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THE ATS-F/NIMBUS-E TRACKING AND DATA RELAY EXPERIMENT

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Abstract

The Tracking and Data Relay Experiment currently being implemented as part of the ATS-F and Nimbus-E applications missions is a major step in the development of technology necessary to an operational system of Tracking and Data Relay Satellites (TDRS). The experiment will provide data on the performance and operational characteristics of the principal elements of a TDRS system, including real-time command and telemetry relay and long-arc range and range-rate tracking of a low altitude satellite through a synchronous relay satellite.

The basic implementation concept is to equip the ATS-F spacecraft to function as a high performance S-band command, data acquisition, and range and range-rate tracking station in equatorial synchronous orbit. The 30 foot diameter ATS-F parabolic reflector will be programmed for open-loop pointing at the Nimbus-E spacecraft as the latter moves across the face of the earth in its 600 nautical mile polar orbit. Nimbus-E will carry a range and range-rate transponder of standard design, modified to provide additional transmit power, and augmented with a steerable antenna of medium directivity to compensate for the greatly increased free space propagation losses encountered in a TDRS geometry.

In addition to range and range-rate tracking, the two-way S-band link between ATS-F and Nimbus-E will be used for command and data transmissions. This may provide greatly increased flexibility in Nimbus spacecraft operations, including a real-time alternate to the tape recorder used in the Nimbus housekeeping telemetry system. Link performance will be evaluated by means of data transmissions at rates up to 400 kilobits per second, with on-line measurement of error rates as the data are received at an ATS ground station.

I. Introduction

Existing space research and applications satellites require the support of an extensive network of ground tracking and telemetry gathering stations augmented by ships and aircraft. There are currently over one hundred such ground stations operated by the United States alone. Many of these stations, however, have specialized capabilities which constrain their use to particular tracking and telemetry data transmission schemes. Thus the tracking and telemetry coverage afforded an earth orbiting spacecraft is obtained by means of a series of relatively short observations. Despite the large number of ground stations many tracking and telemetry data relay gaps exist. This has led to the requirement for orbit computations based on sequential tracking by multiple ground stations, the "dumping" of on-board recorded data at opportune times, and, in the manned spacecraft case, the augmenting of fixed-site ground stations with RF-equipped ships and aircraft.

While the possibility of using synchronous TDRS to supplement and perhaps replace existing ground based facilities was pointed out as early as 1963 by Dr. F. O. Vonbun of the Goddard Space Flight Center (GSFC), the early state of communication satellite technology at that time necessarily precluded any immediate implementation. Subsequently, both NASA and the Air Force have conducted extensive studies in the area of TDRS (1-11).

These studies have shown that a properly instrumented network of synchronous relay satellites can provide complete tracking and data acquisition coverage for a wide range of missions including manned and automated space research and applications spacecraft. Potentially, such a system could reduce the present number of ground stations and at the same time provide significantly increased capabilities in the areas of tracking and communications.

Up to this point in time, these parametric studies have had little impact on the design of next-generation low-orbiting satellite missions which would be the eventual users of a TDRS. Such a system would necessarily impose specific constraints on mission spacecraft, and it is entirely reasonable that managers of future space programs should be reluctant to base the design of their spacecraft on the as yet undefined and unproven support capability of a TDRS.

The Tracking and Data Relay Experiment (T&DRE) described in this paper* is designed to develop and demonstrate critical aspects of the technology necessary to an operational TDRS system within the

* A preliminary description of the ATS-F/Nimbus-E T&DRE was presented at the 1969 International Telemetering Conference[12]. The present paper up-dates the system description and provides additional details on T&DRE implementation and operations.

framework of NASA's ATS and Nimbus applications flight programs. As presently configured, the T&DRE will have the capability of providing limited incidental support to the Nimbus-E mission spacecraft. However, the system design is sufficiently flexible that additional mission spacecraft could be readily accommodated, when provided with the necessary S-band RF equipments. Thus it is anticipated that the T&DRE will provide a comprehensive information base for future operational TDRS system design.

II. Experimental Testbed - General

Implementation Concept

The basic T&DRE implementation concept is to equip the ATS-F spacecraft to function as a high-performance tracking, command, and data acquisition station positioned in synchronous orbit rather than located on the surface of the earth. The Nimbus-E spacecraft would be equipped with a matching range and range-rate transponder, command receiver and decoder, and telemetry transmitter. Forward link (i.e., Ground Station to ATS-F to Nimbus-E) command and tracking signals would originate at one of the several ATS ground stations available for support of the ATS-F mission, and would be relayed on to Nimbus-E via ATS-F using proven communications satellite frequency translation repeater techniques; return link (i.e., Nimbus-E to ATS-F to Ground Station) telemetry and tracking signals would be relayed through ATS-F to the ground using similar techniques, thus minimizing signal processing requirements on ATS-F while providing all the essential telemetry, tracking, and command (TT&C) support functions of an operational TDRS system.

Selected System Configuration

A number of alternate T&DRE system configurations satisfying the basic implementation concept were identified and studied in the initial phase of experiment definition. These included designs based on use of existing integrated TT&C signal structures such as Apollo USB[13] and Air Force SGLS[14] as well as special purpose T&DRE-unique signal structures. The T&DRE system design finally selected for implementation in the ATS-F/Nimbus-E testbed is based upon use of GRARR* S-band signaling techniques between ATS-F and Nimbus-E, thus permitting existing GRARR-equipped STADAN** ground sites to be used for determination of references Nimbus-E orbits, as well as for a general back-up to the T&DRE TT&C support furnished Nimbus via ATS-F. ATS-F would be tied to the ground via high capacity RF links in the common-carrier microwave bands at 6 and 4 GHz, thus completing the forward and return links to Nimbus-E. The major elements of the resulting T&DRE testbed are illustrated in Figure 1. These include a large ATS ground station, the ATS-F spacecraft in synchronous near-equatorial orbit, the Nimbus-E spacecraft in its 600 mile polar orbit, and a STADAN GRARR site. Also shown in Figure 1 are the Nimbus Control Center at GSFC, and a series of Mobile ATS ground stations and/or Experimenter's terminals equipped with Nimbus-E simulators that are used to provide effective multi-station tracking of ATS-F for refinement of the ATS-F orbit and general T&DRE system calibration. Each of the major elements of the T&DRE testbed is discussed below.

III. ATS Ground Stations

General

Present plans call for the ATS-F mission to be supported out of the Rosman, North Carolina ATS site for the first six to eight months after launch when the spacecraft is positioned at 94° West Longitude. Following this initial phase of the mission, the spacecraft will be slowly repositioned eastward to an eventual on-station location at 15° East Longitude for the Indian ITV Experiment. For the latter phase of the mission, the ATS-F spacecraft will be supported out of the ATS transportable ground station currently*** located in Australia in support of the ATS 1-5 series of spacecraft. The transportable station is to be retro-fitted for the ATS-F&G missions and will be relocated in Western Europe prior to repositioning ATS-F to 15° E.

