# N/\S/\
## Technical Memorandum 86127

# ELECTRONIC SWITCHING SPHERICAL ARRAY (ESSA) ANTENNA SYSTEMS

## PERFORMANCE INTERFACE DOCUMENT

Richard Hockensmith

## JULY 1984

PERFORMANCE INTERFACE DOCUMENT
FOR
USERS OF THE TRACKING AND DATA RELAY SATELLITE SYSTEM (TDRSS)
ELECTRONIC SWITCHING SPHERICAL ARRAY (ESSA) ANTENNA SYSTEMS

Prepared by

R. Hockensmith
R. Jackson
R. Moss

July 1984

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

This document has been prepared to complement
information found in the Tracking and Data Relay
Satellite System (TDRSS) User's Guide (STDN 101.2)

## CONTENTS

CONTENTS (Continued)

ILLUSTRATIONS

TABLES

**Page intentionally left blank**

# ACRONYMS

| | |
|---|---|
| ADR | Achievable data rate |
| AM/PM | Amplitude modulation/phase modulation |
| AR | Axial ratio |
| ATS | Applications Technology Satellite |
| | |
| BER | Bit-error rate |
| | |
| CLASS | Communications Link Analysis and Simulation System |
| COBE | Cosmic Background Explorer |
| | |
| DLA | Data Link Antenna |
| DOA | Direction of Arrival |
| DPSK | Differential phase shift keying |
| DSN | Deep Space Network |
| | |
| EIRP | Effective isotropic-radiated power |
| EMSA | Electromechanically steerable antenna |
| EMSAS | Electromechanically steerable antenna system |
| ERBS | Earth Radiation Budget Satellite |
| ESSA | Electronic Switching Spherical Array |
| | |
| FOV | Field of View |
| | |
| GSFC | Goddard Space Flight Center |
| GSTDN | Ground Spaceflight Tracking and Data Network |
| G/T | Gain/temperature |
| | |
| HGA | High-gain antenna |
| HPBW | Half-power beamwidth |
| | |
| JPL | Jet Propulsion Laboratory |
| JSC | Johnson Space Center |
| | |
| KSA | Ku-band single access |
| | |
| LHCP | Left-hand circular polarization |
| | |
| MA | Multiple access |
| MSFN | Manned Spaceflight Network |
| | |
| NASA | National Aeronautics and Space Administration |
| NASCOM | NASA Communications Network |
| NCC | Network Control Center |
| NGT | NASA Ground Terminal |
| | |
| PA | Power amplifier |
| PFD | Power flux density |
| PN | Pseudo random noise |

## ACRONYMS (Continued)

| | |
|---|---|
| RF | Radio frequency |
| RFI | Radio-frequency interference |
| RFPIP | RF performance improvement package |
| RHCP | Right-hand circular polarization |
| | |
| SMA | S-band multiple access |
| SMM | Solar maximum mission |
| SNR | Signal-to-noise ratio |
| SPD | Switching power divider |
| SSA | S-band single access |
| STADAN | Space Tracking and Data Acquisition Network |
| STDN | Spaceflight Tracking and Data Network |
| STS | Space Transportation System |
| | |
| TDRS | Tracking and Data Relay Satellite |
| TDRSS | Tracking and Data Relay Satellite System |
| TWT | Traveling wave tube |
| | |
| UQPSK | Unbalanced quadrature phase shift keying |
| Usat | User Satellite |
| | |
| VSWR | Voltage standing wave radio |
| | |
| WSGT | White Sands Ground Terminal |
| | |
| ZGTF | Zero Gravity Test Facility |
| ZOE | Zone of exclusion |

PERFORMANCE INTERFACE DOCUMENT
FOR
USERS OF TRACKING AND DATA RELAY SATELLITE SYSTEM (TDRSS)
ELECTRONIC SWITCHING SPHERICAL ARRAY (ESSA) ANTENNA SYSTEMS


## INTRODUCTION

The electronic switching spherical array (ESSA) antenna was con-
ceived and its development* initiated in 1976 to fulfill the re-
quirements of a large number of S-band user satellites (Usat's)
that would operate with the planned Tracking and Data Relay Satel-
lite System (TDRSS). The overall requirements necessitated a
greatly increased Usat effective isotropic radiated power (EIRP)
and enhanced receiver sensitivity because of the large transmis-
sion distances involved (up to 26 dB greater path transmission
loss compared to the use of the ground-based tracking and data
station network) and the small Tracking and Data Relay Satellite
(TDRS) antennas (compared with currently employed ground based
antenna sizes). The burden on the Usat's is compounded further
by the user community demands for higher data rates. TDRSS pro-
vides both Ku-band and S-band services, the latter for low and
medium link data rates up to 3 Mbps.

The ESSA antenna has been developed to provide the S-band user
(the basic technique though is not confined to S-band operation)
with inertialess antenna beam steering (zero induced torque noise
into the spacecraft) over $2\pi$ steradians or more spatial coverage
to mitigate TDRSS network scheduling problems. The first unit
is scheduled to fly on the three-axis stabilized Earth Radiation
Budget Satellite (ERBS) due to be launched in the second half
of 1984. A second unit is being built for the spin-stabilized
Cosmic Background Explorer (COBE).

A brief historical account of the evolution of National Aeronautics
and Space Administration's (NASA's) tracking and data handling
facilities is first presented. Then follows a technical disserta-
tion on the requirements for Usat antenna systems which evolves
into a specific description of the basis of operation and implemen-
tation of the ESSA antenna. Interface data and requirements are
then covered. An in-depth description of the ESSA antenna devel-
oped for ERBS by Ball Brothers, Boulder, Colorado is included
as an appendix.

---

*Development and Building of subsequent flight units was by Ball
Aerospace Systems Division, Boulder, Colorado 80306

## HISTORICAL BACKGROUND

The success of all space missions has been based on the ability to gather data in space and to return these data to Earth-based NASA tracking and data acquisition stations. These stations, located in various parts of the Earth, underwent three distinct evolutions:

- Space Tracking and Data Acquisition Network (STADAN)--STADAN, completed in 1958, tracked unmanned spacecraft in Earth orbits from ground facilities that used sensitive receivers and powerful transmitters.

- Manned Spaceflight Network (MSFN)--During the Mercury, Gemini, and Apollo programs of the early 1960's, MSFN provided two-way contact between the ground, the sea, and space for the astronauts.

- Deep Space Network (DSN)--DSN, implemented in the early 1960's, used parabolic dish antennas at three Earth stations located approximately 120° longitude apart, to support NASA lunar and planetary missions. DSN continues to operate and to support planetary missions under Jet Propulsion Laboratory (JPL) management.

The Spaceflight Tracking and Data Network (STDN), which has been in operation from May 1971 to the era of the Tracking and Data

Relay Satellite (TDRS) System (TDRSS) Network, is a combination of the STADAN and the MSFN.

The Ground Spaceflight Tracking and Data Network (GSTDN) is composed of 14 fixed and portable land-based stations that provide direct support to NASA's Earth-orbiting scientific and applications spacecraft and manned spaceflight programs such as the Space Shuttle. The network operation and control and the associated central computing facility for operation and analysis are located at Goddard Space Flight Center (GSFC).

The most significant disadvantage of the STDN is the antennas which are bound to the Earth's surface and create a limited field of view (FOV). This limited FOV is caused by the antenna which transmits and receives signals only when a spacecraft is in view. Therefore, the average coverage a spacecraft may expect to receive from the tracking stations is limited to approximately 15 percent of its orbit.

The TDRSS Network, which is part of the new STDN, will substitute the space segment and one ground station for many of the ground stations within the STDN. Some ground stations such as Bermuda and Merritt Island will remain in operation to provide launch support.

2

## TDRSS NETWORK

It was determined that the GSTDN's limitations could be removed through a new network that used geostationary satellites rather than ground stations for tracking and communicating with user spacecraft. This network could provide coverage for almost the entire orbital period of a user spacecraft, support a number of spacecraft simultaneously, and have a high assurance of availability. Several NASA studies showed that this network was feasible by using state-of-the-art technology developed in the middle to late 1970's and by using the Applications Technology Satellite-6 (ATS-6) and the Nimbus-6 spacecraft as demonstration models. This research led to the development of the TDRSS Network.

The impact on the user spacecraft is the requirement for increased EIRP, higher-gain antennas, higher power transmitters, and more sensitive receivers.

## TDRSS NETWORK CAPABILITIES

The TDRSS Network consists of the TDRSS and a series of associated ground-based organizations. The Network Control Center (NCC), located at GSFC, manages the entire TDRSS Network. The NCC is linked with the NASA Ground Terminal (NGT) and collocates and interfaces with the TDRSS White Sands Ground Terminal (WSGT). Communications between the NGT, the NCC, and the users are through the NASA Communications Network (NASCOM), which is headquartered at GSFC. Other elements of the TDRSS Network include certain Earth stations that are needed during the launch and transfer orbit phases of user spacecraft. GSFC is responsible for developing, operating, and managing the TDRSS Network.

