THE TRACKING AND DATA RELAY SATELLITE SYSTEM:
AN OVERVIEW

Malcolm G. Davis, Jr.
TRW Defense and Space Systems Group
One Space Park
Redondo Beach, CA 90278

ABSTRACT

The Tracking and Data Relay Satellite System (TDRSS) is a shared service system supplying leased communication and tracking services to NASA and commercial Advanced Westar channels to Western Union and the American Satellite Company. An overview of the TDRSS design is presented. The space segment, consisting of four geosynchronous satellites, is described including launch. The spacecraft is described with emphasis on the communications payload covering both the NASA TDRSS and Advanced Westar equipment. The ground terminal located at White Sands, New Mexico, serves as the interface between the four TDRSs and up to 32 user satellites simultaneously for data transmission, tracking and spacecraft control via NASA’s communication network (NASCOM). The functions and characteristics of the White Sands ground terminal are presented.

INTRODUCTION

In the early 1980’s NASA’s Tracking and Data Relay Satellite System (TDRSS) will replace most of the ground stations of the current Spaceflight Tracking and Data Network (STDN). The eight remaining STDN ground stations and the TDRSS will then satisfy the communication and tracking needs of future NASA missions, especially the Space Transportation System (STS). In 1982 the first Tracking and Data Relay Satellite (TDRS) will be carried into low earth orbit by the STS and placed in geostationary orbit by an Inertial Upper State (IUS). Subsequent STS/IUS launches will complete the four-satellite constellation shown in Figure 1.

The TDRSS is a shared service system supplying leased communication and tracking services to NASA and commercial communication channels to Western Union Telegraph Company and the American Satellite Company. Western Union Space Communications, Inc., contracted with NASA to provide telecommunication services for ten years; TRW Defense and Space Systems Group and Harris Government Communication Systems
Division are the principal subcontractors for the spacecraft and ground terminal equipment, respectively. TRW is also responsible for system engineering and integration, and the software for controlling the TDRSS space and ground segments.

SYSTEM DESCRIPTION

In the shared system configuration (Figure 1) NASA’s TDRSS operations are conducted via two satellites in synchronous inclined orbits at 41° and 171°W longitude. The third satellite at 93°W longitude is dedicated to Western Union’s Advanced Westar (AW) service. The fourth satellite is a shared, on-orbit spare at 83°W longitude that provides protection against service outages for either the TDRSS or AW missions, as well as supplemental services for the TDRSS mission and pre-emptible C-band service for the AW mission.

The 130-degree separation of the east and west satellites provides maximum earth coverage consistent with mutual visibility of a single ground terminal located within the United States. The White Sands, New Mexico, location was chosen because its low latitude permits wide separation of the satellites and the low rainfall rates minimize rain-caused link outages. TDRSS earth coverage for a user satellite at 200 km altitude is greater than 85 percent (Figure 2) and increases to 100 percent for satellites above 1200 km. This compares with less than 15 percent coverage available for the current groundbased STDN.

The TDRSS provides tracking and communications support to three classes of NASA user satellites: up to 20 multiple access (MA) users can be tracked simultaneously with command and telemetry support (100 bps to 50 kbps); up to six S-band single access (SSA) and K-band single access (KSA) users are provided tracking, command and telemetry (to 12 and 300 Mbps, respectively) services. The system offers a wide choice of data rates and formats with or without error correction coding.

The Advanced Westar satellite capabilities provided to the Western Union and American Satellite Company include data from 75 bps to 250 Mbps, K-band capacity totaling 1000 Mbps with satellite switching and movable beams, and 12 C-band channels per satellite. Potential uses of these basic capabilities include digital/analog voice (including secure voice), high speed facsimile, video conferencing at 6.5 Mbps, and broadcast-quality video. Because of high radiated power and sensitivity of the satellite, private communication networks using rooftop or parking lot antennas are feasible. The AW earth terminals are not part of the shared service TDRSS; only the space segment is shared between the TDRSS and AW missions.
TELECOMMUNICATION SERVICES

TDRSS service requirements are defined between the radio frequency (RF) interface with user spacecraft and the interface with the NASA Communications Network (NASCOM) at the White Sands ground terminal (WSGT). Figure 3 shows these TDRSS interfaces and the NASA facilities that interconnect the ground communication interface with the user facilities. The radio frequency interface with user spacecraft is defined in terms of signal parameters, RF characteristics, and field-of-view. The ground terminal interface with NASCOM consists of either 1) forward link baseband data channels and detected/decoded return link data channels where standard TDRSS signal structures are used, or 2) intermediate frequency (IF) channels through which NASA can support user-unique signal parameters by using modulators and demodulators on the NASCOM side of the ground terminal interface.