A detailed functional block diagram of the ATS ground station is shown in Figure 2, emphasizing its role in providing T&DRE support functions; a number of ground station equipments associated with other ATS-F&G or ATS-1-5 support functions are not included for simplicity. A summary of RF parameters is given in Table 1, based on preliminary data supplied by the GSFC ATS Project Office.

* Goddard Range and Range-Rate tracking system. This high-performance system was developed at GSFC in the early 1960's for precision tracking of earth-orbiting spacecraft. GRARR capability has been implemented at five sites around the world: Rosman, North Carolina; Fairbanks, Alaska; Santiago, Chile; Tananarive, Malagasy Republic; and Carnarvon, Australia. It should be emphasized that a major retro-fit of the original GRARR system (15,16) took place in the late 1960's. Changes and improvements made included inversion of receive and transmit frequencies and introduction of polarization diversity reception.[17,18]

** Space Tracking and Data Acquisition Network, NASA's world-wide network of ground stations used to support un-manned earth-orbiting scientific and applications satellite programs. In addition to the GRARR sites identified above, the STADAN complex includes numerous MINITRACK sites as well as a number of ground stations dedicated to support of major observatory missions such as ATS and Nimbus.

*** August 1970

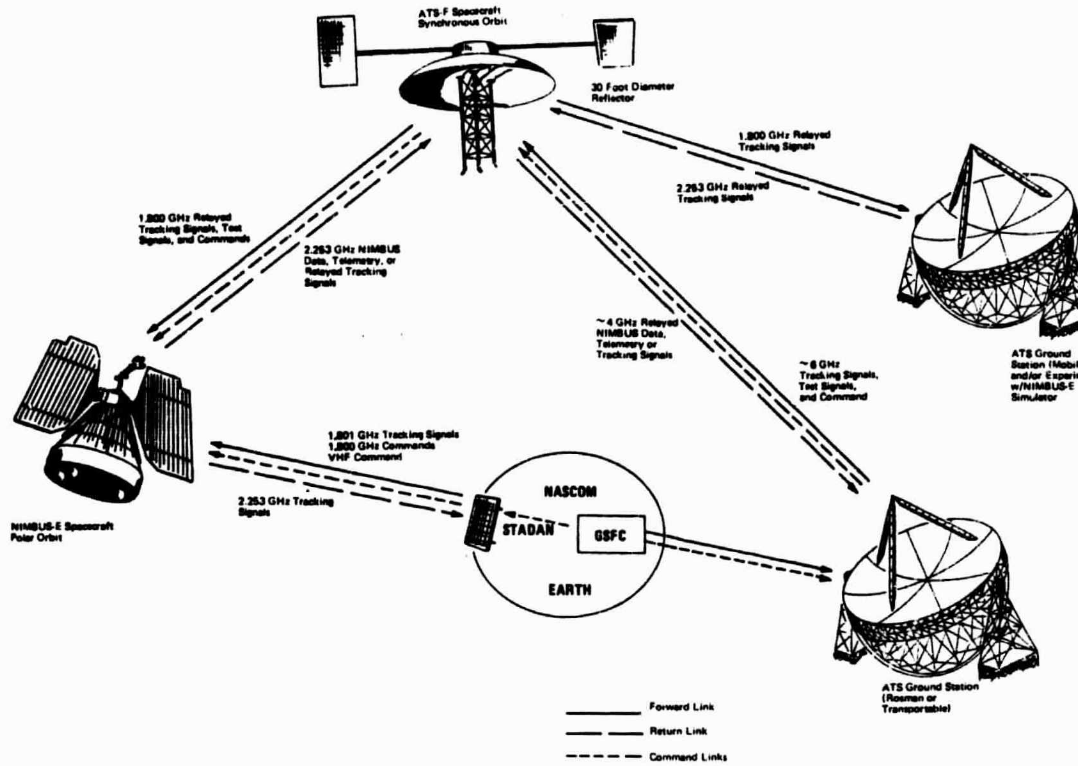

FIGURE 1. TRACKING AND DATA RELAY EXPERIMENT TESTBED CONFIGURATION

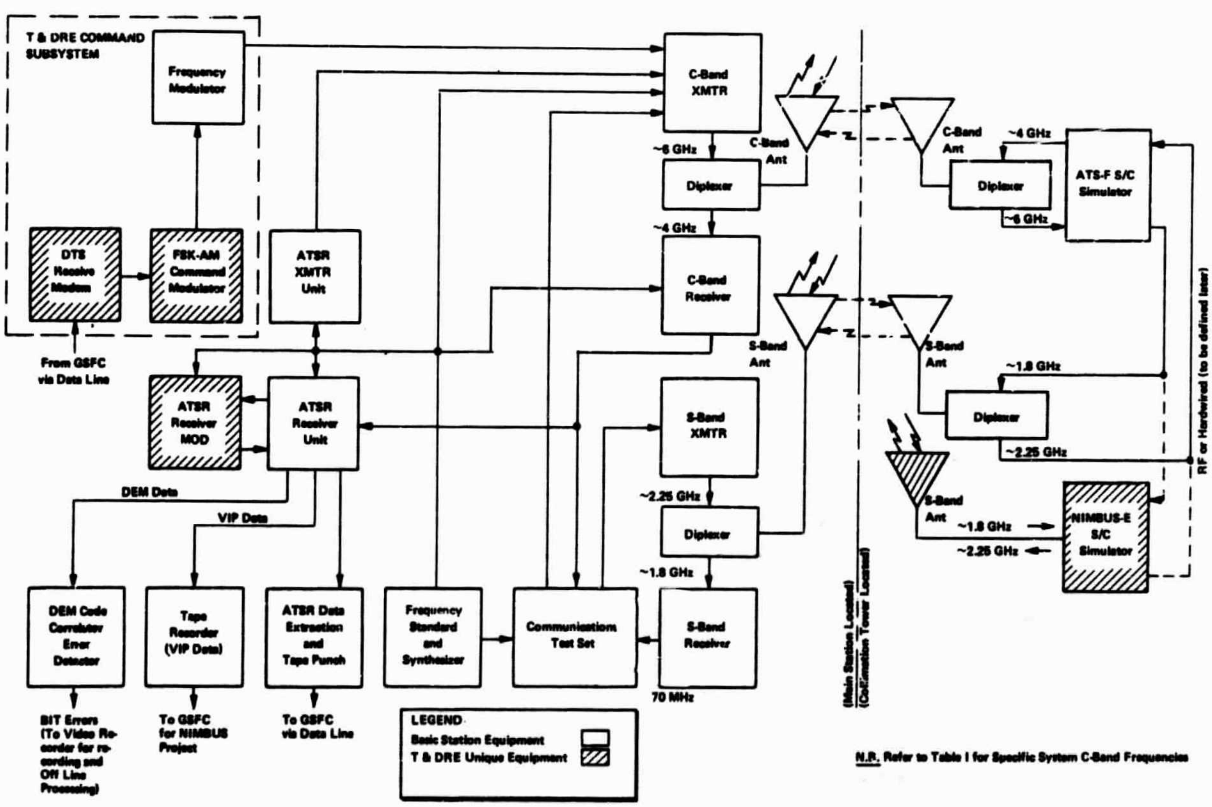

FIGURE 2. ATS GROUND STATION (ROSMAN OR TRANSPORTABLE) T&DRE ELECTRONICS

TABLE 1

ATS GROUND STATION RF PARAMETER SUMMARY

PARAMETER	ROSMAN		TRANSPORTABLE	
	C-Band	S-Band	C-Band	S-Band
Antenna Diameter	85'	15'	40'	15'
Xmit Frequency & BW (MHz)	5950 ± 25 6150 ± 25 6350 ± 25	2250 ± 25	(Same as Rosman)	
Rated Xmit Power	10 kw	100 watts	(Same as Rosman)	
Max. Xmit ERP	+100 dbw	+57 dbw	+94 dbw	+57 dbw
Rcve Frequency & BW (MHz)	3750 ± 25 3950 ± 25 4150 ± 25	1800 ± 25	(Same as Rosman)	
Nominal Rcve System G/T	+40 db/°K	+15 db/°K	+33 db/°K	+15 db/°K

C- and S-Band RF Subsystems

The C- and S-Band transmitters, receivers, diplexers and antennas provide the main RF links between the ATS ground station and the ATS-F spacecraft. In T&DRE operations, all forward link command and tracking signals go up to ATS-F at one of the several 6 GHz C-band frequencies; return link telemetry and tracking signals come back to the ground station at one of the several 4 GHz frequencies. The S-Band RF capability is used primarily for conducting closed loop system RF tests and is not a central element of the T&DRE testbed per se.

ATS-R Subsystem (modified)

The ATS-R[19] transmit and receive units shown together with the station C-band transmit and receive subsystems constitute a high-performance GRARR-derived range and range-rate system which is used to provide basic tracking support for all ATS mission spacecraft. The modification unit shown in Figure 2 permits the ATS-R system to function in a carrier-coherent mode, thus permitting the ATS-F spacecraft to function as a remote GRARR tracking station of essentially standard design. For more details, see Section VI.

Frequency Standard and Synthesizer

This unit provides spectrally pure, phase coherent signals for all critical station operations including ATS-R signal generation and timing, IF/RF and RF/IF frequency conversions, etc. In addition, when the ATS-F spacecraft repeater is operated in a frequency coherent mode for T&DRE range-rate tracking (see Section VI) the station standard becomes the phase reference for all frequency conversion operations in the ATS-F repeater.

T&DRE Command Subsystem

The wire-line modem, FSK-AM command modulator, and 70 MHz frequency modulator shown in Figure 2 receive real-time command signals at 128 bps from the Nimbus Control Center at GSFC and encode them in the proper RF format for transmission to the T&DRE package on Nimbus-E via ATS-F.

DEM Code Correlator/Error Detector