The TDRSS Network provides adequate performance margins, operational flexibility, and high reliability for supporting projected Space Shuttle payloads and free-flying spacecraft during the 1980's. The TDRS, which does not perform signal processing, acts as a bent-pipe repeater that relays signals or data between the user spacecraft and the ground terminal. The space segment is simply designed and highly reliable. The TDRSS Network has three primary capabilities:

- Tracking--The TDRSS Network determines the precise location of orbiting user spacecraft by measuring range (distance) and range rate (velocity) with respect to the TDRS's.

- Telemetry and Data--Each user spacecraft transmits telemetry signals that indicate certain operational parameters (e.g., power level and temperature). The spacecraft also transmits data signals that correspond to the scientific or applications information collected by the spacecraft instruments. The telemetry and data signals are relayed by the TDRS's from the user spacecraft to the WSGT for use by GSFC and the user community.

3

- Command—The WSGT, which sends commmand signals through the TDRS's to user spacecraft, orders the spacecraft to perform certain functions such as aim a camera and fire a thruster. The commands are originated by GSFC or Johnson Space Center (JSC) for unmanned and manned spacecraft, respectively.

To relay large amounts of scientific data from the Space Shuttle or investigatory spacecraft the Network provides:

- Simultaneous service to multiple spacecraft and support for the scientific user community.

- Accurate orbit determination for placement and position of user spacecraft, including determination of the range (distance of the user spacecraft from the relay satellite and ultimately from the ground terminal) and the range rate (velocity at which the user spacecraft is moving).

- Single-access service or multiple-access service, offering options to user spacecraft for radio frequencies (RF's), bandwidths, and rates of data transmission between the spacecraft and the TDRS's.

- Forward-link service provides an uplink from the WSGT to the TDRS and a downlink to the user spacecraft for commands. These links pass through either the multiple access S-band RF or the single access S-band and Ku-band RF's.

- Return-link service provides an uplink from the user spacecraft to the TDRS and a downlink to the WSGT for telemetry and data. Up to 20 links are available on the multiple-access RF.

- Pseudorandom noise (PN) coding applies to data streams that are used for transmission and some reception. PN coding, which is primarily used for meeting Earth flux density regulations, provides security from interception and protection against additive noise disturbances. For example, telemetry data generated by the user spacecraft are transmitted in a data stream with PN coding to the TDRS at S-band RF. The TDRS transmits these data to the WSGT through the Ku- band return link. When the data reach the ground station, an algorithm (i.e., a mathematical procedure) is applied to decode the data. The data are then sent to the user by NASCOM.

TDRS OPERATIONS

The TDRS's, which operate from geostationary orbits, are used for tracking and data transfer to allow a greater FOV. To achieve cost savings by using only one ground station and two relay satellites, it is necessary to locate the satellites at certain fixed positions relative to the ground station. This configuration,

however, has an undesired result: the Earth blocks either relay
satellite from viewing the user spacecraft for a portion of the
spacecraft's orbit. This blockage, which specifically applies
to user spacecraft with orbital heights of less than 1200 km,
may extend to 15 percent of the orbit. The blockage occurs over
the Indian Ocean and is termed the Zone of Exclusion (ZOE). A
spacecraft that orbits above 1200 km receives 100-percent cover-
age from the TDRSS Network.

The TDRSS Network provides bent-pipe communications links from
user spacecraft to relay satellite to ground station and vice
versa. This state-of-the-art telecommunications service is based
on a successful experiment that involved the ATS-6 and the Nimbus-6
spacecraft during the mid 1970's. The ATS-6's Tracking and Data
Relay Experiment demonstrated that the Earth orbiting Nimbus-6
could be commanded from a ground station by the ATS-6 Earth-
synchronous satellite. Data generated on board the Nimbus-6 were
sent back to the ATS-6 and were relayed at the ATS-6 to the
ground. In addition, the range and range-rate measurements of
the Nimbus-6 through the ATS-6 determined the relative distance
and velocity of the two spacecraft. These measurements were then
compared with similar direct measurements made by the ground sta-
tion.

## PERFORMANCE CONSIDERATIONS

### IMPACTS OF ANTENNA SYSTEM PERFORMANCE ON ACHIEVABLE DATA RATE

Reliable TDRSS link performance at the desired data rate depends
on how well a Usat antenna system performs. Users using TDRSS
S-band return-link service at low- to medium-data rates require
an antenna with moderate gain. Although the beamwidths associated
with these moderate-gain antennas are greater than 10°, some method
for steering the beam must be provided. In the range of interest,
the pointing accuracy requirements are modest. The ESSA antenna
can provide the user with the requisite beam steering free of
the problems associated with torque noise induced into the space-
craft that are often associated with mechanically steered (gim-
balled) antenna systems.

ESSA antenna system performance is principally directed toward
TDRSS return-link service performance because the antenna gains
required for low- to medium-data rate return-link service are
usually greater than those required for forward-link command data
rates.

### TRADEOFFS BETWEEN ANTENNA GAIN AND TRANSMITTER POWER

Usat antenna system performance for the TDRSS return-link services
is a key factor in maintaining and pointing the required EIRP
toward a TDRS for achieving the desired data rate at an acceptable
bit-error rate (BER) under dynamic tracking conditions. The EIRP
is the sum (in dB units) of the antenna RF gain and the transmitter

5

power available at the antenna input port (transmitter power less
RF transmission line and network losses). Once the required EIRP
has been estimated by the methods described in the section "Relat-
ing Required Antenna Gain and Transmitter Power to Achievable Data
Rate," an important tradeoff between transmitter power and antenna
gain occurs. This tradeoff process is impacted by numerous con-
siderations such as:

- Primary power requirements

- Weight and moment

- Achievable steering angles

- Transmitter power amplifier (PA) location with respect
  to the antenna as it impacts moment and RF transmission
  line losses

- Antenna minor-lobe performance and transmitter power impact
  on flux density limits

- State-of-the-art limitations on achievable transmitter
  power with high reliability

The highest available nominal power output of the NASA GSTDN/TDRSS
transponder, which operates at S band, is 5 W (7 dBw). At present,
solid-state high efficiency S-band PA's, which may be inserted
between the transponder and the antenna, are in the final stages
of advanced development. These amplifiers are rated in the 10
to 30 W (10 to 14.8 dBw) range. Less efficient PA's have been
used on previous ·missions.

RELATING REQUIRED ANTENNA GAIN AND TRANSMITTER POWER TO ACHIEVABLE
DATA RATE

User operations with TDRSS are detailed in the "Tracking and Data
Relay Satellite System (TDRSS) Users' Guide," (STDN 101.2) here-
after referred to as the Users' Guide. The Users' Guide contains
the methods used for determining Usat/TDRSS forward- and return-
link performance. Important Usat parameters are the receiver
system antenna gain/temperature (G/T) ratio as it affects forward-
link performance and the EIRP as it determines the return-link
performance. The Users' Guide includes example link calculations
that provide a convenient checklist of particulars such as loss
items which usually need to be considered. GSFC Code 800 provides
a computerized end-to-end simulation and analysis called the Com-
munications Link Analysis and Simulation System (CLASS) which
analyzes Usat/TDRSS performance.

Figure 1 is an example of TDRSS S-band forward-link Usat ESSA
gain requirements versus command data rate. Figure 2, which is
similar to Figure 1, is an example of ESSA gain requirements versus

