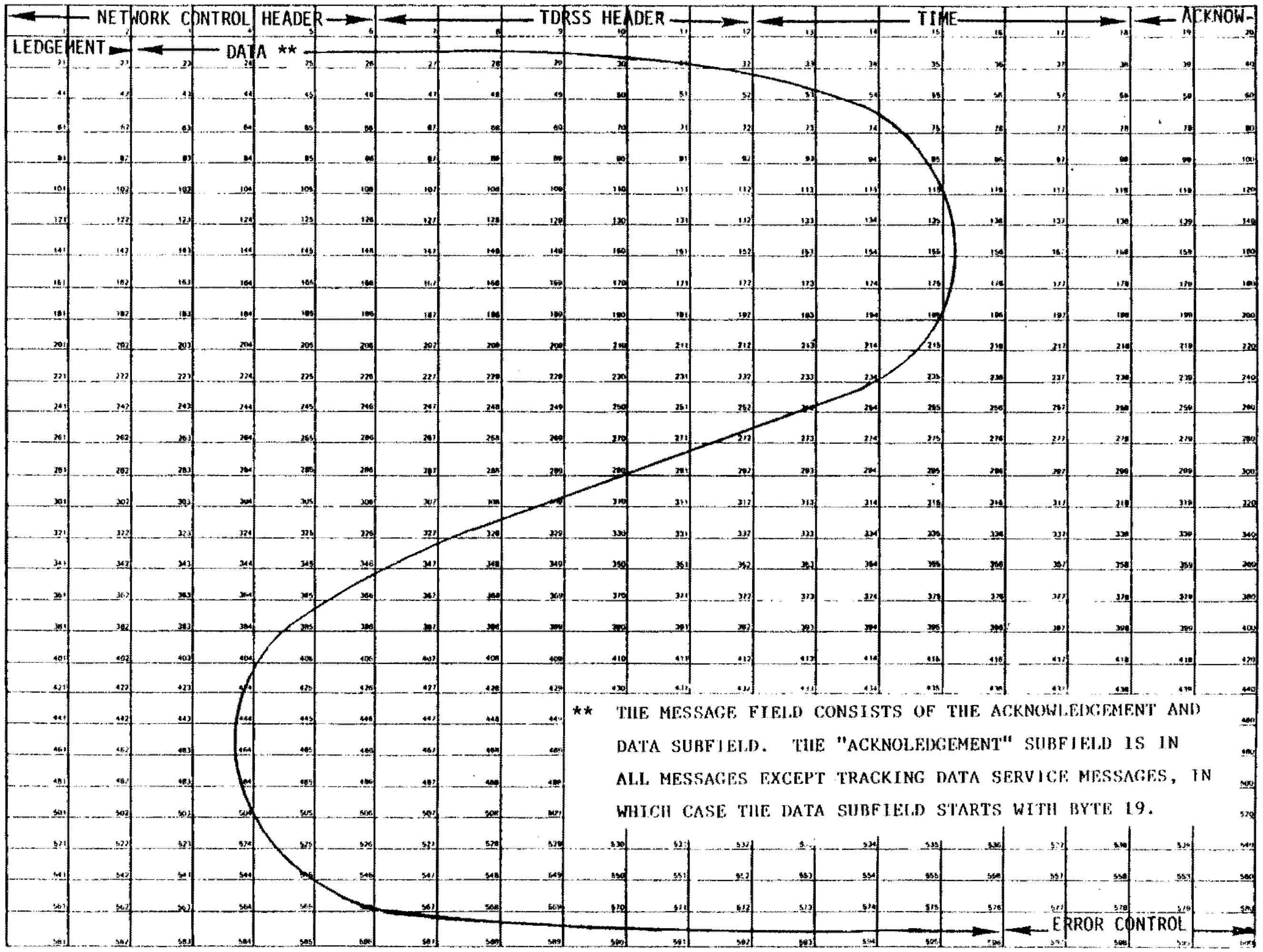
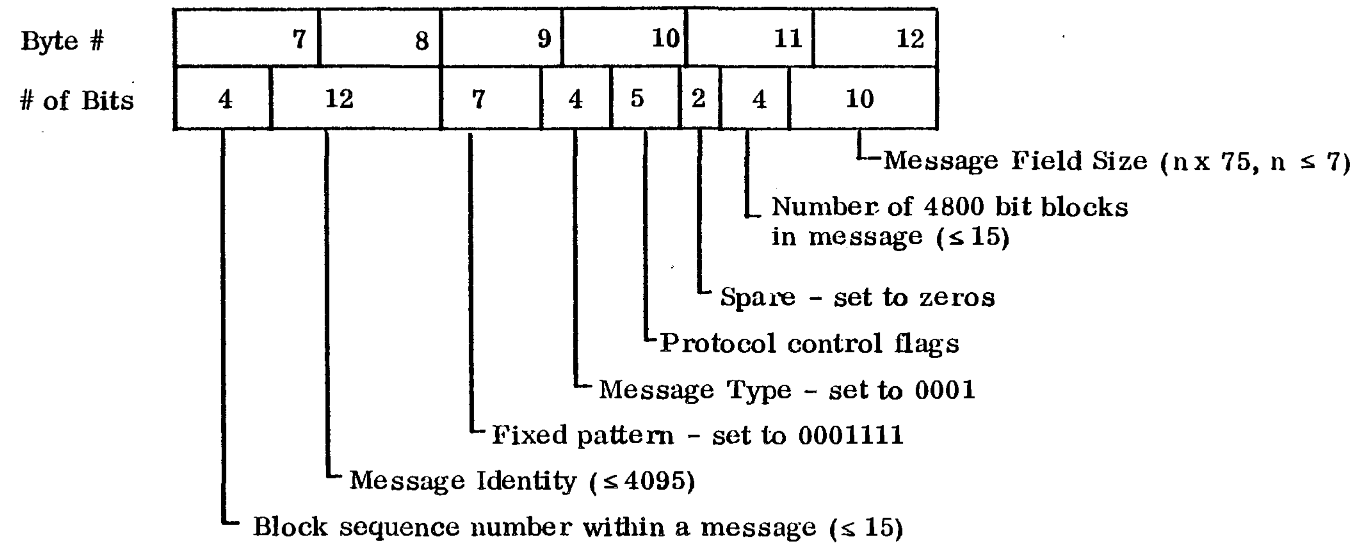