This unit processes M-sequence pseudo-noise data generated in the digital evaluation module (DEM) in the Nimbus-E T&DRE package and counts transmission errors in real time, thus performing an online T&DRE link performance evaluation. The individual error counts are recorded in real time along with time tags on a video instrumentation recorder for an off-line statistical analysis of error patterns, distributions, etc.

ATS-F Spacecraft Simulator

This unit, located on a collimation tower several miles from the basic station, is an electrical equivalent of the ATS-F spacecraft repeater. It is required for calibration of the T&DRE range and range-rate tracking system described in Section VI as well as a reference against which to measure ATS-F spacecraft repeater performance characteristics after launch.

Nimbus-E Spacecraft Simulator

This unit is a simplified version of the Nimbus-E T&DRE flight package. Essentially, it is a single channel GRARR transponder which can be tied in with the ATS-F spacecraft repeater on the collimation tower to close the T&DRE range and range-rate links for purposes of calibrating range measurements and zero-setting of doppler for range-rate.

Communications Test Set

This is a complex of standard 70 MHz test equipment for measuring frequency response, delay characteristics, gain stability, and other parameters of RF links to and from the ATS-F spacecraft, thus permitting in-orbit evaluation of repeater performance and comparison with pre-launch test data and/or data taken in the link with the ATS-F spacecraft simulator on the collimation tower.

IV. ATS-F Spacecraft

General

The ATS-F spacecraft and its various subsystems and experiment packages are treated in detail in a companion paper[20] and are not discussed at any length here. With reference to Figure 3, the three spacecraft subsystems of particular importance to the T&DRE are the earth-coverage C-Band antenna, the two-way coherent communications repeater, and the 30' parabolic reflector and S-Band feed subsystem. Each of these is treated briefly in the following.

Earth Coverage Antenna

As the ATS-F spacecraft is a fully stabilized vehicle, the C-band earth coverage antenna implementation is much simpler than that encountered in earlier ATS series spacecraft. A broad-beam linear polarized horn antenna with a three degree beamwidth of 17° is a proposed approach. Because the ATS-F spacecraft will be pointed away from the subsatellite point while tracking Nimbus-E, it will be necessary under certain conditions to operate the ground/ATS-F links well outside the nominal 3- db beamwidth of the planned earth-coverage antenna. Reference to Table A of the Appendix will indicate that this will provide ample link capacity when used in conjunction with the Rosman and Transportable ground stations discussed in Section III.

Communications Repeater

A functional block diagram of the ATS-F spacecraft communications repeater required for the T&DRE is shown in Figure 3. A distinctive feature of this repeater is that all frequency conversions can be performed in a phase-coherent manner, referenced back to the frequency standard at the ATS ground station. This is done by locking a narrow-band phase-locked loop on the discrete carrier component of an angle-modulated signal received from the ATS ground station. This coherent mode of T&DRE repeater operation is strictly necessary only when making range-rate measurements between ATS-F and Nimbus-E. Under other T&DRE modes of operation use of the crystal oscillator shown in Figure 3 will be satisfactory.

Present program plans call for the repeater subsystem shown in Figure 3 to be implemented as part of an integrated communications repeater serving not only T&DRE requirements but also those of other ATS-F communications-related experiments including ITV and PLACE. A preliminary description of the overall ATS-F communications subsystem is given in reference 20.

30' Parabolic Reflector

A description of the ATS-F 30' antenna proper is also available in reference 20. For T&DRE operations in the S-band frequency region, the nominal 3 db beamwidth of the reflector will be of the order of 1.7°, well within the pointing accuracy and platform stability design objectives of the overall ATS-F spacecraft. Thus, it is planned to perform all ATS-F T&DRE antenna pointing using programmed open loop techniques.