Figure 1. Example of TDRSS Forward Link Service User ESSA Directional Antenna Gain Versus Command Data Rate
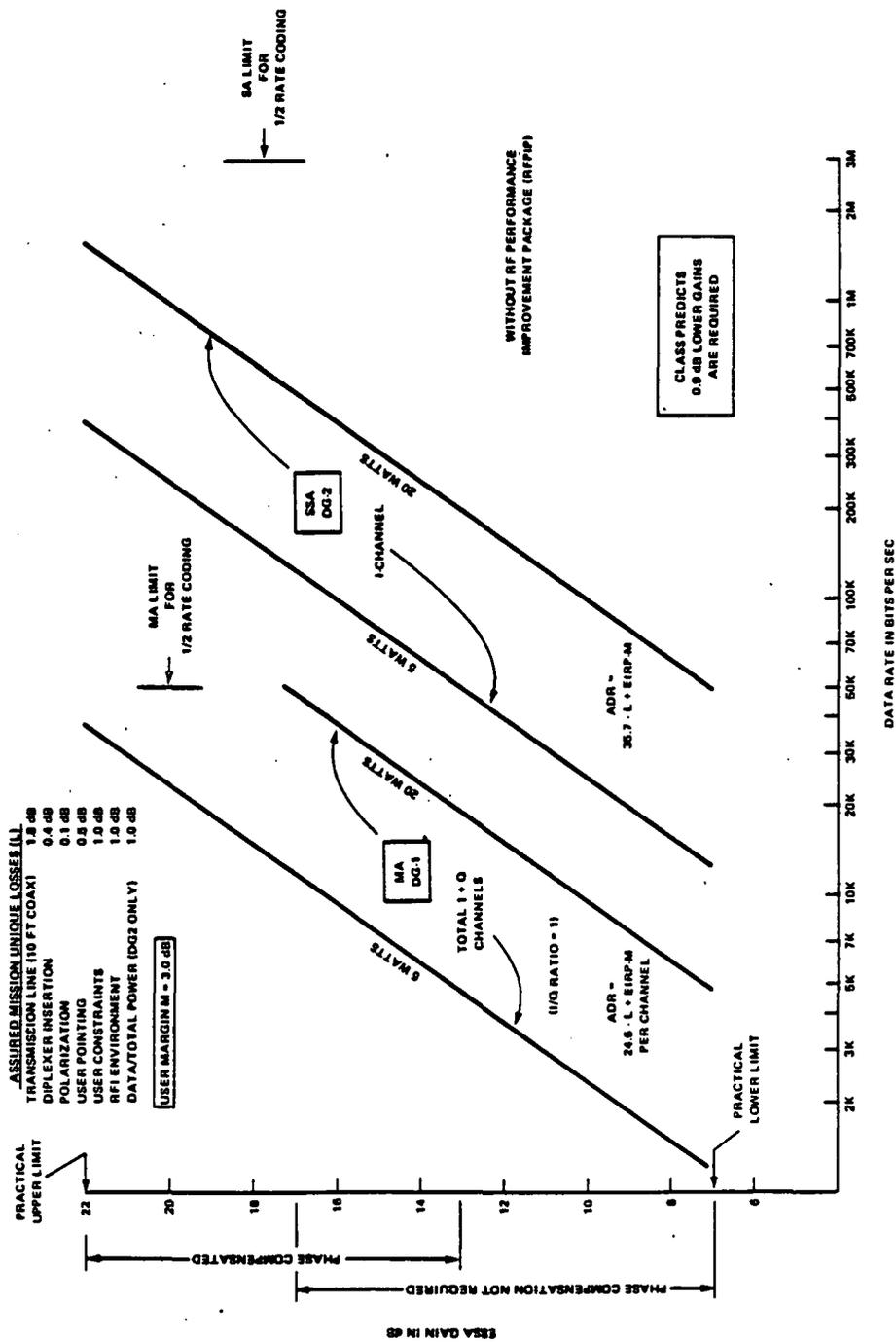
Figure 2. Example TDRSS Forward Link Service User
ESSA Directional Antenna Gain Versus Return-Link Data Rate

8

return-link data rate* as determined by CLASS. In these examples 10 feet of coaxial cable has been used to connect the transponder with the ESSA antenna.

These figures also indicate other assumed system parameters. The practical range in gain of S-band ESSA antennas is considered to be 7 to 22 dB.

Figure 1 shows that in MA forward-link service an ESSA gain of about 7 and 10 dB is required, respectively to support 1 and 2 Kbps command data rates using a single transponder at a time (configuration A). When the user desires that the command signal be simultaneously available to both transponders (configuration B), the ESSA gain required is approximately 3 dB greater (i.e., 10 and 13 dB). Use of the ESSA antenna for S-band single access (SSA) forward-link service results in a capability that substantially exceeds normal command rates currently used.

Figure 2 shows that when a 20-W transmitter is used, a 17-dB gain ESSA is required for the 50 Kbps upper limit in multiple access (MA) return-link service. This antenna could support a 500-Kbps link in single access return service. To support a 3 Mbps SSA return link (the upper limit), the antenna gain required (on the order of 25 dB) is beyond the practical limit for ESSA antennas.

A 7-dB ESSA can accommodate a 1 Kbps MA return link and a 5 Kbps return link with a 5 W and a 20 W transmitter, respectively.

The section "RF Performance Improvement Package (RFPIP)," discusses the performance advantage of moving the receiver preamplifier and the transmitter PA directly to the ESSA antenna port.

ANTENNA SYSTEM RF PERFORMANCE

The practical achievable gain of conventional electromechanically steered parabolic disk S-band antennas is limited by geometric optic considerations to a minimum of 21 dB. Steerable planar arrays can be designed for less gain but at the risk of induced torque-noise problems. The ESSA, which offers an important choice of antenna system in the 7 to 22 dB directional gain range for Usat return-link low- to medium-data rates, does not induce torque, momentum, or torque noise into the spacecraft.

Directional radiated transmit beams and receive beams can be formed throughout a practical limit of 300° total cone angle. PA's up to 30 W and a low-noise receiver preamp may be incorporated within the ESSA package. Figure 3 shows that ESSA applications can be

---

*Appropriate dB adjustments have been included to reflect the difference between the CLASS analysis performed by GSFC Code 800 and the example parameters used in Figures 1 and 2.

GPS

TDRS
WEST

EARTH

TDRS
EAST
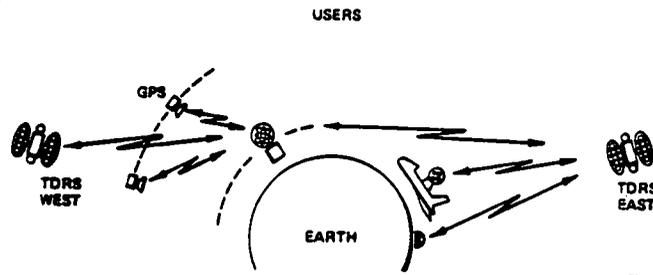
Figure 3. ESSA Applications

used for multiple types of spacecraft or for ground applications.
This figure implies that other antenna systems can be integrated
into or onto the ESSA for purposes other than NASA data links.

Appendix A includes a description of the ESSA system performance
as built and qualified for the Earth Radiation Background Experi-
ment. The following brief overview details how performance require-
ments are set:

- The mission defined science data rate is established.

- The onboard data handling data-link components and the
  TDRSS capability, schedule, cost, and performance tradeoffs
  (i.e., recorder rates, transmit RF power, antenna gains,
  receiver sensitivities, command data rates, and TDRS availa-
  bility) are performed.

- The component specifications including coverage gain and
  ESSA controller interface requirements are prepared.

ESSA antenna gain is primarily a function of antenna size (diam-
eter). For very large spacecraft, coverage is usually limited
to a hemisphere ($2\pi$ steradians) by the spacecraft blocking the
radiated beam. Because the blockage problem is not as severe
for smaller spacecraft, the coverage area can be up to a 300°
cone angle practical limit. Coverage is limited by the direc-
tion in which the -10 dB beam edge impinges on the spacecraft
and on the solar arrays.

Within the coverage region, single, multiple beam or omni modes
of operation can be implemented as shown in Figure 4. The highest
gain achievable is for single beam operation. With multibeam
operation the gain of each beam is reduced in proportion to the
number of beams. In the omni mode, the gain is likely to be -2
or -3 dB and the coverage achievable varies with the size of the
antenna, the configuration, and the number of element sets being
optimized for each size antenna. (A 7 dB ESSA provides good omni
coverage, whereas a 13 dB ESSA has to use a rapidly switched pair

of cloverleaf patterns for the transponder receiver to achieve
lock condition on the forward-link signal throughout the coverage
region.)
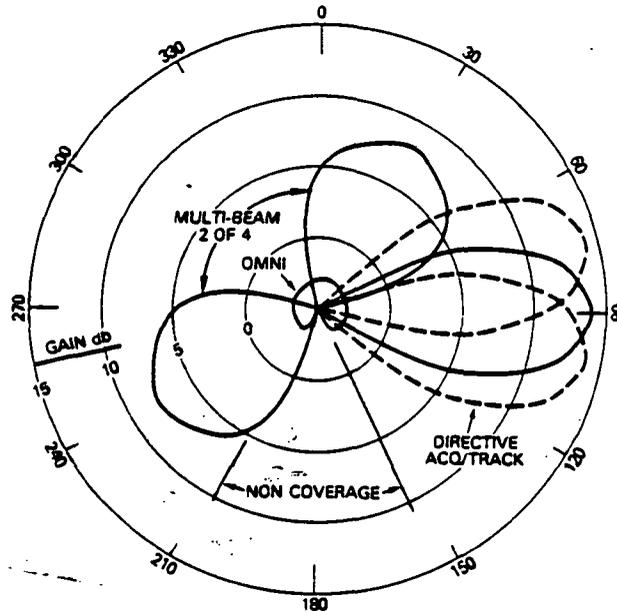


Figure 4.  ESSA Multimode


## ANTENNA SYSTEM FUNCTIONAL DESCRIPTION

The ESSA antenna can form beams of nearly constant gain throughout
the coverage region.  The antenna described in Appendix A has
1807 unique beams to cover a hemispherical region.  Figure 5 is
a functional diagram of the antenna system which consists of RF
components, a microprocessor, and the switch drivers.