Figure 6-3. Structure of a 4800-bit Data Block

Byte	Contents
1 through 6	Network Control Header, will have pattern 46 6E E4 F9 4F $0B_{16}$
7 through 12	TDRSS Header, the 48 bits are arranged in 8 fields, as follows:



13 through 18	Bits set to 1_2
19 through 596	1 to 7 UTDF frames, arranged contiguously starting with byte 19. Extra space is filled with $C9_{16}$ pattern in each byte (bytes 544 through 596 will always be so filled).
597 through 600	Set to 1_2

Figure 6-4. General Structure of the 4800-bit Data Tracking Data Blocks

Bytes 1 through 6 :	Network control header
Bytes 7 through 12 :	TDRSS header
Bytes 13 through 18 :	Time field (logical 1's)
Bytes 19 through 596 :	Data field Tracking No. 1 : 75-byte data set Tracking No. 2 : 75-byte data set Tracking No. K : 75-byte data set
	Filler $(C9)_{16}$ required
Bytes 597 through 600:	Error control field (logical 1's)

Note

$K \leq 7$

Figure 6-5. Tracking Data Message Transmission Format

APPENDIX A. REFERENCES

APPENDIX A. REFERENCES

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APPENDIX B. EQUIVALENCE OF SPECIAL RELATIVISTIC AND RANGE-DIFFERENCE FORMULATIONS OF DOPPLER MODELS

APPENDIX B. EQUIVALENCE OF SPECIAL RELATIVISTIC AND RANGE-DIFFERENCE FORMULATIONS OF DOPPLER MODELS

B.1 GENERAL

The number of cycles counted by the nondestruct Doppler Counter, Δn, is a function of f_{in}, the input frequency to the Counter, and $T_{L+1}-T_L$, the Doppler Count interval, that is,

$$\Delta n = \int_{T_L}^{T_{L+1}} f_{in}(t)dt$$

Where:

T_L and T_{L+1} are the beginning and the end of the count interval, respectively

$$f_{in}(t)=\begin{cases} 2.40 + Fd \text{ MHz for K-band} \\ 0.24 + Fd \text{ MHz for S-band} \end{cases} \quad \text{(refer to para 3.4)}$$

Fd is the instantaneous Doppler frequency and is given as follows:

For one-way $Fd = \beta 1_i \beta 2_i F_o + \alpha 3_i \beta 2_i bFp - (Fref + bFp)$

For two-way $Fd = \alpha 1_i \alpha 2_i \beta 1_i \beta 2_i Fref + \alpha 3_i \beta 2_i bFp - (Fref - bFp)$

For hybrid $Fd = \alpha 1_i \alpha 2_i \beta 1_j \beta 2_j\ Fref - \alpha 3_j \beta 2_j bFp - (Fref + bFp)$

For the convenience of the following derivation, the f_{in} is rewritten as

$$f_{in}(t) = A\,\alpha 1 \alpha 2 \beta 1 \beta 2 + B \alpha 3 \beta 2 - C$$

Where: A, B, and C are constants over the counting interval.

The subscripts i, j can be used interchangeably and therefore, can be omitted in the subsequent derivation. For one-way Doppler $A = F_o = Fref + \Delta f$ is assumed to be constant and set $\alpha 1 = 1$ and $\alpha 2 = 1$.

Expressions are derived for αk and βk in terms of relativistic Doppler ratios. Two forms are considered for the range rate; one is expanded in terms of the time derivatives of range, and the other is expanded in terms of the instantaneous velocities of the WSGT, TDRS, and User SC. The latter expansion is solved for the relativistic Doppler ratio, and a parallel manipulation of the former expansion yields the Doppler ratio in terms of range derivatives which is simply integrated to give the range difference formulation used in the TDRSS model (reference 15).

B.2 DEFINITION OF TERMS (see figure 4-2)

Term	Definition
$\overline{X}GT(1)$ and $\overline{V}GT(1)$	WSGT position and velocity at transmit time t_o
$\overline{X}GT(2)$ and $\overline{V}GT(2)$	" " " " " receive time t_4
$\overline{X}GT(3)$ and $\overline{V}GT(3)$	" " " " " transmit time t_5
$\overline{X}TD(1)$ and $\overline{V}TD(1)$	TDRS " " " " forward relay t_1
$\overline{X}TD(2)$ and $\overline{V}TD(2)$	" " " " " return relay t_3
$\overline{X}U$ and $\overline{V}U$	User " " " " receive time t_2
C	Velocity of light,
Unit vectors	$\hat{U}1 \equiv \frac{\overline{X}TD(1) - \overline{X}GT(1)}{\lvert\overline{X}TD(1) - \overline{X}GT(1)\rvert}$
	$\hat{U}2 \equiv \frac{\overline{X}U - \overline{X}TD(1)}{\lvert\overline{X}U - \overline{X}TD(1)\rvert}$
	$\hat{U}3 \equiv \frac{\overline{X}TD(2) - \overline{X}U}{\lvert\overline{X}TD(2) - \overline{X}U\rvert}$
	$\hat{U}4 \equiv \frac{\overline{X}GT(2) - \overline{X}TD(2)}{\lvert\overline{X}GT(2) - \overline{X}TD(2)\rvert}$
	$\hat{U}5 \equiv \frac{\overline{X}TD(2) - \overline{X}GT(3)}{\lvert\overline{X}TD(2) - \overline{X}GT(3)\rvert}$