In addition to physical pointing of the antenna structure (i.e., boresight), a supplementary mode of S-band beam steering is available on ATS-F. This secondary mode uses multiple-feed electronic scanning of the reflector to produce a discrete number of off-boresight beams. The maximum planned off-boresight scan angle is of the order of ± 6 degrees, insufficient to provide the T&DRE required cone of coverage of approximately 20 degrees. Thus, some degree of boresight pointing will be required even when using the ATS-F electronically scanned S-band feed system to track Nimbus-E.

Summary of ATS-R T&DRE Parameters

A summary of major ATS-F T&DRE parameters is given in Table 2, based on preliminary data supplied by the GSFC ATS Project Office[21].

V. Nimbus-E T&DRE Subsystem

General

The Nimbus-E spacecraft configuration is illustrated in Figure 4, showing the locations and general form factors of the several elements which constitute the T&DRE flight package. These elements are: a top-mounted quad helix array S-band antenna on an x-y gimbal assembly and mount; a drive electronics package for the gimbal assembly; a two-channel GRARR transponder augmented with an S-band output power amplifier; and a digital electronics package containing the T&DRE command decoder, antenna programmer, and related circuitry.

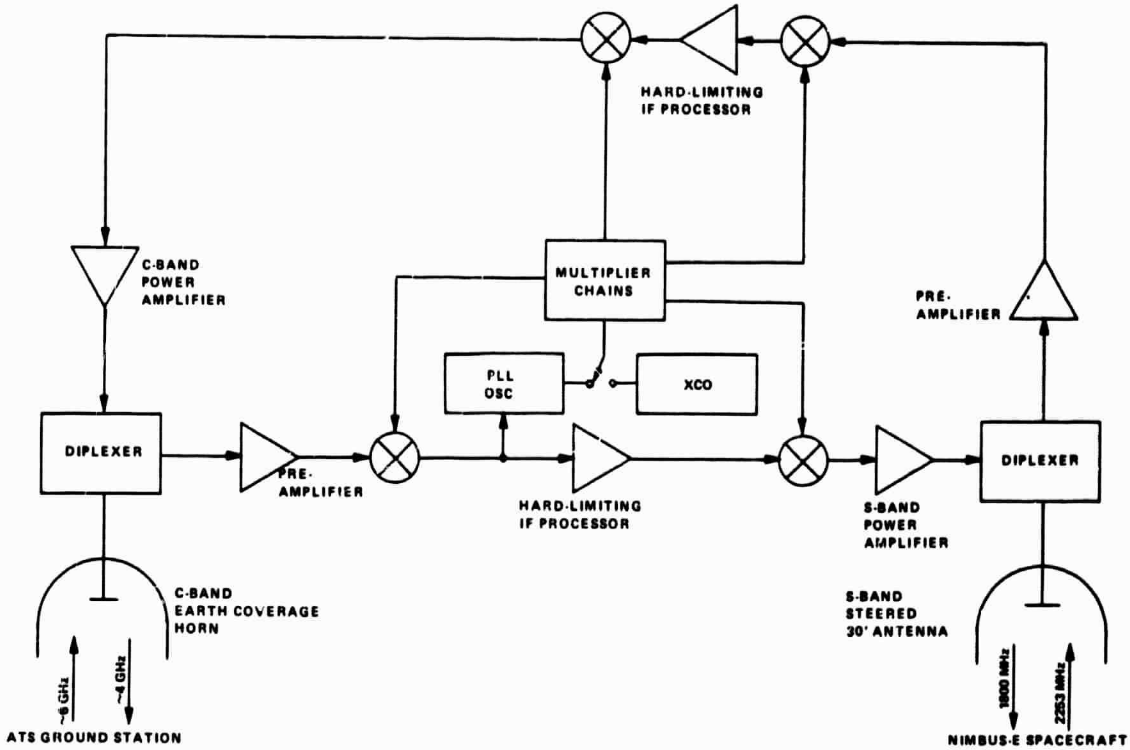

FIGURE 3. ATS-F ELECTRONICS FOR T&DRE

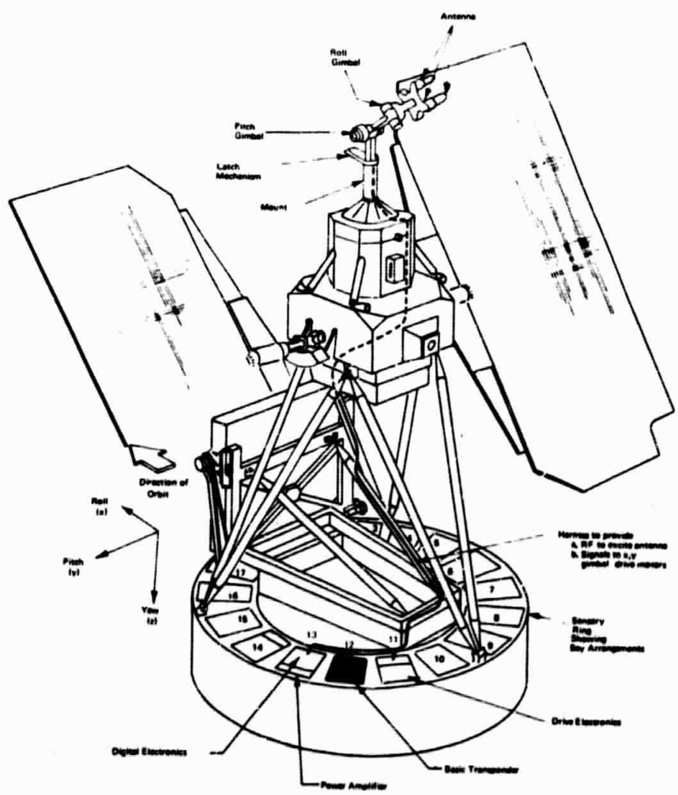

FIGURE 4. NIMBUS-E SPACECRAFT SHOWING T&DRE EQUIPMENTS

TABLE 2

SUMMARY OF ATS-F T&DRE PARAMETERS

Parameter	Receive G/T, 6 GHz	Xmit EIRP, 1.8 GHz	Receive G/T, 2.25 GHz	Xmit EIRP, 4 GHz	Repeater Bandwidth
Nominal value	-16 db/°K	+50.5 dbw	+9.5 db/°K	+30 dbw	≥ 12.0 MHz (either link)

Interconnection and interfacing of these subsystem elements with each other and with the various subsystems of the Nimbus-E spacecraft are shown in detail in Figure 5 and discussed briefly below.

Quad Helix Antenna

For operations with ground based GRARR S-band tracking stations, it is standard practice to use omni or broad beam antennas on earth-orbiting mission spacecraft. In the present system, the greatly increased free space propagation losses encountered in links to and from ATS-F require that the G/T and EIRP parameters of the Nimbus-E T&DRE transponder be augmented by at least ten db if tracking data uncertainties due to additive system receiver noise are to be kept at an acceptable level. This requires the use of a steerable directive S-band antenna on Nimbus-E. The selected implementation is a top mounted, fully gimbaled array of 4 circularly polarized helical elements above a ground plane. This design provides a pattern directivity of approximately 16 db in links with ATS-F under virtually all conditions of spacecraft mutual visibility. A helical array was chosen rather than a small dish because the former provides the desired gain while occupying a considerably smaller dynamic volume envelope, an important consideration in the present case because of the proximity of spacecraft control system gas jets to the top mounted antenna and gimbal structures.