The overall RF system consists of the antenna system, and a space-
craft RF network that connects the antenna system to two redundant
transponders.  The antenna system includes RF power amplifiers,
preamplifiers, switches, and diplexers--if these components are
required at or within the antenna by the systems tradeoff analyses.
The antenna input is connected to a switching power divider (SPD)
that connects the input to the $\eta$ outputs.  For single beam opera-
tion, $\eta$ radiating elements that are connected in a cluster form
the antenna aperture to produce the desired gain in the desired
direction.  The microprocessor and the switch drivers cause the
appropriate elements to be switched on and off.  $\eta$  is a unique
number optimized for a given antenna size.  Other antennas can
be integrated into the ESSA if no more than one or two elements
of a cluster are replaced; the removal or nonuse (failure) of
an element in a cluster does not significantly degrade perform-
ance.
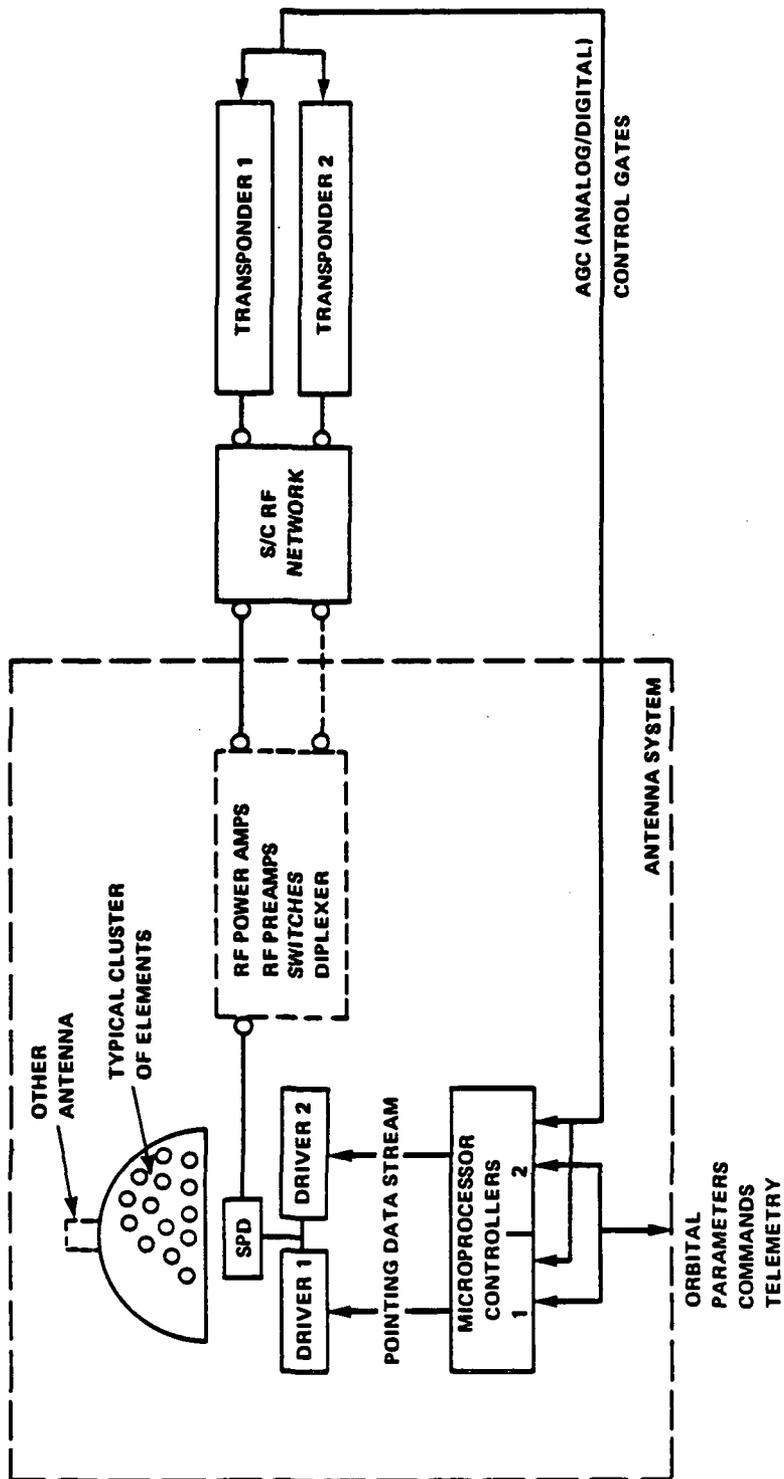
Figure 5. Antenna System Functional Diagram

When a beam is directed toward the Earth with the power amplifier activated, the resulting EIRP must be limited in accordance with Figure 6.

ELEMENT SELECTION PROCESS

For single beam operation, the number of active elements in a cluster is a unique, fixed number that increases with the desired gain. As the desired gain increases, the size of the ESSA also increases to accommodate the necessary elements within a cluster on the curved surface within established displacement limits from a tangent plane. Therefore, the ESSA size and the number of elements increase with design gain. With phase correction of the element driving currents, more elements per cluster can be used for a given size ESSA. This topic is discussed in more detail in the section "Antenna RF Detailed Performance."

The section, "Antenna System RF Performance," discusses how the ESSA can be implemented for single beam, multibeam, or omnidirection coverage. Operating modes that can be implemented are:

- Directional beam
- Program track
- Retrodirective
- Special

The spherical coordinates of the ESSA antenna ($\theta$, $\phi$) are defined as: $\theta$, the angle from the center line of symmetry of the antenna at the end opposite the truncation sometimes referred to as the zenith or the pole, and $\phi$, the angle in the equatorial plane calculated in accordance with the right-hand rule about the zenith from some fixed point. Figure 7 is an example of the COBE ESSA coordinates. Once the coordinates are established and the location of the elements are defined according to these coordinates, the microprocessor outputs a serial-data stream to the driver registers and turns on the appropriate PIN diode switch drivers that close the microwave path to the desired radiating elements. The following paragraph gives an overview of the microprocessor's function for each of the operating modes from most simple to most complex.

Directional Beam--The desired directional beam-pointing angles ($\theta$, $\phi$) (with a granularity commensurate with the beam-pattern characteristics, usually within a few tenths of a dB of a beam peak) are inputted to the processor. The processor determines the best set of $\eta$ elements to form this directional beam in the desired direction and outputs the data to the driver electronics. (See Appendix A for typical pattern crossover information.) The Figure 7. Enlarge Bottom View of COBE Observatory and Coordinates beam of the antenna is formed and has a gain equal to or greater than the designed gain.
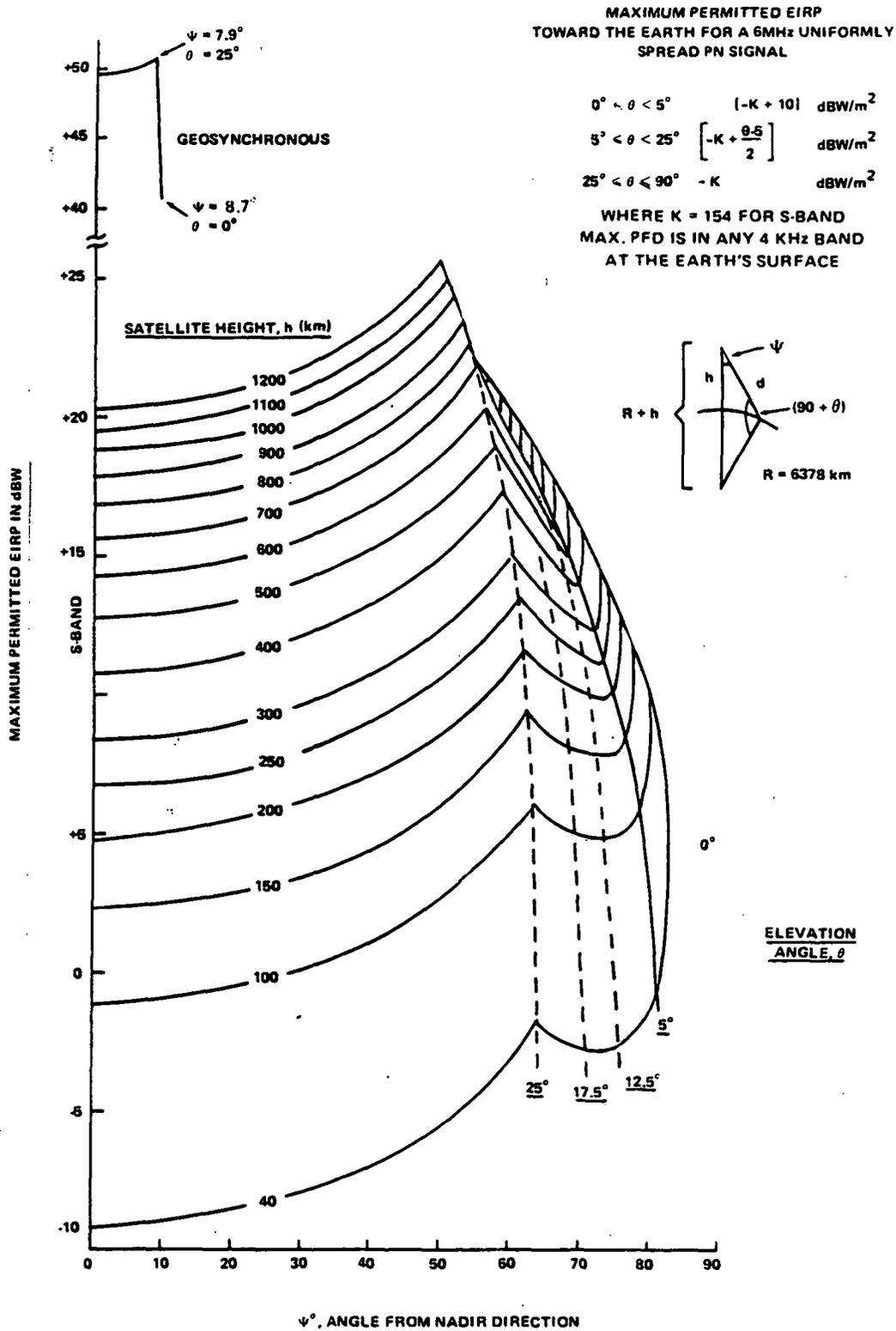
Figure 6. Maximum Permitted EIRP Toward the Earth for a 6 MHz
Uniformly Spread PN Signal