B. 3 RELATIVISTIC DOPPLER RATIOS

Refer to figure 4-2; the Doppler shifts for each leg are given by:

Uplink at t_0

$$\alpha 1 = \sqrt{\frac{1 - |\vec{V}TD(1)|^2/c^2}{1 - |\vec{V}GT(1)|^2/c^2}} \cdot \left[\frac{1 - \hat{U}1 \cdot \vec{V}GT(1)/c}{1 - \hat{U}1 \cdot \vec{V}TD(1)/c}\right]$$

Forward link

$$\alpha 2 = \sqrt{\frac{1 - |\vec{V}U|^2/c^2}{1 - |\vec{V}TD(1)|^2/c^2}} \cdot \left[\frac{1 - \hat{U}2 \cdot \vec{V}TD(1)/c}{1 - \hat{U}2 \cdot \vec{V}U/c}\right]$$

Return link

$$\beta 1 = \sqrt{\frac{1 - |\vec{V}TD(2)|^2/c^2}{1 - |\vec{V}U|^2/c^2}} \cdot \left[\frac{1 - \hat{U}3 \cdot \vec{V}U/c}{1 - \hat{U}3 \cdot \vec{V}TD(2)/c}\right] \qquad \text{(I)}$$

Downlink

$$\beta 2 = \sqrt{\frac{1 - |\vec{V}GT(2)|^2/c^2}{1 - |\vec{V}TD(2)|^2/c^2}} \cdot \left[\frac{1 - \hat{U}4 \cdot \vec{V}TD(2)/c}{1 - \hat{U}4 \cdot \vec{V}GT(2)/c}\right]$$

Uplink at t_5

$$\alpha 3 = \sqrt{\frac{1 - |\vec{V}TD(2)|^2/c^2}{1 - |\vec{V}GT(3)|^2/c^2}} \cdot \left[\frac{1 - \hat{U}5 \cdot \vec{V}GT(3)/c}{1 - \hat{U}5 \cdot \vec{V}TD(2)/c}\right]$$

Assuming that the speed of the WSGT is constant:

$$|\vec{V}GT(1)| = |\vec{V}GT(2)| = |\vec{V}GT(3)|$$

$$\alpha 1 \alpha 2 \beta 1 \beta 2 = \left[\frac{1-\hat{U}1 \cdot \vec{V}GT(1)/c}{1-\hat{U}1 \cdot \vec{V}TD(1)/c}\right]\left[\frac{1-\hat{U}2 \cdot \vec{V}TD(1)/c}{1-\hat{U}2 \cdot \vec{V}U/c}\right]\left[\frac{1-\hat{U}3 \cdot \vec{V}U/c}{1-\hat{U}3 \cdot \vec{V}TD(2)/c}\right]\left[\frac{1-\hat{U}4 \cdot \vec{V}TD(2)/c}{1-\hat{U}4 \cdot \vec{V}GT(2)/c}\right] \qquad \text{(II)}$$

Similarly for the two-leg path originating at t_5:

$$\alpha 3 \beta 2 = \left[\frac{1-\hat{U}4 \cdot \vec{V}TD(2)/c}{1-\hat{U}4 \cdot \vec{V}GT(2)/c}\right]\left[\frac{1-\hat{U}5 \cdot \vec{V}GT(3)/c}{1-\hat{U}5 \cdot \vec{V}TD(2)/c}\right] \qquad \text{(III)}$$

B.4 RANGE-RATE FORMULATION

From consideration of the light time involved in traversing each leg:

$$\Delta t_j = (t_{j-1} - t_j)$$

One expression for the distance between the corresponding objects is:

$$Rj = c\, \Delta t_j$$

The locations of the station, relay, and target at each time are known, and the alternative expression is:

$$Rj = |\bar{X}_i - \bar{X}_k|$$

Where i and k denote TD, GT, and U at different time.

The eight equations based on range are as follows:

$$\begin{aligned} R1 &= c(t_0 - t_1) \\ R2 &= c(t_1 - t_2) \\ R3 &= c(t_2 - t_3) \\ R4 &= c(t_3 - t_4) \end{aligned} \qquad \text{(IV)}$$

$$\begin{aligned} |\bar{X}GT(1) - \bar{X}TD(1)| &= c(t_0 - t_1) \\ |\bar{X}TD(1) - \bar{X}U| &= c(t_1 - t_2) \\ |\bar{X}U - \bar{X}TD(2)| &= c(t_2 - t_3) \\ |\bar{X}TD(2) - \bar{X}GT(2)| &= c(t_3 - t_4) \end{aligned} \qquad \text{(V)}$$

Taking derivatives with respect to t_0 yields range rates:

(1) From equation IV

$$c\left(1 - \frac{dt_1}{dt_0}\right) = \frac{dR1}{dt_0}$$

$$c\left(\frac{dt_1}{dt_0} - \frac{dt_2}{dt_0}\right) = \frac{dR2}{dt_0}$$

$$c\left(\frac{dt_2}{dt_0} - \frac{dt_3}{dt_0}\right) = \frac{dR3}{dt_0}$$

$$c\left(\frac{dt_3}{dt_0} - \frac{dt_4}{dt_0}\right) = \frac{dR4}{dt_0}$$

Solving for $\frac{dt_4}{dt_0}$ by summing all four equations:

$$\frac{dt_4}{dt_0} = 1 - \frac{1}{c}\left(\frac{dR1}{dt_0} + \frac{dR2}{dt_0} + \frac{dR3}{dt_0} + \frac{dR4}{dt_0}\right) \qquad \text{(VI)}$$