TDRSS services include forward link communications, return link communications, two-way range measurement, and one- or two-way doppler measurement. Forward link services are provided via a data (or IF) interface between the NASA White Sands facility and the ground terminal and the transmission of an appropriately modulated signal in the direction of the desired user spacecraft by a TDRS. Return link service is defined in terms of an achievable data rate at the ground terminal interface as a function of effective isotropic radiated power (EIRP) radiating from the user spacecraft in the direction of a TDRS at a standard range of 43,000 km.

The forward and return link services are categorized as multiple access, S-band single access, and Ku-band single access. SSA and KSA services can be configured to support the special requirements of the space shuttle. The forward and return link frequency plan is shown in Figure 4. A summary of service capabilities is presented in Tables I, II, and III. All forward link services include pseudo-noise (PN) modulation to enable the measurement of round-trip range delay.

<table>
<thead>
<tr>
<th>Service</th>
<th>MA</th>
<th>SSA</th>
<th>KSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of view (Relative to nadir for each TDRS)</td>
<td>±13° conical</td>
<td>±22.5° East-West</td>
<td>Elliptical</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>6</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>EIRP (dBw)</td>
<td>34</td>
<td>43.0</td>
<td>46.5</td>
</tr>
<tr>
<td>Data rate</td>
<td>0.1 - 10 kbps</td>
<td>0.1 - 300 kbps</td>
<td>1 kbps - 25 Mbps</td>
</tr>
</tbody>
</table>

Table 1. Forward Link Service
Data group 1 (DG1) return link service includes PN modulation and provides range measurement capability in addition to return link telemetry and one- or two-way doppler measurement. Data group 2 (DG2) return link service provides return link telemetry and one- or two-way doppler measurement. Convolutional coding is available on all return link services.

Multiple access service provides simultaneous real-time and dedicated return-link service to low earth orbiting user spacecraft with data rates up to 50 kbps. Multiple access return link support can be provided to each of 20 users during the entire portion of the orbit that it is visible to one or more of the TDR satellites. All MA users operate at the same carrier frequency (2287.5 MHz) and are separated at the ground terminal by means of unique PN codes. One forward link is available from each of the three in-orbit satellites and is time shared among the 20 MA users.

### Table II. Return Link Services

<table>
<thead>
<tr>
<th>Service</th>
<th>MA</th>
<th>SSA</th>
<th>KSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of view</td>
<td>Same as forward link services</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>6</td>
<td>10</td>
<td>225</td>
</tr>
<tr>
<td>Data rate*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data group 1 (DG 1)</td>
<td>0.1 - 50 kbps</td>
<td>0.1 - 300 kbps</td>
<td>1 - 300 kbps</td>
</tr>
<tr>
<td>Data group 2 (DG2)</td>
<td>NA</td>
<td>1 kbps - 12 Mbps</td>
<td>1 kbps - 300 Mbps</td>
</tr>
<tr>
<td>Achievable data rate** (dB relative to 1 bps)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DG1 without coding</td>
<td>NA</td>
<td>29.8 + EIRP_u</td>
<td>27.6 + EIRP_u</td>
</tr>
<tr>
<td>DG1 with coding</td>
<td>24.4 + EIRP_u</td>
<td>35.0 + EIRP_u</td>
<td>28.6 + EIRP_u</td>
</tr>
<tr>
<td>DG2 without coding</td>
<td>NA</td>
<td>30.8 + EIRP_u</td>
<td>32.8 + EIRP_u</td>
</tr>
<tr>
<td>DG2 with coding</td>
<td>NA</td>
<td>36.0 + EIRP_u</td>
<td>38.0 + EIRP_u</td>
</tr>
</tbody>
</table>

* DG1 and DG2 are not available simultaneously.