14

TOP DECK

SPIN DIRECTION
(COUNTER CLOCKWISE
ABOUT +X AXIS)

PITCH BACK IN XY PLANE
FROM −X AXIS TOWARD −Y

+Z LOCATION FOR DLA

SUN SENSORS FOR DLA
(IN SPIN PLANE)
3 PLCS.

+Z

+X (DOWN)

+Y

TRANSPONDERS

ESSA CONTROLLER

VENT TUBE

ESSA HARNESS

DLA STRUCTURE

(ELECTRONIC
SWITCHING
SPHERICAL ARRAY)

RF COAX

OMNI/VENT
TUBE

φ = 0
+Z

φ = 90

SPIN DIRECTION
φ

θ = 0

θ = 90 +Y
φ = 270

θ

φ = 180

−SPIN AXIS (+X)
ANTENNA CENTERLINE

ANTENNA COORDINATES

Figure 7. Enlarged Bottom View of COBE Observatory and Coordinates

15

Program Track--The program track mode uses uplinked ephemeris
data obtained from space tracking the user spacecraft and the
data relay satellite (and attitude data if not acquired from on
board the user spacecraft.) The microprocessor calculates the
direction to the TDRS's (east and west) in a local nonrotating
coordinate reference frame. The following summary details how
the processor determines the pointing for the COBE spacecraft.

COMPUTING TDRS POINTING DIRECTIONS FOR THE ESSA/ERBS AND ESSA/COBE
SATELLITES

The pointing direction to the synchronous TDRS satellite is com-
puted for low-Earth orbiting ESSA/ERBS (nonrotating) using five
coordinate rotations to bring the TDRS pointing vector into local
satellite coordinates. The TDRS direction is first defined in
a geocentered coordinate system that has its Z axis along the
TDRS orbit normal and the X axis pointing at TDRS. A coordinate
rotation brings the X axis into the equatorial plane followed by
a rotation around the new X axis (through the TDRS orbit inclina-
tion) to position both the new X axis and the Y axis in the equa-
torial plane. A rotation around the Earth polar axis brings the
new X axis onto the satellite orbit's ascending node. A rotation
around the X axis brings a new Y axis into the orbit plane. The
final rotation is then made in the orbit plane to bring the X
axis onto the satellite position vector. The coordinate system
is then translated from the center of the Earth to the satellite.
The pointing direction to TDRS is now explicitly defined because
the antenna pole is always along the local vertical and another
antenna orthogonal axis is always along the velocity vector.

The ESSA/COBE rotating TDRS pointing direction is computed in a
very similar manner. First, the Sun direction is defined in satel-
lite local coordinates using the procedure previously described,
with the Sun's ecliptic plane angle and the ecliptic plane inclina-
tion from the equatorial plane substituted for the TDRS equivalent
angles. The coordinate system is not translated because the dis-
tance from the center of the Earth to COBE is trivial compared
to the distance from COBE to the Sun. A sixth rotation angle is
computed for a rotation about the velocity vector to place the
X axis 94° from the Sun and to define the Sun direction in non-
rotating satellite coordinates. The TDRS vector is brought through
the same five rotations and the coordinate transformation that
was previously described for ERBS. This vector, which is also
brought through the sixth rotation previously described, defines
the TDRS vector in COBE nonrotating coordinates. Knowledge of
the Sun direction and the TDRS direction in this common reference
frame allows a Sun pulse to periodically reset the spin plane
angle ($\phi$). The spin angle is extrapolated using a 250-ms pulse
from the COBE spacecraft and self-derived knowledge of the spin
rate. The angle $\theta$ from the pole of the antenna to TDRS is explicit-
ly defined by the TDRS vector.

Details of how rotations are performed and all angle definitions are considered unnecessary, because implementation and orbit conditions are usually user unique. Therefore, the software is expected to require some modification for each user. Specific users should consult the appropriate spacecraft project. The following list is an example of the preliminary list of the COBE ephemeris parameters that are to be uplinked for antenna beam pointing to the TDRS:

- UM--Orbit plane angle for the COBE spacecraft

- UMTW--Orbit plane angle for TDRS west

- UMTE--Orbit plane angle for TDRS east

- UMS--Ecliptic plane angle from the vernal equinox to the Sun

- RHOC--Angle from the vernal equinox to the COBE orbit ascending node

- RHOW--Angle from vernal equinox to the TDRS orbit ascending node

- RORATE--Rate of change of the COBE orbit node

- UMRATE--UM rate of change

- AI--Orbit inclination of COBE orbit

- AITW--Orbit inclination of the TDRS west orbit

- AITE--Orbit inclination of the TDRS east orbit

- ***--(The inclination of the apparent Sun's orbit is a constant)

- SELTDR--Flag for selecting east/west TDRS

These calculations, which are performed every 15 s with the exception of adding $\Delta\phi$ for rotation every 250 ms, are outputted to the drivers for updating the PIN switches. An estimate of pointing error for the 1 rpm COBE is $\pm0.27°$ during a 20-min eclipse (no Sun pulse).

Other pointing errors for a COBE-like antenna are beam granularity $\pm2.2°$, long-term track $\pm1°$ (2-day period), spin angle drift during one spin update $\pm0.75°$, and antenna mechanical misalignment $\pm0.5°$. All of these errors would not cause the coverage gain to change.

## Retrodirective

In the retrodirective mode, the microprocessor processes receive signal level changes from the transponder receiver. This receiver's input signals levels are a function of the antenna element set conditions as controlled by the processor. When the signal level difference sets are programmed into the microprocessor memory, and the timing between the receiver (to perform its functions) and the processor are properly gated (to perform independently), the receive signal direction of arrival (DOA) in ($\theta$, $\phi$) can be determined and the set of elements that produce the highest antenna gain in the DOA direction are switched on. Figure 8 shows the sequence of events between the transponder and the 13 dB gain size ESSA with respresentative function time allocations. Because other ESSA sizes may have slightly different patterns for the omni mode (described in the section on "Antenna Performance)", the initial sequence may be different. For the 13 dB gain ESSA the sequences are as follows:

a. The antenna is being switched at a 200-Hz rate between two sets of element conditions that effect an omni type low-gain coverage. This switching continues until a signal is present and a PN lock of the transponder occurs. This process may take as long as 20 s for very low RF signal levels.

b. The set of elements that results in the strongest signal is selected and remains in this condition until the carrier is acquired by the transponder.