(2) From equation V:

$$c\left(1 - \frac{dt_1}{dt_0}\right) = \hat{U}1 \cdot \left(\vec{V}GT(1) - \vec{V}TD(1)\frac{dt_1}{dt_0}\right)$$

$$c\left(\frac{dt_1}{dt_0} - \frac{dt_2}{dt_0}\right) = \hat{U}2 \cdot \left(\vec{V}TD(1)\frac{dt_1}{dt_0} - \vec{V}U\frac{dt_2}{dt_0}\right)$$

$$c\left(\frac{dt_2}{dt_0} - \frac{dt_3}{dt_0}\right) = \hat{U}3 \cdot \left(\vec{V}U\frac{dt_2}{dt_0} - \vec{V}TD(2)\frac{dt_3}{dt_0}\right)$$

$$c\left(\frac{dt_3}{dt_0} - \frac{dt_4}{dt_0}\right) = \hat{U}4 \cdot \left(\vec{V}TD(2)\frac{dt_3}{dt_0} - \vec{V}GT(2)\frac{dt_4}{dt_0}\right)$$

Solve for $\frac{dt_1}{dt_0}$:

$$\frac{dt_1}{dt_0} = \left(\frac{1 - \hat{U}1 \;.\; \vec{V}GT(1)/c}{1 - \hat{U}1 \;.\; \vec{V}TD(1)/c}\right)$$

$$\frac{dt_2}{dt_0} = \frac{dt_1}{dt_0}\left(\frac{1 - \hat{U}2 \;.\; \vec{V}TD(1)/c}{1 - \hat{U}2 \;.\; \vec{V}U/c}\right)$$

$$\frac{dt_3}{dt_0} = \frac{dt_2}{dt_0}\left(\frac{1 - \hat{U}3 \;.\; \vec{V}U/c}{1 - \hat{U}3 \;.\; \vec{V}TD(2)/c}\right)$$

$$\frac{dt_4}{dt_0} = \frac{dt_3}{dt_0}\left(\frac{1 - \hat{U}4 \;.\; \vec{V}TD(2)/c}{1 - \hat{U}4 \;.\; \vec{V}GT(2)/c}\right)$$

Solve for $\frac{dt_4}{dt_0}$:

$$\frac{dt_4}{dt_0} = \left[\frac{1-\hat{U}1\cdot\vec{V}GT(1)/c}{1-\hat{U}1\cdot\vec{V}TD(1)/c}\right]\cdot\left[\frac{1-\hat{U}2\cdot\vec{V}TD(1)/c}{1-\hat{U}2\cdot\vec{V}U/c}\right]\cdot\left[\frac{1-\hat{U}3\cdot\vec{V}U/c}{1-\hat{U}3\cdot\vec{V}TD(2)/c}\right]\cdot\left[\frac{1-\hat{U}4\cdot\vec{V}TD(2)/c}{1-\hat{U}4\cdot\vec{V}GT(2)/c}\right] \qquad \text{(VII)}$$

Comparing equation VII with equations II and VI:

$$\frac{dt_4}{dt_0} = \alpha1\alpha2\beta1\beta2 = 1 - \frac{1}{c}\frac{d}{dt_0}(R1 + R2 + R3 + R4)$$

Following the similar procedure for the two-leg path R4 + R5:

$$\alpha 3\beta 2 = 1 - \frac{1}{c}\frac{d}{dt_0}(R4 + R5)$$

For one-way Doppler, $\beta 1 \beta 2$ is given by:

$$\beta 1 \beta 2 = \sqrt{\frac{1 - |\vec{V}GT(2)|^2/c^2}{1 - |\vec{V}U|^2/c^2}} \left[\frac{1 - \hat{U}3 \cdot \vec{V}U/c}{1 - \hat{U}3 \cdot \vec{V}TD(2)/c}\right]\left[\frac{1 - \hat{U}4 \cdot \vec{V}TD(2)/c}{1 - \hat{U}4 \cdot \vec{V}GT(2)/c}\right]$$

Expand in power series of (1/c) as follows:

$$\sqrt{\frac{1 - |\vec{V}GT(2)|^2/c^2}{1 - |\vec{V}U|^2/c^2}} = 1 - \frac{1}{2}\frac{|\vec{V}GT(2)|^2}{c^2} + \frac{1}{2}\frac{|\vec{V}U|^2}{c^2} + \text{(higher order terms)}$$

$$\frac{1 - \hat{U}3 \cdot \vec{V}U/c}{1 - \hat{U}3 \cdot \vec{V}TD(2)/c} = (1 - \hat{U}3 \cdot \vec{V}U/c)\{1 + \hat{U}3 \cdot \vec{V}TD(2)/c + [\hat{U}3 \cdot \vec{V}TD(2)/c]^2 + \cdots\}$$

$$= 1 - \hat{U}3 \cdot \frac{[\vec{V}U - \vec{V}TD(2)]}{c} - \frac{[\hat{U}3 \cdot \vec{V}U][\hat{U}3 \cdot \vec{V}TD(2)]}{c^2}$$

$$+ [\hat{U}3 \cdot \vec{V}TD(2)/c]^2 + \text{(higher order terms)}$$

$$\frac{1 - \hat{U}4 \cdot \vec{V}TD(2)/c}{1 - \hat{U}4 \cdot \vec{V}GT(2)/c} = [1 - \hat{U}4 \cdot \vec{V}TD(2)][1 + \hat{U}4 \cdot \vec{V}GT(2)/c + [\hat{U}4 \cdot \vec{V}GT(2)/c]^2 + \cdots\}$$