**EIRP_u = EIRP of user spacecraft, dBw.
Table III. Shuttle Ku-Band Return Link Services

<table>
<thead>
<tr>
<th>Mode*</th>
<th>Channel 1</th>
<th>Channel 2</th>
<th>Channel 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>192 kbps</td>
<td>16 kbps - 2 Mbps</td>
<td>2 - 50 Mbps</td>
</tr>
<tr>
<td>Mode 2</td>
<td>192 kbps</td>
<td>16 kbps - 2 Mbps</td>
<td>4.2 MHz analog or TV</td>
</tr>
</tbody>
</table>

* Modes 1 and 2 not available simultaneously.

Single access services are supported via two large (4.9 m), deployable antennas on each TDRS. Each SA antenna can provide circularly polarized SSA and KSA service simultaneously. The single access antennas are gimballed to support user spacecraft over the required field of view. Because of the narrow beamwidth at Ku-band, KSA operation includes an autotrack loop closed through the ground terminal. For SSA operation, the SA antenna can be open-loop pointed.

In addition to relaying command and telemetry data to and from user spacecraft, the TDRSS provides accurate tracking of these spacecraft by measuring one- and two-way doppler and two-way range. Hybrid tracking employs both TDRS-East and TDRS-West to make two simultaneous measurements of two-way doppler and range, thereby enhancing the accuracy of orbit determination. The quantity of forward link, return link, and tracking services available from each TDRS and the total system is summarized in Table IV.

SPACE SEGMENT

The shared service TDRSS space segment consists of four identical and interchangeable TDRS spacecraft, each incorporating both TDRSS and Advanced Westar communication payloads. Once in orbit, each satellite is configured to perform the desired mission: TDRSS, AW, or spare.

The TDRS (Figure 5) is a large spacecraft that measures 16.4 m (53.8 ft) from edge to edge of the 4.9-m antennas and weighs almost 5000 pounds at launch. Approximately 1300 pounds of the launch weight is propellant for attitude control, station-keeping, and station changes during the 10-year life of the spacecraft. The spacecraft is three-axis stabilized with sun-oriented solar panels; the yaw axis is normally pointed at the nadir. Antenna pointing is accomplished by mechanically steering the 4.9-m single access and 2.0-m space-ground link antennas and electronically steering the multiple-access array. The spacecraft is configured in three modules: 1) the spacecraft equipment module houses the attitude control; telemetry, tracking, and command (TT&C); electrical power; propulsion; and thermal control subsystems; 2) the payload equipment module contains telecommunications equipment; and 3) the antenna module supports the deployable and fixed antennas and the multiple-access array.
Table IV. TDRSS Service Capabilities

<table>
<thead>
<tr>
<th>Service</th>
<th>MA</th>
<th>SSA</th>
<th>KSA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Forward link services</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quantity of links per TDRS</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total links for the TDRSS</td>
<td>3*</td>
<td>6*</td>
<td>6*</td>
</tr>
<tr>
<td><strong>Return link services</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quantity of links per TDRS</td>
<td>20</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total links for the TDRSS</td>
<td>20</td>
<td>6*</td>
<td>6*</td>
</tr>
</tbody>
</table>

* Includes services from an in-orbit spare satellite

**COMMUNICATIONS PAYLOAD**

The communications subsystem configuration (Figure 6) combines the TDRS mission equipment and Advanced Westar K-band equipment in an integrated design. A separate C-band transponder and antenna provide the Advanced Westar C-band communication services. Simultaneous operation in the TDRS and Advanced Westar K-band modes is not required: switching between the two modes is provided for failure or overload conditions and is accomplished by command from the TDRSS ground terminal. Sharing equipment between the two payloads increases redundancy for the TDRS mission while meeting all performance requirements for both missions.

**TDRS Mission Equipment**

Principal elements of the TDRS payload include:

- K-band space-ground link equipment
- Forward and return processors
- K- and S-band single access equipment
- S-band multiple access equipment
- Frequency generation equipment.
The K-band space-ground link equipment includes a 2.0-m gimballed antenna plus the K-band receivers, upconverters, and TWTA’s that provide the communications interface with the TDRSS ground terminal. All of this equipment is shared between the TDRSS and Advanced Westar missions. The forward and return processors demultiplex and multiplex the forward and return services, respectively. The AW processor routes the spacecraft switched time division multiple access (SSTDMA) signals between receive and transmit K-band antennas.