The T&DRE antenna is being designed and fabricated in-house at GSFC. Preliminary pattern measurements reproduced in Figure 6[22] indicate peak net gains of 16 db at 2253 MHz and 14 db at 1800 MHz and on-axis axial ratios of approximately 1.5 db. Off-axis linear characteristics shown in Figure 6 indicate broad regions free from deep nulls. This will permit reliable tracking and commanding from ground based STADAN sites in the sidelobes and backlobes of the T&DRE antenna, thus permitting simultaneous communications with ATS-F and STADAN using a single S-band antenna subsystem on Nimbus-E.

Gimbal Assembly and Mount

The x-y gimbal system to be used in the T&DRE was developed by Ball Brothers Research Corporation[23] and is being supplied by the Nimbus-E spacecraft prime contractor to T&DRE specifications as part of the basic spacecraft. Studies[24] have shown that for an x-y gimbal arrangement, alignment of the upper gimbal with the spacecraft roll axis and the lower gimbal with the pitch axis (see Figure 4) is the preferred arrangement for a system using programmed pointing in the Nimbus-E/ATS-F orbital geometry. The present design provides antenna pointing to approximately ±110° in both gimbal axes. This will provide a satisfactory link to ATS-F for approximately 80% of all periods of spacecraft mutual visibility. The 20% total intra-spacecraft occultation is due to a combination of effects including insufficient gimbal drive angle capability, Nimbus-E solar paddle blockage, etc.

RF signals will be fed through the gimbal assembly using standard cable wrap techniques. The design objective on total RF system losses through the overall gimbal system is 1.0 db, with performance to be maximized at the transmit frequency of 2253 MHz.

Antenna Drive Electronics

The pair of gimbals will be mechanically driven to discrete positions* using DC stepper motors operating through harmonic drives. These motors will obtain their drive signals from an electronics package located in the Nimbus-E sensory ring (Figure 4). The drive electronics unit, controlled by a programmer unit located in the T&DRE digital electronics package, is being supplied with the gimbal assembly proper by the Nimbus-E spacecraft prime contractor.

Two Channel GRARR Transponder

The T&DRE range and range-rate transponder is a two-channel version of the general transponder described in reference 25. System IF beamwidths have been selected for compatibility with a maximum range sidetone frequency of 100 kHz, providing a capability for range resolution of the order of meters.

* An alternate approach considered early in the program approximates the desired gimbal angles using a scheme of discrete sequenced gimbal rates[24].

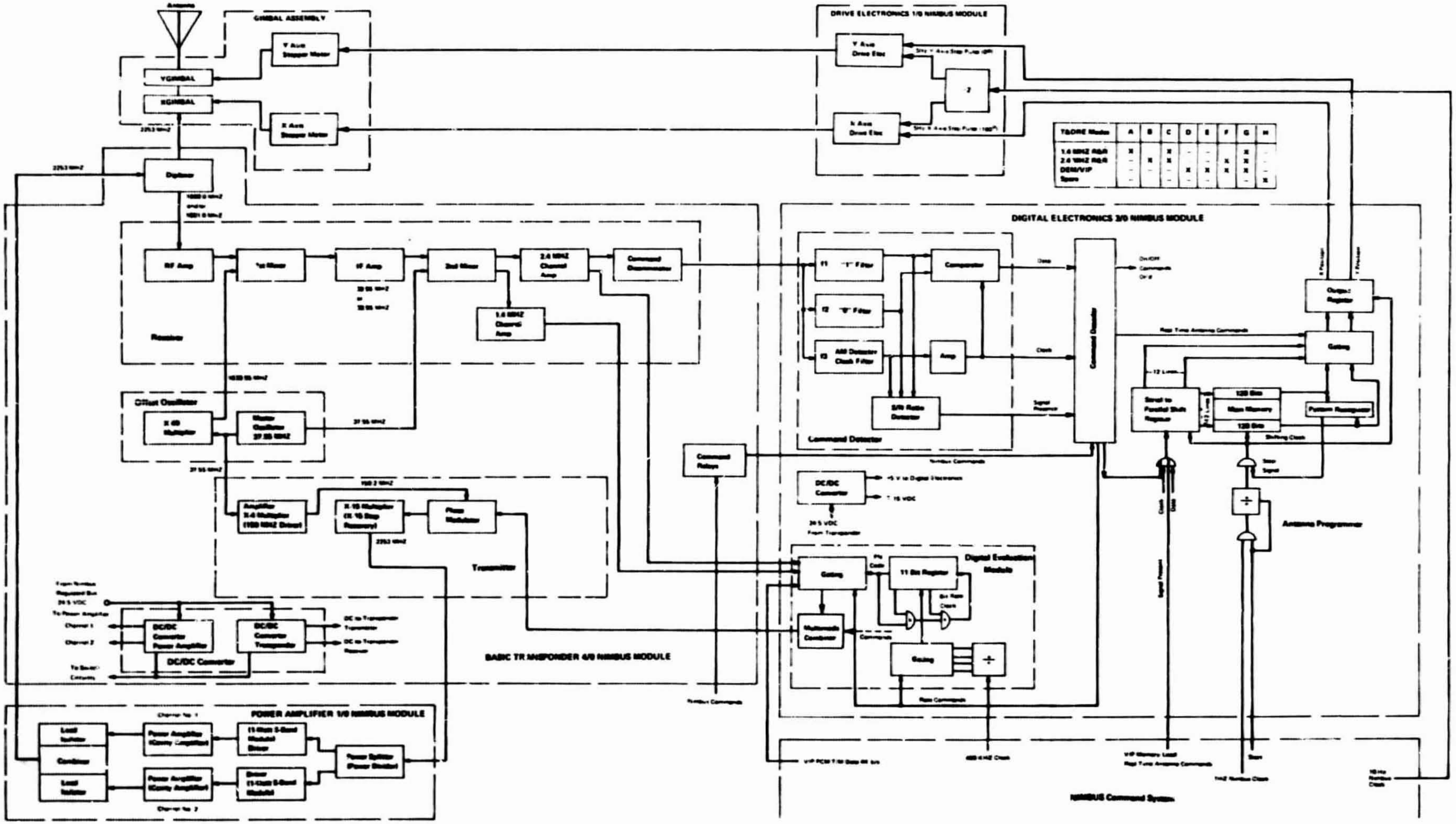

FIGURE 5. NIMBUS-E T&DRE ELECTRONICS BLOCK DIAGRAM

The 2.4 MHz channel shown in Figure 5 is used when the transponder is interrogated with a signal from ATS-F and the 1.4 MHz channel is associated with tracking from a ground based STADAN station.