$$= 1 - \hat{U}4 \cdot \frac{[\vec{V}TD(2) - \vec{V}GT(2)]}{c} - \frac{[\hat{U}4 \cdot \vec{V}TD(2)][\hat{U}4 \cdot \vec{V}GT(2)]}{c^2}$$

$$+ [\hat{U}4 \cdot \vec{V}GT(2)/c]^2 + \text{(higher order terms)}$$

To the first order of (1/c), $\beta 1 \beta 2$ can be approximated by the following:

$$\beta 1 \beta 2 = 1 - \left[\hat{U}3 \cdot \frac{\vec{V}U - \vec{V}TD(2)}{c} + \hat{U}4 \cdot \frac{\vec{V}TD(2) - \vec{V}GT(2)}{c}\right] + \text{(higher order terms)}$$

Or, in terms of the relative range rates:

$$\beta 1 \beta 2 \cong 1 - \frac{\dot{R}3 + \dot{R}4}{c}$$

Note

The magnitude of the 2nd order term in $\beta 1 \beta 2$ is dominated by $|\vec{V}U|^2/2c^2$. For a user spacecraft with $|\vec{V}U| \cong 7$ km/sec and transmit frequency of 2 GHz (S-band), the 2nd order one-way Doppler effect can be as large as 0.54 Hz. Therefore, for one-way Doppler, the 2nd order term can be significant and should be properly modeled.

B. 5 DOPPLER FORMULA

The preceding derivation yields the following results:

$$\alpha1\alpha2\beta1\beta2 = 1 - \frac{1}{c}(\dot{R}1 + \dot{R}2 + \dot{R}3 + \dot{R}4)$$

$$\beta1\beta2 \cong 1 - \frac{1}{c}(\dot{R}3 + \dot{R}4) \quad \text{to the first order of } \frac{1}{c}$$

$$\alpha3\beta2 = 1 - \frac{1}{c}(\dot{R}4 + \dot{R}5)$$

For one-way Doppler:

$$\dot{R}3 = \dot{R}3_i$$

$$\dot{R}4 = \dot{R}4_i$$

$$\dot{R}5 = \dot{R}5_i$$

$$\beta1_i\beta2_i \cong 1 - \frac{1}{c}(\dot{R}3_i + \dot{R}4_i)$$

$$\alpha3_i\beta2_i = 1 - \frac{1}{c}(\dot{R}4_i + \dot{R}5_i)$$

For two-way Doppler:

$$\dot{R}1 = \dot{R}1_i$$

$$\dot{R}2 = \dot{R}2_i$$

$$\dot{R}3 = \dot{R}3_i$$

$$\dot{R}4 = \dot{R}4_i$$

$$\dot{R}5 = \dot{R}5_i$$

$$\alpha1_i\alpha2_i\beta1_i\beta2_i = 1 - \frac{1}{c}(\dot{R}1_i + \dot{R}2_i + \dot{R}3_i + \dot{R}4_i)$$

$$\alpha3_i\beta2_i = 1 - \frac{1}{c}(\dot{R}5_i + \dot{R}4_i)$$

For hybrid Doppler:

$$\dot{R}1 = \dot{R}1_i$$

$$\dot{R}2 = \dot{R}2_i$$

$$\dot{R}3 = \dot{R}3_j$$

$$\dot{R}4 = \dot{R}4_j$$

$$\dot{R}5 = \dot{R}5_j$$

$$\alpha1_i\alpha2_i\beta1_j\beta2_j = 1 - \frac{1}{c}(\dot{R}1_i + \dot{R}2_i + \dot{R}3_j + \dot{R}4_j)$$

$$\alpha3_j\beta2_j = 1 - \frac{1}{c}(\dot{R}5_j + \dot{R}4_j)$$

B. 6 AVERAGE DOPPLER

From the Doppler formulas summarized in B.5, f_{in} (t) can be rewritten as:

$$f_{in}(t) = -a\frac{\dot{R}L}{c} - b\frac{\dot{R}s}{c} + F_c$$

For one-way:

$a = Fref$

$b = bFp$

$$Fc = \begin{cases} \Delta f + 2.40 \text{ MHz} & \text{(KSA)} \\ \Delta f + 0.24 \text{ MHz} & \text{(MA and SSA)} \end{cases}$$

$\dot{R}L \cong \dot{R}3_i + \dot{R}4_i$

$\dot{R}s = \dot{R}5_i + \dot{R}4_i$

For two-way:

$a = Fref$

$b = bFp$

$$Fc = \begin{cases} 2.40 \text{ MHz} & \text{(KSA)} \\ 0.24 \text{ MHz} & \text{(MA and SSA)} \end{cases}$$

$\dot{R}L = \dot{R}1_i + \dot{R}2_i + \dot{R}3_i + \dot{R}4_i$

$\dot{R}s = \dot{R}5_i + \dot{R}4_i$

For hybrid:

$a = Fref$

$b = bFp$

$$Fc = \begin{cases} 2.40 \text{ MHz} & \text{(KSA)} \\ 0.24 \text{ MHz} & \text{(MA and SSA)} \end{cases}$$

$\dot{R}L = \dot{R}1_i + \dot{R}2_i + \dot{R}3_j + \dot{R}4_j$

$\dot{R}s = \dot{R}5_j + \dot{R}4_j$

The average Doppler count Δn accumulated over the time interval from T_L to T_{L+1} can be expressed as follows:

$$\Delta n = \int_{T_L}^{T_{L+1}} f_{in}(t)\, d\tau$$

$$= -a\frac{1}{c}\int_{T_L}^{T_{L+1}} \dot{R}L\, d\tau - b\frac{1}{c}\int_{T_L}^{T_{L+1}} \dot{R}s\, d\tau + F_c \int_{T_L}^{T_{L+1}} d\tau$$