c. Sets of elements are then sequenced to cover the coverage region to determine the set that results in the strongest signal. To coarsely determine the direction of arrival (DOA), alternately switching between the best omni set and the different sets may be necessary.
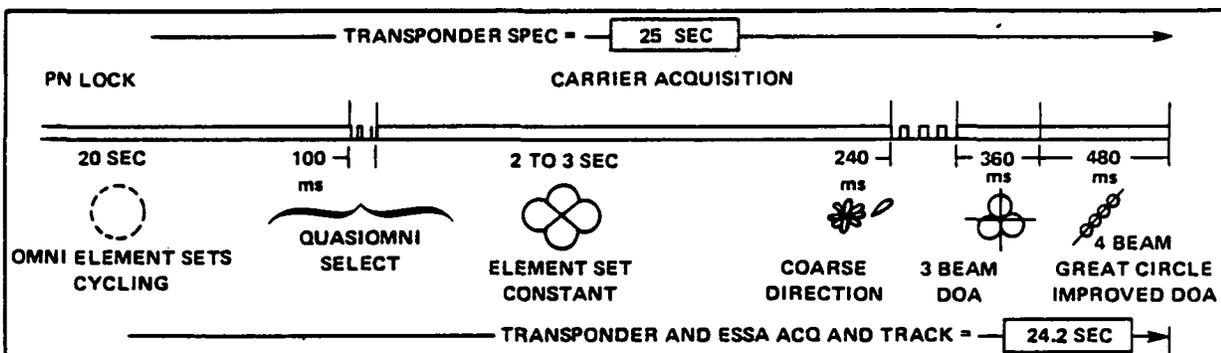


Figure 8.   Timing Diagram Example

18

d. Three new sets are sequenced or may be included in the best coarse set about the center of the coarse set look angle. These sets establish the location within the coarse DOA beam, which is usually repeated three or more times to obtain a statistical sample. A new beam is then formed at this new DOA.

e. To determine a more precise DOA, four new beams are formed on a line through the new DOA angle and the coarse angle. These beams are formed a number of times to achieve an accurate DOA.

The increased acquisition time for the ESSA DOA process is 5 s, increasing the total acquisition time to approximately 25 s maximum for three-axis stabilized satellites.

The time is slightly longer for spin-stabilized spacecraft, because the processor has to establish spin rate and direction. If these variables are known, the processor "looks ahead" in $\phi$ and the acquisition time is roughly that of the three-axis satellite.

COBE and ERBS do not use the retrodirective feature.

Special

Some of the special modes are:

● Omni-fixed mode--In the omni-fixed mode, switches are set at one condition for receiving commands or for transmitting low data rate telemetry. The conditions for best omni fixed mode are believed to be antenna-size dependent.

● Multibeam mode--In the multibeam mode, switches are set so that two or more beams are simultaneously formed in two or more directions. The coverage gain decreases in inverse proportion to the number of beams (i.e., for two beams equal, one half the gain (a 3-dB decrease) with correspondingly increased beam widths). This mode could be programmed to track both east and west TDRS's simultaneously.

ANTENNA DETAILED RF PERFORMANCE

The ESSA antenna owes its unique characteristics to the geometry of its design. This design, which may use clusters of antenna elements located on a spherical surface, has both advantages and disadvantages. The obvious advantage is that the ESSA antenna can scan over a large coverage region with little change in beam width or gain. One disadvantage is that the curvature of the sphere causes a phase change across the aperture. (See Figure 9.) When this phase change approaches 180°, destructive interference is set up which reduces the gain. Phase compensation for the elements will eliminate this effect but at the expense of adding complexity to the system. Another limitation is that

DESIRED
POINTING
DIRECTION

X$^\theta$ RADIUS

PLANAR WAVE

Δφ

SPERICAL WAVE
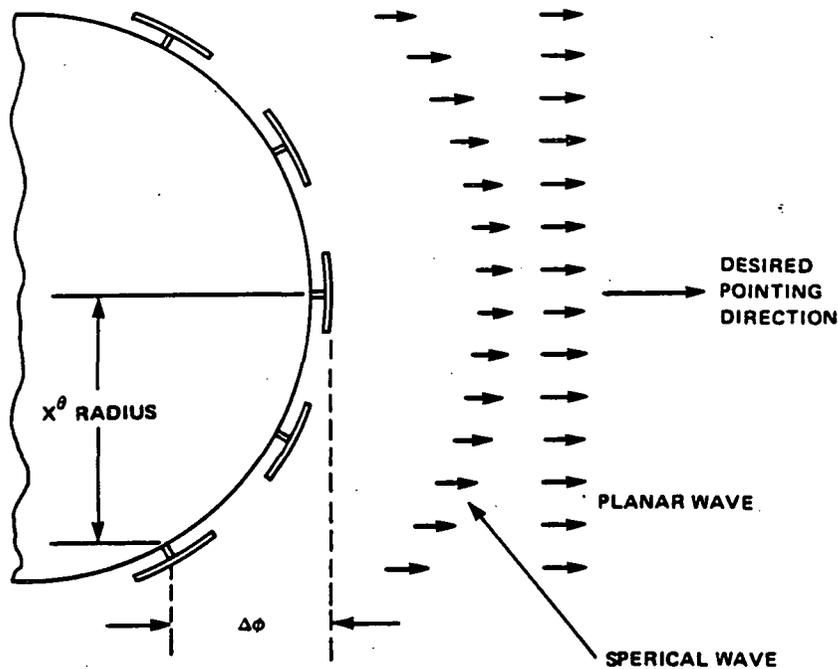
**Figure 9. Phase Delta Limits Element Cluster Diameter**

the cluster-edge elements produce pattern maxima which do not point along the desired pointing direction, thus broadening the beam and limiting the peak gain.

Because of these factors, the ESSA antenna peak gain and the number of active elements used to achieve this gain are directly related to the size of the ground plane sphere. By using icosahedron geometry and element-to-element spacing held to within the 0.65 to 0.75 $\lambda$ range, all ESSA beams are made to have virtually the same gain.

The coverage region is determined by the extent of the sphere's coverage by elements. For a beam to be formed in a given direction, elements must exist within an X° radius of the desired pointing direction. Therefore, the sphere's coverage by elements must be larger than its actual pointing angle. Table 1 lists the total number of elements required for cone half-angle coverage of 82° and 90° for various sizes of compensated and noncompensated ESSA's.

Table 2 shows the number of elements used in a typical element clusters.

Figure 10 is a comprehensive plot of gain versus diameter for both phase compensated and noncompensated element sets. To relate to Tables 1 and 2, the diameter, which is in wavelengths, must be multiplied by the wavelength of 2.287 GHz (ERBS and COBE return-link frequency).

20

Table 1
Total Number of Elements for Various Diameter
S-Band ESSA's

| Diameter (in) | Cone Half-Angle Coverage (deg) | Total Number of Elements Noncompensated | Total Number of Elements φ Compensated |
|---|---|---|---|
| 10 | 82 | 25 | -- |
| | 90 | 25 | -- |
| 15 | 82 | 31 | 36 |
| | 90 | 36 | 36 |
| 20 | 82 | 61 | 76 |
| | 90 | 76 | 81 |
| 25 | 82 | 111 | 136 |
| | 90 | 116 | 146 |
| 30 | 82 | 145 | 181 |
| | 90 | 151 | 206 |
| 35 | 82 | 220 | 250 |
| | 90 | 250 | 280 |
| 40 | 82 | 226 | 266 |
| | 90 | 256 | 291 |
| 80 | 82 | 970 | 1250 |
| | 90 | 1100 | 1370 |

## Antenna Beams

The unique construction of the ESSA antennas combined with the microprocessor controlled switching power divider produces a feasible number of useful variations in performance.

The directional beam mode has already been described with a high gain beam instantly formed in any desired coverage direction. In addition, the microprocessor will allow either two or more beams to be formed simultaneously or a selected pattern of elements, spread over the entire surface, to be turned on to produce omni-directional coverage.

The antenna elements are circularly polarized (IEEE left-hand circular (LHC) for TDRS operation) with a axial ratio of < 3 dB maintained over the peak of the beam. Figure 11 is helpful in establishing total system loss when operating with the specified TDRS antenna axial ratio.