Two 4.9-meter antennas with associated S- and K-band receivers and transmitters provide the communications interface with the SSA and KSA users. A 30-element antenna array with associated multi-channel receivers and transmitters interfaces with the MA users. The frequency generation equipment provides the reference frequencies for up- and down-conversion in the various repeater channels.

Forward link signal flow is as follows: The TDRSS ground terminal transmits a composite signal of MA, SSA, KSA, TT&C, and pilot tone signals which is received by the spacecraft 2.0-m space/ground link (SGL) antenna. The SGL antenna has a two-axis gimbal drive and is pointed to the White Sands terminal using ground commands.

The SGL receive equipment translates the up-link signal to an intermediate frequency (IF), amplifies it and sends it to the forward processor assembly. The forward processor assembly filters and demultiplexes this composite signal into the five separate signals that were multiplexed at the ground terminal. The MA portion of the signal is translated into the forward link S-band frequency and sent to the MA transmit assembly where it is divided among 12 elements of the helix phased array. The transmit array beam is steered by phase shifters under ground command.

The SSA output from the forward processor is routed to the compartment mounted on the back of the SA antennas where the signal is amplified by the SSA 26-watt TWTA for transmission. A KSA signal is also sent at an intermediate frequency from the forward processor assembly to the SA antenna compartment where a KSA upconverter converts it to K-band. One of the 1.5 watt TWTA’s amplifies this signal for transmission. The TT&C portion of the composite signal is sent from the forward processor assembly to the TT&C subsystem after it has been downconverted to S-band. The forward processor assembly sends the pilot tone signal to the spacecraft master frequency generator as a control reference to supply coherent conversion frequencies throughout the system.

Return link operation is similar to forward link operation except the flow is reversed. Signals received at the 4.9-m antenna are isolated from the transmit signals by diplexers, amplified by parametric amplifiers, downconverted to intermediate frequency, and sent to the return processor assembly. The MA return link signal is received by 30 MA antenna
elements and amplified by individual S-band preamplifiers. The 30 signals differ only in phase, and the MA receive assembly down-converts each to a unique IF frequency. The signals are then frequency-division multiplexed into a single signal that is routed to the return processor assembly.

The return processor assembly accepts the MA signal, the SSA signal, and the low data rate KSA signal and multiplexes them with the TDRS telemetry and downlink pilot tone. This FDM composite IF signal is translated to K-band by the K-band upconverter, amplified by a 30-watt K-band TWTA, and transmitted to the TDRSS ground terminal through the SGL antenna. KSA high data rate return link signals are not multiplexed on the composite signal; they are routed to a separate K-band upconverter and 30-watt TWTA for transmission to the ground terminal by the SGL antenna.

**Advanced Westar Equipment**

The Advanced Westar subsystem consists of C-band and K-band equipment. A 12-channel C-band transponder and antenna essentially duplicate the service provided by the existing Westar satellite. The Advanced Westar K-band system consists of three area-coverage and three spot-coverage channels. Two single access antennas and the space/ground link (2-meter) antenna offer spot coverage; area coverage is provided by a separate Advanced Westar K-band antenna and the space/ground link antenna.

The SA spot coverage receive channel utilizes a transfer switch to select the input from either the KSA diplexer or the Advanced Westar diplexer. The receive signal is then amplified, downconverted, and sent to the Advanced Westar processor assembly and thence at IF to the KSA upconverter. The signal is then amplified in the 1.5-watt TWTA and coupled through the transmit section of the Advanced Westar diplexer to the antenna switch. The 1.5-watt TWTA is shared with the TDRS mission by means of transfer switches that select KSA or Advanced Westar diplexers.