The variable of integration, τ, is the proper time and is related to t by:

$$d\tau = \sqrt{1 - \frac{|\bar{V}GT|^2}{c^2}}\, dt$$

Where:

$$\frac{|\bar{V}GT|^2}{c^2} \approx 10^{-12}$$

which is negligible. Making the substitution for τ:

$$\Delta n = -a\frac{\Delta RL}{c} - b\frac{\Delta Rs}{c} + F_c\, \Delta t$$

Where:

$$\Delta RL \equiv RL\,(T_{L+1}) - RL\,(T_L)$$

$$\Delta Rs \equiv Rs\,(T_{L+1}) - Rs\,(T_L)$$

APPENDIX C. DETERMINATION OF THE TDRS EFFECTIVE RETURN FREQUENCY TRANSLATION FOR THE SSA SERVICE

APPENDIX C. DETERMINATION OF THE TDRS EFFECTIVE RETURN FREQUENCY TRANSLATION FOR THE SSA SERVICE

C.1 INTRODUCTION

C.1.1 For the SSA service, the TDRS effective return frequency translation, bF_p, is a combination of the TDRS upconversion and return SSAFS frequency translation (refer to section 2.2). The TDRS upconversion is fixed at 12475 MHz for both SSA-1 and SSA-2. The return SSAFS frequency translation is set by ground command, in discrete 0.5 MHz, to accommodate the SSA downlink frequency allocations: 13677.5 MHz for SSA-1 and 13697.5 MHz for SSA-2. The return SSAFS tuning step, m, is determined by the ADPE at WSGT, based on the SHO specified user spacecraft receive center frequency, F_{URC}, and zero system dynamics (zero Doppler). The value of m is then transmitted via the uplink TTC channel to the TDRS prior to the start of the SSA service.

C.1.2 In section 4, the bF_p is computed from Fref, the Doppler extraction reference frequency available in the tracking data message, and the known SSA downlink frequency. Fref is derived from F_{URC}, compensated for the forward Doppler, and is defined only after compensation is inhibited on the forward link. Depending on the value of F_{URC} and the dynamic conditions (forward Doppler compensation), the bF_p computed from this algorithms may differ from the actual value by ±0.5 MHz.

C.2 DETERMINATION OF THE bF_p

C.2.1 The actual value of the bF_p can be computed as follows (see figure C-1 and section 2.2):

$$bF_p = f_{c4} - f_m$$

where f_{c4} = the TDRS upconversion = 12475 MHz

f_m = the return SSAFS frequency translation = 900 + m(0.5) MHz

Substitute the values of f_{c4} and f_m into the equation for bF_p:

$$bF_p = 11575 - m(0.5) \text{ MHz} \quad (1)$$

m is determined by the ADPE frequency computation algorithms as follows:

$$m = \text{Round}\left[\frac{F_{UTC} + f_{c4} - 900 - (f_{c6} + f_{c7} + f_{c8} + F_{GIF})}{0.5}\right] \quad (2)$$