The various modes of transponder operation are tabulated in Figure 5. In addition to the three pure range and range-rate modes indicated, the transponder can also transmit selected combinations of telemetry and tracking signals, including Nimbus 4 kbps housekeeping telemetry (VIP), predetermined DEM data, etc. An additional mode of operation not tabulated is command retransmit. Commands to the T&DRE package received via ATS-F are routed through the 2.4 MHz transponder channel to a command receiver/detector located in the digital electronics package. The incoming RF command signals are, however, automatically retransmitted back to ATS-F as sidebands on the 2253 MHz RF carrier. This provides a quasi real-time command reception verification capability of the ATS ground station.

The transponder proper is being built and integrated in-house at GSFC with specific sub-elements (e.g., the receiver and offset oscillator) being procured from industry[26].

S-Band Power Amplifier

As noted above, the basic GRARR transponder does not have sufficient transmit power to meet T&DRE link design objectives without some augmentation. The present design calls for the milli-watt level transponder power output to be increased to a nominal 4 watt level in a redundant S-band power amplifier whose basic configuration is shown in Figure 5. Activation of both power amplifier channels produces an optional high-level power output of approximately 8 watts, thus providing increased flexibility in T&DRE return link operations. The 1 watt driver stage is solid state and, being developed and supplied from an industrial source[27]. Design and construction of the final cavity amplifier and integration of the overall unit is being performed in-house at GSFC.

Digital Electronics Package

The principal elements of the digital electronics package are a GSFC standard PCM/FSK-AM command detector and decoder for handling T&DRE commands routed through ATS-F, an antenna programmer for controlling the drive electronics package of the T&DRE gimbal subsystem, and a digital evaluation module (DEM) which generates a pre-determined M-sequence pseudo-noise code for T&DRE return link performance evaluation.

The antenna programmer unit has a memory capable of storing 128 pairs of 6 bit words, each pair representing a discrete combination of x and y gimbal angles. The programmer clocks out new position information at intervals of approximately 2.8 minutes. This suffices to keep Nimbus-E antenna pointing errors well within the nominal 10° 1 db beamwidth of the quad helix array antenna under virtually all system orbital geometries. Programmer loading may be accomplished through the Nimbus housekeeping command system or through the T&DRE link via ATS-F; real time updates of antenna position are likewise possible using either command link.

The DEM generates an M-sequence 2047 bits long which will be correlation-detected at the ATS ground station to evaluate T&DRE return link performance. A capability exists for commanding pre-determined errors into the transmitted bit stream, thus providing a capability for on-line check out of the DEM correlator at the ATS ground station. The selected system bit rates for DEM data are 400, 200, 100, and 50 kbps.

The digital electronics package of the T&DRE is being designed and integrated in-house at GSFC, with certain sub-units being fabricated by industrial sources[28].

Nimbus-E Spacecraft Interfaces

In addition to the routine power and command experiment/spacecraft interfaces characteristic of all Nimbus-E flight experiments, the T&DRE package has two distinctive features. First, Nimbus-E VIP (Versatile Information Processor) housekeeping telemetry can be transmitted to the ground via the T&DRE return link. This is done by coupling the VIP 4 kbps split-phase data stream into the signal combining circuitry of the digital electronics package through a buffer amplifier. This provides a capability for receiving near-continuous real-time Nimbus-E housekeeping telemetry. Such data is ordinarily obtained via the Nimbus High Data Rate Storage System (HDRSS) tape recorder subsystem, which records the VIP data when the spacecraft is out of sight of its data acquisition facility (DAF) and plays back at a 32:1 speed-up ratio when over the DAF.

A second special interface is required to permit T&DRE antenna programmer memory loading via the normal Nimbus-E housekeeping command system. The approach selected is to connect, on command, the VIP Memory Program Line of the VIP Command System to the serial-to-parallel input shift register of the antenna programmer. This provides an additional capability for commanding the movement of the steerable directive S-band antenna by utilizing the Nimbus Command Link (Nimbus Control Complex/STADAN Station/Nimbus-E Spacecraft).

Summary of Nimbus-E T&DRE Parameters

A summary of major Nimbus-E T&DRE parameters is given in Table 3.

TABLE 3

Summary of Nimbus-E T&DRE Parameters

Parameter	ATS-F/Nimbus-E Link		STADAN/Nimbus-E Link	
	Receive G/T 1.800 GHz	Xmit EIRP 2.253 GHz	Receiver G/T 1.801 GHz	Xmit EIRP 2.253 GHz
Nominal Value	-19.0db/°K	+20 dbw	-73db/°K*	-26* dbw

* Anticipated worst case condition corresponding to operations in T&DRE antenna pattern nulls 30 db below isotropic.

VI. Four-way Tracking System Implementation

Given the basic concept of equipping ATS-F to function as a GRARR tracking station in synchronous oribt, it is possible to identify a number of possible approaches to T&DRE system implementation. A number of candidate approaches were studied in the course of evolution of the hybrid ATSR/GRARR scheme described in this paper. These include: (a) flying a stable oscillator, GRARR signal synthesizer, and range and doppler measuring equipments on ATS-F, and telemetering observed tracking data to the ground via the ATS-F spacecraft TT&C subsystem; (b) originating and terminating forward and return link tracking signals at the ATS ground station, using incoherent frequency translation techniques to relay signals to and from Nimbus-E; (c) same as (b), but using coherent frequency translation techniques in the ATS-F communications repeater.

Method (a) did not appear warranted in view of its increased cost and complexity relative to methods (b) and (c) while not offering any significant advantages in either system operations or performance. Methods (b) and (c), frequently termed "bent-pipe" schemes, appeared to entail roughly equivalent penalties in terms of ATS-F spacecraft hardware, but differed considerably in terms of ground instrumentation requirements. Method (c), described in this paper, was selected on the criteria of minimum overall system cost and complexity while meeting all T&DRE tracking system objectives.

Hybrid ATSR/GRARR Four-way Tracking

As is clear from Figure 2, the T&DRE range and range-rate tracking system makes extensive use of existing ATSR instrumentation. This is possible because the side-tone ranging techniques used in the two systems are essentially the same. The fundamental difference in the two systems is that GRARR observes one-way doppler on an RF carrier and ATSR measures two-way doppler on one of the several range side-tones. Thus, by modifying the ATSR receiving equipment to permit GRARR-type doppler measurements, it is possible to have the ATSR system function in a carrier-coherent manner, providing a considerably lower system thermal noise threshold than that possible with the ATSR system proper.*

Operation is as follows. The ATSR signal synthesis unit is operated in a 100 kHz side-tone ranging mode. The tracking signal is converted to C-band and transmitted to ATS-F with all frequency synthesis and conversions operations under the control of a frequency standard in the ATS ground station. The signal is received at ATS-F and coherently translated to 1.8 GHz, at which point it appears to be a standard GRARR format tracking signal. It is relayed to Nimbus-E, handled in the conventional GRARR format, and retransmitted back to ATS-F for coherent retransmission to the ground. Upon reception at the ATS ground station, range measurements are made in a conventional manner and range-rate measurements are made using a T&DRE-unique ATSR modification unit which makes coherent carrier manner doppler measurements. Finally, the observed data (with time tags) are punched out on paper tape for transmission or shipment to GSFC.