**GROUND SEGMENT**

The TDRSS ground terminal is located on a 9-acre site at White Sands, New Mexico (Figure 7). A 30,000 sq ft one-story structure houses the communications equipment, computers, and NASCOM interface equipment, as well as control and display equipment, offices, and support operations. The TDRSS terminal equipment (Figure 8) consists of the antennas, RF/IF and signal processing equipment, computers and control/display equipment, and support equipment and facilities required to monitor and control the four operational satellites and handle the user traffic to and from the NASCOM interface.
Three 18-m (60 foot) K-band antennas provide the user traffic interface with the three TDRSs. Roof-mounted Ku- and S-band antennas provide the user simulation interfaces with the TDRS. A separate 6-m antenna supplies backup S-band TT&C support to the four satellites.

The simulation/verification subsystem simulates user forward and return RF links through any of the three TDRSs. This capability enables user satellites to conduct prelaunch or factory system comparability tests through the entire TDRSS. User forward and return operational and simulation traffic interface in digital format through a collocated NASCOM facility. The single access services also provide an intermediate frequency interface for users who require analog data or special modulation formats. Special single access modems accommodate space shuttle-unique data and modulation formats.

The user traffic flow and TDRS control and display functions are shown in Figure 9. User forward data is received from the NASCOM interface, routed to the appropriate SA or MA modulator, combined with a PN code, and QPSK-modulated with a second PN code (used for two-way range measurements) onto an IF carrier. The carrier and code frequencies are doppler-compensated for predicted user motion to facilitate rapid user signal acquisition. The carrier is then upconverted to K-band, amplified, and combined with the other uplink signals for transmission to the TDRS via the 18-m antenna.

The composite return link signals are processed through a low noise preamplifier, downconverted, demultiplexed, and routed IF amplification and demodulation equipment. The 30 MA signals are down-converted to a common IF using the TDRS telemetry carrier as a reference to remove TDRS doppler and preserve phase coherency. The 30 outputs are routed to 20 sets of beam-forming equipment where they are combined in the proper phase relationship to produce maximum gain in the direction of the desired user. After demodulation and error correction decoding, the 20 outputs are routed to the NASCOM interface.

Two-way range and range-rate measurements are accomplished by comparing the phase and frequency of the forward link code and carrier with the return code and carrier. The resulting measurements are formatted, precisely time-tagged, and transferred to the NASCOM interface. All station time and frequency references are derived from a precision cesium frequency standard. One-way doppler is measured by comparing the return link carrier frequency with the local frequency standard.

All scheduling, configuration control, status reporting and user ephemeris data are handled in a computer-to-computer interface through the NASCOM facility. Normal operation of the satellites and the user simulation and traffic channels is completely automatic. Control consoles provide continuous status monitoring of the entire system and a backup manual.
The automatic data processing equipment (ADPE) (Figure 10) and software are functionally distributed among five computer types: central, ground segment control (SC), TT&C, inter-processor multiplexer (IPM), TDRSS operations control center (TOCC) and data bus. The IPMs manage ground station message traffic between computers and to and from the NASA interface (NIU). Each PDP 11/70 TT&C computer (four operational, one spare) performs all functions related to the real-time operation of one TDRS. Two SC computers manage ground terminal operations and provide the man-machine interface with operating personnel via the TOCC. The central computer exercises overall control of the TDRSS in response to NASA or ground terminal operator direction.

The central computer is a dual processor Univac 1110 (Figure 11), selected for its computational capacity and cost. As configured for TDRSS, one central processor unit can handle all TDRSS system functions under normal operating conditions. The IPMs are fully redundant with only one operating at a time. Both are accessible to the central ADPE for switchover in case of a failure.

ACKNOWLEDGEMENT

The author wishes to acknowledge the contributions of many colleagues in the preparation of this paper. In particular he has drawn heavily on the work of those authors whose papers are listed as references. Additional details on specific aspects of TDRSS can be found in these references.

REFERENCES


Figure 1. TDRSS/Advanced Westar Shared Space Segment Configuration

Figure 2. TDRSS Zones of Exclusion
Figure 3. STDN/TDRSS Configuration

Figure 4. Forward and Return Link Frequency Plan
Figure 5. TDRSS Configuration

Figure 6. TDRSS/Advanced Westar Communications Payload
Figure 7. TDRSS Ground Terminal, White Sands

Figure 8. TDRSS Ground Terminal Configuration
Figure 9. Ground Segment Processing of User Traffic and TDRSS TT&C

Figure 10. TDRSS ADPE Block Diagram
Figure 11. Central ADPE and Interfaces