21

Table 2
Required Number of Cluster Elements
for Various Diameter ESSA's

| Sphere Diameter (in) | No Phase Compensation | 2 Bit or Full Phase Compensation |
|---|---|---|
| 10 | 5 | -- |
| 15 | 6 | 6 |
| 20 | 6 | 11 |
| 25 | 11 | 16 |
| 30 | 12 | 26 |
| 35 | 16 | 35 |
| 40 | 16 | 36 |
| 80 | 17 | -- |
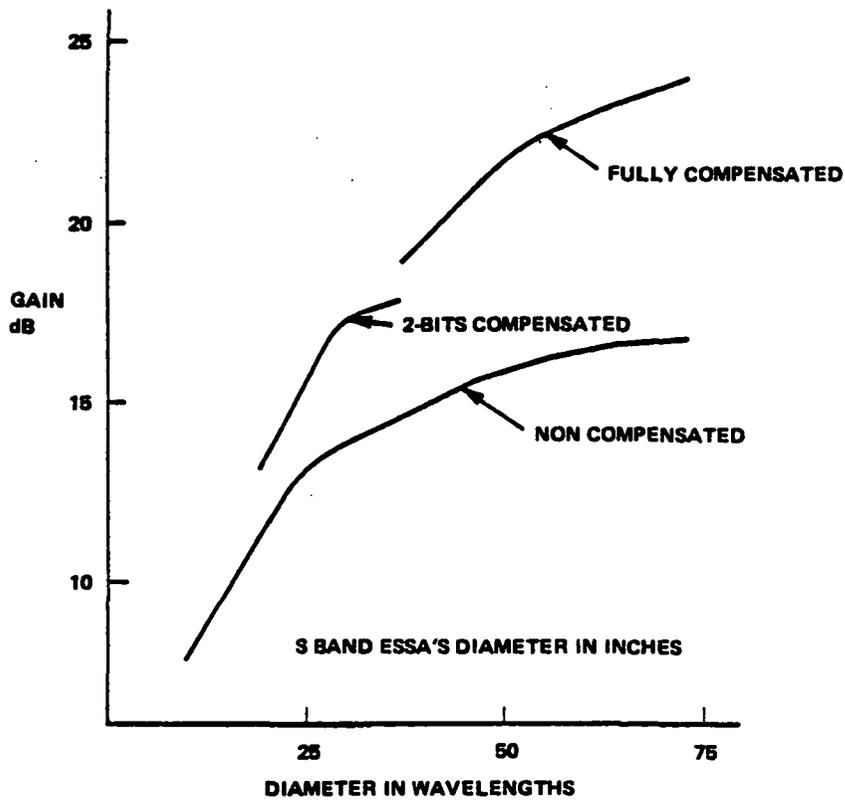


Figure 10.  ESSA Gain Versus Diameter

22

Power Handling Capability--The power handling characteristics of the S-Band ESSA's are designed to be compatible with currently available transponders and power amplifiers (2-1/2 to 30 W). Future models of transponders and power amplifiers are expected to have outputs in this range. The smaller ESSA's with four active elements have been tested with 10 W input power. The COBE 30-inch ESSA with 12 active elements has been tested with 30 W input power.

Voltage Standing Wave Ratio and Input Impedance--The voltage standing wave ratio (VSWR) is < 2:1 over the range of use with lower VSWR at the transmit frequency. The RF input impedance is 50-$\Omega$ nominal.
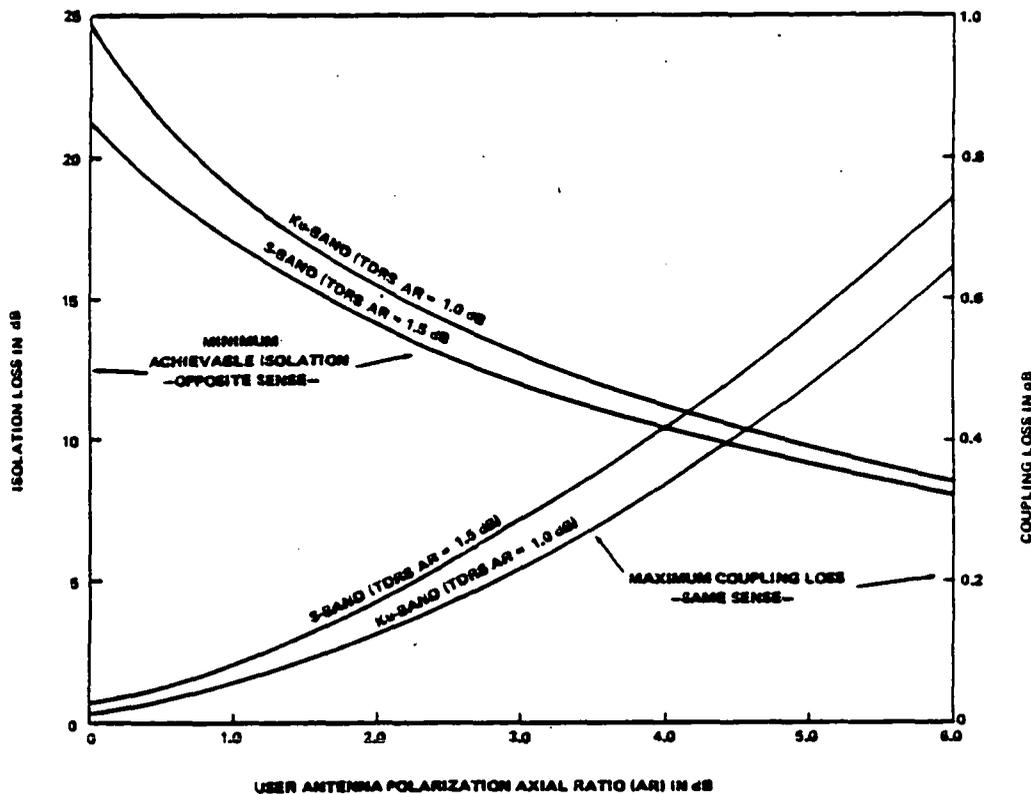


Figure 11. User/TDRS Elliptical Polarization Isolation and Coupling Losses

IMPLEMENTATION

General

The ESSA antenna may be designed in a variety of physical configurations. Spherical or cylindrical radii can be selected with different surface areas to effect the following shapes: truncated spheres, hemispheres, and long or short, full or partial cylinders. The only requirement of these radii is surface symmetry, which ensures that the transmission paths from the single input to each of the radiating elements are equal. The ESSA approach can be

implemented in the microwave frequency range from a few hundred MHz up to 15 GHz.

The highest achievable frequency, 15 GHz, is limited by the practical fabrication and assembly of the transmission RF components. Usually, ESSA antennas are mounted onto masts that can be folded or erected to deploy the antennas away from the spacecraft so that the maximum coverage can be achieved. Microwave power amplifiers, preamplifiers, diplexers, filters, and RF switches can be either integrated into or located nearby the ESSA antenna for optimizing the RF design in conjunction with other spacecraft design considerations. (See the "Interface" section.) Usually, the microprocessor and the transponders are located within the spacecraft body, because the cables connecting to the antenna are not of a critical nature.

The ESSA antenna can accommodate the integration of other antennas and experiment apertures onto it. An ESSA's antenna beam performance is not seriously degraded in the coverage region if the removal or the failure of one or two radiating elements or switches occurs.

The ESSA antenna includes redundant dual drivers, processors, and associated power supplies that are used to turn the switches on or off.

LOCATION/COORDINATES/ALIGNMENT

During the early phases of a spacecraft project, a primary activity is selecting a location for the antenna system. Usually, the antenna must be deployed away from the spacecraft body to achieve the requisite large coverage region (greater than $2\pi$ steradians). This location will tend to minimize significant electrical interference with parts or appendages of the spacecraft. The antenna's beam should never be directed toward parts of the spacecraft, because this action would cause degradation of ESSA RF performance and/or possible degradation of spacecraft components caused by the impingement of the high RF field.

Because the coverage region is typically a hemisphere or greater, the location should be on the side of the spacecraft that views either or both of the data relay satellites most frequently. Data relay satellite access time for these desired locations should be established in early planning phases to ensure adequate contact time and to ensure that onboard communications and data-handling subsystems are not seriously impacted and are of a practical design.

Once the ESSA location is determined, both the antenna coordinates relative to the spacecraft and the alignment accuracies of these sets of coordinates must be defined. Stiffness and accuracy requirements of the deployment boom or mast must be determined, because alignment errors of antenna to mast and mast to spacecraft

must be identified. The usual method for determining these alignment errors and perturbations is to control manufacturing tolerances and measurements using optical cubes or other means depending on the alignment tolerances required.

## OPERATION

To meet launch environmental and safety requirements, the usual antenna configuration that evolves must be caged to the spacecraft body during launch operations. Once the spacecraft is at or near final orbit and the spacecraft attitude becomes stabilized, the antenna is uncaged, deployed from the spacecraft, operationally validated, and routinely operated to meet mission data acquisition requirements. The caging points and design are expected to be unique and the holding and release methods will have to be proven.

## LIFETIME

The antenna system is designed to reliably operate, assuming a 50-percent duty cycle ("on/off") of continuous operation, during the total lifetime of the space mission and the test and storage periods before launch. A design margin of two or more lifetimes is used.

## SINGLE-POINT FAILURES

Single-point failures are minimized in accordance with good spacecraft design practices. ESSA electronic functions are redundant. Deployable boom or masts and the actual antenna are nonredundant. From the perspective of cost and complexity a completely separate ESSA with electronic cross strapping is the best approach if the antenna is to be redundant. The best location for a redundant antenna is on the opposite side of the spacecraft, and when both antennas are operational the coverage is nearly $4\pi$ steradians.

## TEST REQUIREMENTS

Tests are performed to ensure the following:

- Adequacy of the functional performance requirements

- Capability to withstand environmental conditions

- Life expectancy

- Unit performance during preintegration, postintegration, and prelaunch activities

The project will determine the amount of testing for the antenna system and components and the extent of modifying or designing additions to the antenna system. To define the extent of required testing, previous testing and test levels should be compared. It should be emphasized that if this system does not function the

mission will probably be degraded because of a lack of scientific data for medium data missions or a reduction of high to low command and telemetry data rates.