where F_{UTC} = the user spacecraft transmit center frequency

$= \frac{240}{221} F_{URC}$ for coherent mode

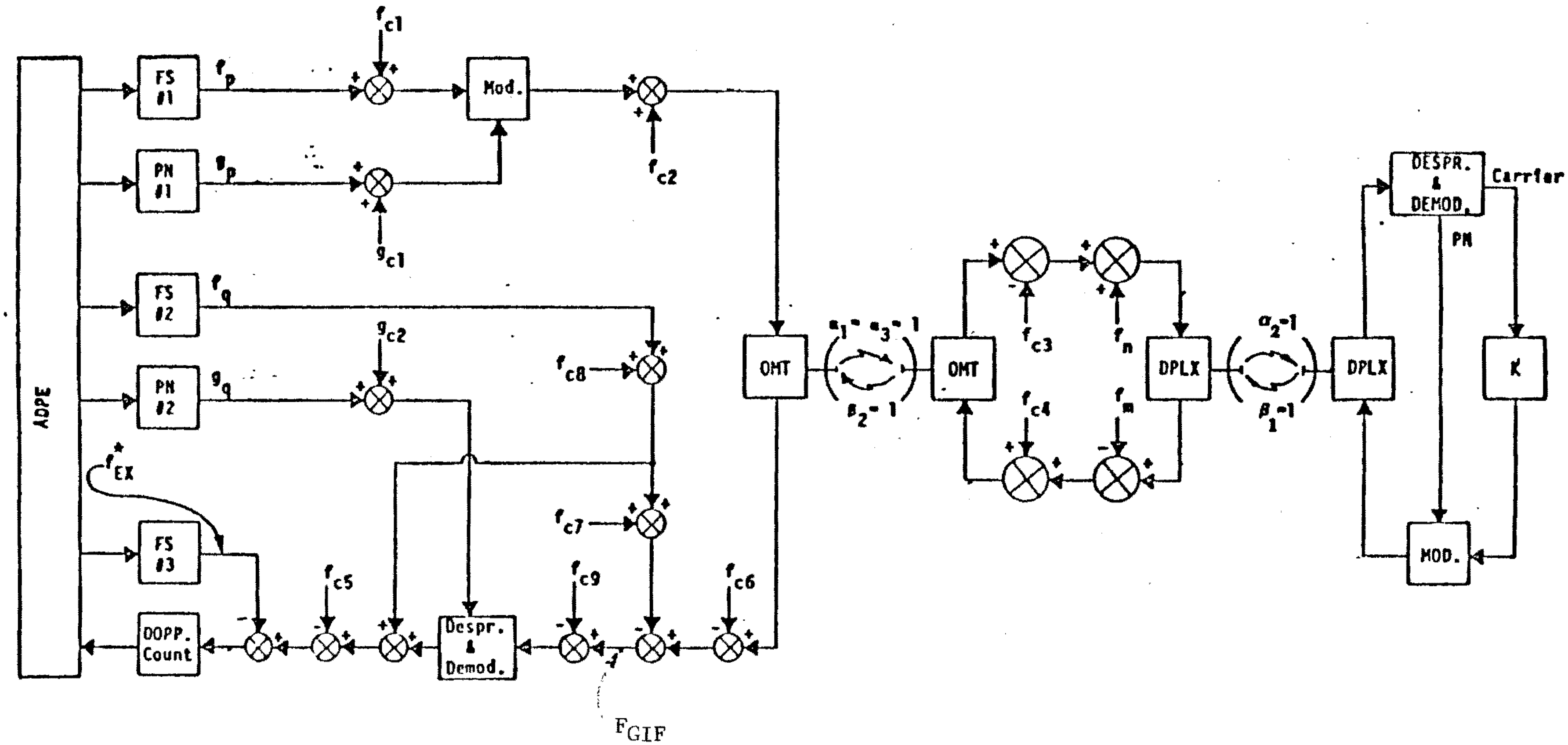

Figure C-1. SSA System Frequency Model Under Zero Doppler Conditions

f_{c6} = down-conversion at WSGT

$$= \begin{cases} 11440 \text{ MHz} & \text{for SSA-1} \\ 11460 \text{ MHz} & \text{for SSA-2} \end{cases}$$

$f_{c7} + f_{c8}$ = the frequency translation in the Doppler corrector with zero Doppler compensation and fine tuning

= 1867.5 MHz

F_{GIF} = intermediate frequency

= 370 MHz

Note

Round[X] means round off X to the nearest integer value. This is accomplished by truncating (X + 0.5) for $X \geq 0$, or truncating (X - 0.5) for $X < 0$.

Substitute these values into (2) and simplify

$$m = \text{Round}[2\,F_{UTC}] - 4205 \quad \text{for SSA-1}$$
$$= \text{Round}[2\,F_{UTC}] - 4245 \quad \text{for SSA-2}$$

Finally, the actual value of bF_p can be computed from equation (1) as follows:

a. For SSA-1:

$$bF_p = 11575 - \left(\text{Round}[2\,F_{UTC}] - 4205\right)0.5 \text{ MHz}$$
$$= 13677.5 - \text{Round}[2\,F_{UTC}]0.5 \text{ MHz} \qquad (3)$$

b. For SSA-2:

$$bF_p = 11575 - \left(\text{Round}[2\,F_{UTC}] - 4245\right)0.5 \text{ MHz}$$
$$= 13697.5 - \text{Round}[2\,F_{UTC}]0.5 \text{ MHz} \qquad (4)$$

C.2.2 In section 4, bF_p is computed from Fref as follows:

a. For SSA-1:

$$bF_p = 13677.5 - \text{Round}[2\,\text{Fref}]0.5 \text{ MHz} \qquad (5)$$

b. For SSA-2:

$$bF_p = 13697.5 - \text{Round}[2\,\text{Fref}]0.5 \text{ MHz} \qquad (6)$$

Fref is an **integer multiple** of 240 Hz and is determined by the ADPE after the forward compensation is inhibited. Fref can be written as follows:

$$\text{Fref} = \frac{240}{221}\left(F_{URC} + fd + r \right)$$

where fd = the forward Doppler compensation and $|fd| < 0.090$ MHz

r = the rounding factor needed to round (F_{URC} + fd) to the nearest integer multiple of 221 Hz. $|r| < 221$

Fref can be rewritten as follows:

$$\text{Fref} = F_{UTC} + \delta$$

$$\text{with } -0.097 \text{ MHz} < \delta < +0.097 \text{ MHz}$$

C.2.3 Comparing equations (3) and (5), (4) and (6), the difference, Δ, between the bF_p's can be given by

$$\Delta = (0.5 \text{ MHz}) \left(\text{Round}[2 F_{UTC}] - \text{Round}[2 F_{UTC} + 2\delta] \right)$$

Therefore, for value of F_{UTC} such that

$$2\text{xxx}.153 \text{ MHz} < F_{UTC} < 2\text{xxx}.347 \text{ MHz}$$

and

$$2\text{xxx}.653 \text{ MHz} < F_{UTC} < 2\text{xxx}.847 \text{ MHz}$$

The bF_p computed from Fref may differ from the actual value by either -0.5 MHz or +0.5 MHz depending on the the dynamic conditions (forward Doppler compensation). This ±0.5 MHz error in bF_p will show up as a slowly varying bias in the computed Doppler as follows:

$$B = -\frac{\dot{R}4 + \dot{R}5}{c} (\pm 0.5 \text{ MHz})$$

For maximum TDRS dynamics,

$$\dot{R}4 \cong \dot{R}5 \cong 35 \text{ m/sec}$$

$$\ddot{R}4 \cong \ddot{R}5 \cong 0.003 \text{ m/sec}^2$$

Then,

$$B \cong 0.120 \text{ Hz}$$

$$\dot{B} \cong 10^{-5} \text{ Hz/sec}$$

C.2.4 To obtain the correct value of bF_p, changes in the algorithms given in section 4 are required. One possible modification is to obtain F_{URC} from the SHO and determine bF_p from equation (3) or (4). This method requires additional information not available in the tracking data.