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* The increased range-rate noise sensitivity of the ATSR system is seldom a problem in normal ATSR operations, as the large channel capacity of C-band space/ground links in the ATS program generally provides ATSR tracking data whose quality is limited only by system instrumentation uncertainties. The details of the ATSR modification unit for carrier doppler measurement in the T&DRE testbed were worked out by T. J. Grenchik of GSFC.

Data Format and Performance Objectives

With reference to Figure 1, let r_1, r_2, and $\dot{r}_1$ and $\dot{r}_2$ be the instantaneous range and range-rate parameters of the ground/ATS-F and ATS-F/Nimbus-E test-bed. T&DRE range data are taken in the form $2(r_1 + r_2)$. Range-rate data are taken in the form $[(a_1 + a_2)\bar{\dot{r}}_1 + a_2\bar{\dot{r}}_2]$, where a_1 and a_2 are known constants related to the frequency translation ratios of ATS-F spacecraft coherent communications repeater, and the bar superscripts refer to the data averaging interval tentatively selected as ten seconds for T&DRE operations.

Tracking data uncertainties are of two types, bias and random. The former are due to uncertainties in physical constants, group delay variations in various elements of the RF tracking link, and other mechanisms which introduce "step" type errors into measured data. Random errors are generally attributable to either finite master oscillator phase noise of additive system thermal noise.

T&DRE design objectives for bias uncertainties in raw tracking data are 4.0 meters in range and 0.6 centimeters in range-rate. Design objectives for random uncertainties in range-rate are 2.0 meters in range and 0.05 centimeters/second in range-rate. These numbers neglect uncertainties due to atmospheric effects (of interest only in special system geometries), and ignore the uncertainty in the speed of light. They do include allowances for finite system phase jitter and thermal noise and group delay uncertainties in the ATS-F repeater and Nimbus-E transponder.

Based on the availability of long-arc (i.e., continuous except during earth-occultation) tracking data in the formats and of the qualities specified, studies[28] have shown that it should be possible to determine the Nimbus-E orbit on-line to within 50 meters in a total elapsed time of several hours. This constitutes a substantial improvement over ground-based tracking systems, which typically require days and weeks of off-line data processing to determine orbits which at best are known only to within hundreds of meters. Verification of these theoretical studies is considered the major scientific and applications goal of the T&DRE.

Turn-around Tracking Mode

While the prime T&DRE tracking mode is that involving Nimbus-E, there is a secondary mode of system operation which is of considerable interest in the context of overall program operations. This involves interrogation of ground-based Nimbus-E simulators (i.e., GRARR transponders) from ATS-F to obtain four-way tracking between ATS-F and known sites on the surface of the earth. A single turn-around link of this type is indicated in Figure 1. Use of several Nimbus-E simulators will permit effective multi-station tracking of ATS-F. It is anticipated that this will permit refinement of the ATS-F orbit above and beyond what can be accomplished in tracking from a few fixed sites. This may be particularly helpful in the latter phases of the ATS-F mission when only a single station (the Transportable) is available for TT&C support of the spacecraft.

The major advantage of performing four-way tracking between ground sites using the ATS-F T&DRE testbed is the minimal RF complexity required at the turn-around site. Alternative turn-around tracking techniques (e.g., ATSR using side-tone doppler) require relatively large G/T and EIRP parameters at the turn-around site relative to those required with ATSR/GRARR techniques using Nimbus-E simulators (see Table 3). This suggests that the T&DRE testbed will provide the most flexible and cost-effective approach to high-performance multi-station tracking of ATS-F for orbit up-date and refinement throughout the mission.

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Appendix

Nominal System Power Budgets

Illustrative power budgets for the principal RF links involved in the T&DRE are given in Table A. In each case, the parameter computed is the ratio of available RF signal power P_r to white gaussian thermal noise power spectral density KT at the input of the receiver of the link in question. This is a useful measure of the information capacity of the RF channel. Because of the great disparity in the P_r/KT ratios available in the ATS-F/Nimbus-E and Ground/ATS-F links, signal/noise degradation due to tandem link effects is expected to be minor except under conditions of severe RFI from earth-based emitters operating in the 1.8 and 2.253 GHz regions. A preliminary survey[29] has indicated that such sources will cause only incidental interference with T&DRE operations on a long term basis.

Similarly, no attempt has been made to take into account multipath effects due to signal reflections from the surface of the earth. While such reflections may be a significant problem in an operational TDRS system[9], studies have shown[30] that multipath will have neglible effects on communications and tracking in the T&DRE S-band test-bed except under the pathological conditions

TABLE A

Illustrative System Power Budgets

Parameter	Ground/ ATS-F (6 GHz)	ATS-F/ Nimbus-E (1.8 GHz)	Nimbus-E/ ATS-F (2.253 GHz)	ATS-F/ Ground (4 GHz)	STADAN/ Nimbus-E (1.8 GHz)	Nimbus-E/ STADAN (2.253 GHz)
1. Xmit EIRP (dbw)	+94.0	+50.5	+20.0	+30.0	+70.0*	-26.0
2. Antenna point loss (db)	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
3. Free space loss (db)	-200.0	-191.0	-192.5	-196.8	-159.2	-161.7
4. Polarization loss (db)	-1.0	-0.5	-0.5	-1.0	-3.0	-1.0***
5. Receiver G/T (db/°K	-16.0	-19.0	+9.5	+40.0	-73.0	+7.0
6. Boltzmann's constant (db/°K-Hz)	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
7. P_r/KT (db-Hz) (add 1-5, subtract 6)	+104.6	+67.6	+63.1	+99.8	+66.4**	+43.9**

* Representative value for Rosman, Fairbanks, Tananarive, and Carnarvon; Santiago will provide a link some 6 db stronger.

** Corresponds to the worst-case Nimbus-E antenna conditions of Table 3 above. The link will generally be ten or more db better than that computed here.

*** All STADAN S-Band sites except Santiago have polarization diversity reception, thus making this a conservative number.

which exist when Nimbus-E is entering into or emerging from earth occultation, at which times loss of data is to be expected.