Note

For NASA standard TDRSS S-band user transponder, the F_{UTC} will be assigned in integer multiples of 0.5 MHz; i.e., 2xxx.5 MHz. Therefore, for user spacecraft equipped with the standard TDRSS S-band transponder, the algorithms presented in section 4 can be applied without any modification.

APPENDIX D. ACRONYMS AND ABBREVIATIONS

APPENDIX D. ACRONYMS AND ABBREVIATIONS

ACS	attitude control subsystem
ADPE	automatic data processing equipment
AGC	automatic gain control
AW	Advanced WESTAR
BER	bit error rate
BPF	bandpass filter
BPSK	binary phase shift key
CEP	circular error probability
CMD	command
CNR	carrier to noise ratio
CTFS	common timing and frequency standard
CTU	command and telemetry unit
dB	decibal
dBW	decibal referred to 1 watt
DG1	data group 1
DG2	data group 2
DTFS	discipline time frequency standard
EIRP	effective isotropic radiated power
ETC	Engineering Test Center, Greenbelt, Maryland
FDM	frequency-division multiplexing
FOV	field, fields of view
FWD	forward
GIPA	ground implemented phased array
GSFC	Goddard Space Flight Center
GT	ground terminal
G/T	antenna gain-to-noise temperature ratio
IF	intermediate frequency
kb	kilobit
kbps	kilobit per second
kHz	kilohertz
KSA	Ku-band (15.35 to 17.25 GHz) single access
LHC	left-hand circular (polarization)
LNA	low noise amplifier
LO	local oscillator
LPF	low pass filter
LSB	least significant bit
LSS	least significant symbol (or syllable)
MA	multiple access
MAR	multiple-access receiver
MARFG	multiple-access receiver frequency generator
Mb	megabit
MFG	master frequency generator
MHz	megahertz
MSB	most significant bit
MSS	most significant symbol (or syllable)

NASA	National Aeronautics and Space Administration
NASCOM	NASA Communications Network
NRZ	nonreturn to zero
O-C	observed minus computed
OMT	orthomode transducer
Pacq	probability of correct acquisition
PLO	phase-locked oscillator
PN	pseudonoise
PNL	pseudonoise length
PNR	pseudonoise rate
PSK	phase-shift keying
QPSK	quadriphase shift keying
RF	radio frequency
RHC	right-hand circular (polarization)
RMDU	remote multiplex demultiplex unit
rms	root mean square
RTN	return
SA	single access
SAW	surface acoustic wave (filter)
SC	spacecraft
SGL	space-to-ground link
SHO	service schedule order
SIC	support identification code
SQPN	staggered quadriphase pseudonoise
SQPSK	staggered quadriphase shift keying
SSA	S-band (1550 to 5200 MHz) single access
SSAFS	S-band single-access frequency synthesizer
SSTDRSS	Shared Service Tracking and Data Relay Satellite System
STDN	Spaceflight Tracking and Data Network
TCXO	thermal-controlled crystal oscillator
TDPS	tracking data processing system
TDRS	Tracking Data and Relay Satellite
TDRSS	Tracking Data and Relay Satellite System
TLM	telemetry
TOCC	TDRSS Operational Control Center
TTC	telemetry, tracking, and command
TWTA	traveling wave tube amplifier
UTC	Universal Time Coordinated
VCO	voltage-controlled oscillator
VCXO	voltage-controlled crystal oscillator
VIC	vehicle identification code
WSGT	White Sands TDRSS ground terminal

APPENDIX E. GLOSSARY

APPENDIX E. GLOSSARY

Term	Explanation
channel	link subdivision used for information transfer and/or two-way range measurement
chip	one bit of a PN sequence as opposed to data bits
command channel	forward link service data channel
convolutional encoding	sequential coding technique whereby check digits are continuously interleaved in the coded bit stream
Costas loop	compound phase lock loop carrier recovery technique used for demodulating double sideband, suppressed carrier signals by generating a coherent phase reference through the use of both inphase (I) and quadrature (Q) channels
data rate	the rate of the digital information data signal before convolutional encoding and/or conversion to biphase format
diplexer	instrument which enables antenna to simultaneously transmit and receive signals
Doppler	change in frequency with which waves from a given source reach an observer when source and observer are in motion with respect to each other
downlink	the link from the TDRS to the WSGT
ephemeris	tabular statement of the assigned places of a celestial body for regular intervals
forward link	the link from the TDRS to the user spacecraft
I channel	data channel supported by 0- and 180-degree phase modulation of the reference carrier
link	includes either all data and/or range channels provided by a TDRSS forward or return service to a user spacecraft; in the case of SA service, a link is defined relative to a specific antenna on a particular TDRS; in the case of MA service, a link is defined relative to a particular TDRS
multiple access	a class of service providing S-band support for a number of relatively low data rate users (up to 50 kbps)
multiplexer	instrument which combines parallel bit streams

Term	Explanation
Q-channel	data channel supported by ±90 degree phase modulation of the reference carrier
range channel	forward link subdivision used for transferring the PN code used for two-way range measurement
return link	the link from the user to the TDRS
signal EIRP	= total EIRP - L_p - L_t (dBW) where L_p = losses resulting from imperfect antenna pointing (dB) L_t = all tandem link losses including power robbing caused by noise and spurious signals (dB)
single access	a class of service providing support for a single user and capable of higher data rates.
SQPN modulation	modulation process in which the phase of the PN clock modulating the Q channel is delayed 1/2 chip relative to the phase of the PN clock modulating the I channel
SQPSK modulation	a quadriphase process in which the data bits of the Q channel are delayed 1/2 bit period relative to the I channel
spread spectrum	system in which the transmitted signal is spread over a wide frequency band, accomplished by modulating with the information to be sent and with a wideband encoding signal
uplink	the link from the WSGT to the TDRS

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