Range and Range-rate Requirements

Detailed analyses[31,32] have shown that the forward and return link channel capacities of Table A are more than ample to keep tracking system noise-type uncertainties below the levels quoted in Section VI. At issue in these analyses is the extent to which the two-way tracking link is affected by weak signal/noise ratios in the forward link, a problem not usually encountered in ground-based GRARR tracking applications. Range and range-rate data taken in links with STADAN sites will, in general, also have vanishingly small uncertainties due to additive thermal noise. There can be situations, however, in which T&DRE tracking data from STADAN may be poor or unusable; this would occur when the effective T&DRE antenna directivity in the direction of the STADAN site becomes less than -30 db below isotropic, corresponding to operations in an extreme pattern null. However, as the STADAN/Nimbus aspect angle is constantly changing, any such extreme nulls are not expected to produce significant losses of tracking data. At any rate, the problem does not appear to warrant use of an independent downward-looking T&DRE antenna on Nimbus-E, a possibility considered in the early stages of experiment definition.

Command Link Requirements

The data rate in the T&DRE command link is 128 bps. This suggests that an ultra-reliable link could be obtained with forward link channel capacities several orders of magnitude less than those anticipated in the T&DRE forward link. This is not so in the present case due to a number of constraints which obtain in the T&DRE test-bed. First, no attempt is being made to pre-correct for the relatively large carrier doppler shifts ($\pm$50 kHz or more) encountered in a TDRS geometry at S-band. Second, the T&DRE command system uses FM carrier modulation with discriminator detection in a noise bandwidth at least that associated with the nominal doppler spread. Thus, the initial FM detection stage in command reception will be subject to FM threshold effects when the forward link P_r/KT ratio gets below some 60 db-Hz. Under these conditions, it is apparent that while sufficient forward link channel capacity exists for reliable T&DRE command operations under nominal link conditions, performance may be marginal or worse when operating in the side and back-lobes of the Nimbus-E T&DRE antenna. This is not considered to constitute a significant problem because of the experimental nature of the overall T&DRE system.

Telemetry Power Requirements

The nominal return link channel indicated in Table A are more than sufficient to provide highly reliable transmissions of 4 kbps VIP data from

Nimbus-E to the ground via ATS-F. To perform a more meaningful evaluation of T&DRE return link performance, DEM telemetry (see Section V) will be transmitted at rates of 50, 100, 200, and 400 kbps.

The selected format for all T&DRE return link telemetry is split-phase data phase modulating the 2.253 GHz carrier with phase deviations of $\pm 70^{\circ}$ peak. Signal detection at the ATS ground station will be done using a high-performance carrier-tracking phase demodulator(19) which will track the residual carrier component of the transmitted signal under all system doppler conditions. Examination of the return link channel capacities of Table A suggests that this implementation will provide received baseband data with energy contrast ratios in the range of +6 to +15 db under nominal link conditions, thus providing an opportunity to examine the performance threshold of the T&DRE return link in some detail.

Mixed Format Power Requirements

The above discussions of T&DRE return link power requirements did not address the question of mixed modes of system operation. With reference to the table in Figure 5, there are a number of composite T&DRE transmit modes, e.g. two-channel tracking, tracking plus VIP, etc. The T&DRE return link has been sized to provide extremely high quality data in the 2.4 MHz single channel tracking mode. Mixed modes of operation are considered secondary for purposes of system sizing and no specific design objectives have been established for such modes at this point in time.

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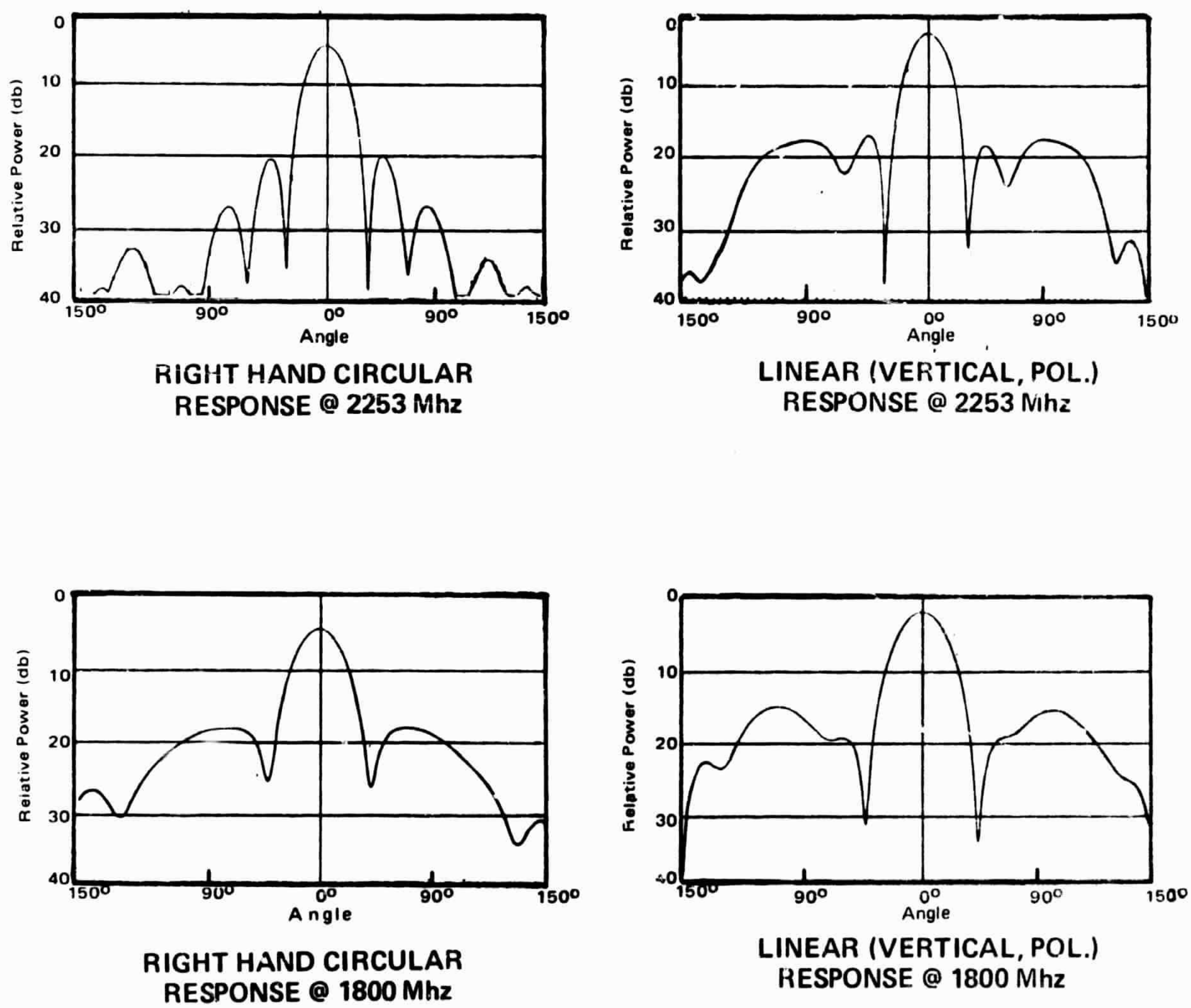

FIGURE 6. NIMBUS-E T&DRE ANTENNA PATTERNS