Testing that can be performed after integration onto a spacecraft is limited to operability--not capability. Some operability testing require special tools that allow for monitoring the antenna and for ensuring that the proper switching has occurred and that the selected elements are radiating. Ground-test equipment should be modified or designed for simulating the specific spacecraft interface level acceptance testing and for monitoring and supporting the system spacecraft level testing.

HANDLING AND STORAGE

Every antenna system should have handling and storage tools and containers. The antennas, which may be large and fragile, require a container that can be safely handled by two or more persons. The complete antenna system, for this same reason, will not be installed onto the spacecraft except for special tests and pre-launch assembly. This storage container would have multiple purposes such as handling, storage, and shipping.

INTERFACES

GENERAL

Interfaces are usually mission unique because ESSA's, which can be designed in a variety of shapes and sizes, contain microwave passive and active devices and possibly RF performance improvement packages (RFPIP). Included in this section are typical RF performance improvement data and plots of estimated weight and power requirements as a function of spherical ESSA radii.

RF Performance Improvement Package

The RFPIP is an assembly of microwave passive and active components that can be integrated into the ESSA antenna for large sizes or integrated near the antenna for small sizes. Figure 12 shows the possible packaging arrangements.

The RF performance of an ESSA with an RFPIP is characterized by a considerably improved system noise figure and is characterized Figure 12. Integrated RFPIP and ESSA Packaging Approach by an efficient transmit power system. The interconnections with switches are the choice of the user. The estimated additional weight and power consumed are for an ESSA with a complete RFPIP (i.e., two power amplifiers and two preamplifiers switches and diplexers). The weight of an RFPIP package is 10 lbs plus the weight of a thermal radiator, if required. An efficient 20 W power amplifier, which may need a thermal radiator, has not been designed. The power consumed by an RFPIP package for a 10 W power amplifier is estimated to be 25 W and the 20 W power amplifier is estimated

Figure 12. Integrated RFPIP and ESSA Packaging Approach

27
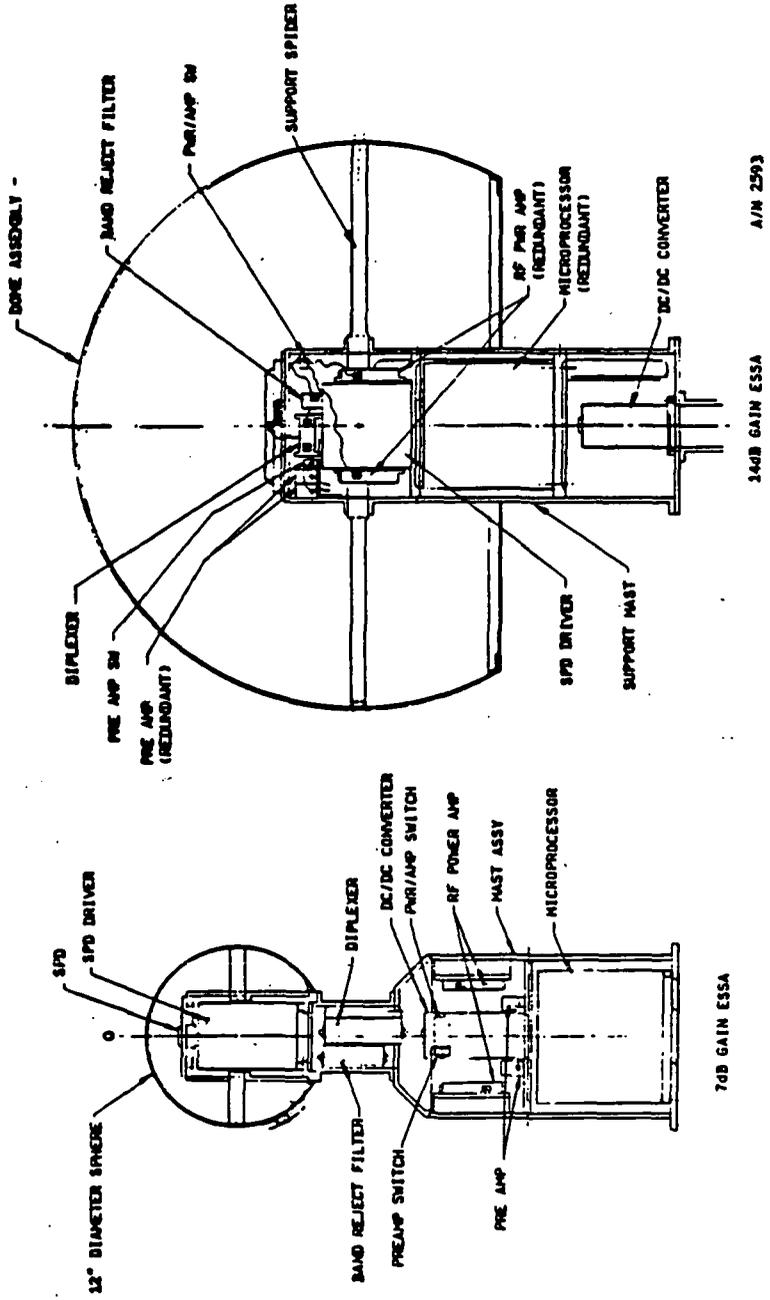
to be 53 W. The total power and weight of the ESSA antennas without RFPIP's are included in the section "Mechanical Interface."

## MECHANICAL

All ESSA's will require some means of attaching and positioning the antenna to the spacecraft body when the spacecraft is in orbit and possibly during space transportation system (STS) payload launch operations. Booms/masts, cages, latches, and other mechanisms and devices may be used. The ESSA could include these items if a simple attachment location could be defined on the spacecraft body at an early period, the attachment/deployment subsystem could be coordinated between the designers and manufacturers of the spacecraft and the ESSA and the attachment/deployment subsystem could remain the spacecraft manufacturer's responsibility. Variations of existing designs would be adequate for meeting the uniqueness of most missions.

Because the release and positioning of the ESSA are critical to the mission, relevant items must be carefully designed and extensively tested. Alignment measurements of the operational position of the antenna must be completed to remove fixed, accumulated assembly, and integration errors if programmed track-type antenna control is used.

Table 3 is the estimated weight of an S-Band ESSA without an RFPIP package. The weight includes redundant electronics (microprocessor and switch driver) and the antenna for the noncompensated and compensated apertures with 1 bit and 2 bit compensation.

## THERMAL

Each mission should have thermal designs validated to ensure that the components remain within operational temperature limits and that distortion of antenna masts does not cause the antenna to point outside the allowable pointing errors. Thermal designs are expected to allow for a wide range of active devices which perform thermal control through the antenna.

The antenna system is thermally isolated from the spacecraft to the maximum extent possible. The complex thermal model of the antenna system is simplified to include only a few nodes for incorporating into the entire spacecraft thermal model.

## ELECTRICAL

The electrical interfacing of the ESSA connectors, power, grounding, command and data handling, and timing require only minimal concern to ensure that they are compatible with the total spacecraft. Figure 13 shows the interface planned for the COBE spacecraft. Modifications and additions of electronics and thermal controls to current designs are a minor effort in comparison with the total effort of building and testing an entire ESSA system.

Table 3
Estimated Weight of S-Band ESSA's

| Diameter (in) | Noncompensated | 1-bit Compensation | 2-bit Compensation |
|---|---|---|---|
| 12 | 38 | -- | -- |
| 16 | 53 | 67 | 81 |
| 30 | 66 | 92 | 106 |
| 40 | 130 | 148 | 163 |

The ESSA's antenna control processor includes testing software so that it can be completely tested as a spacecraft subsystem to minimize integration complexities.

Ground-support equipment should emulate spacecraft electrical (nonRF) interfaces and monitor spacecraft engineering-type data during testing and integration stages.

Two RF interfaces that should be considered are: the microwave signal interface with onboard microwave components by RF transmission lines that require compatible connectors and the effects of scattering or reflections from spacecraft structure and appendages.

Table 4 shows the spacecraft power interface estimates for the combined microprocessor, the SPD, the SPD driver, and the phase shifters (if any). The dominant source of power consumption is the microprocessor which requires approximately 20 W. The SPD driver requires approximately 2 W of dc power and an additional 100 MW for each phase shifter and SPD PIN diode that is turned on. Each forward biased PIN diode consumes an additional 20 MW of power. The amount of power that is needed to back bias the PIN diodes in the SPD and the phase shifters is approximately 0.1 W. Table 4, which uses power consumption data in conjunction with the values in Tables 2 and 3, has been constructed to show the total power required for a range of S-Band ESSA sizes.

TORQUE DISTURBANCE

During mission operations, the ESSA is an electronically steered antenna with no moving parts and generates no torque disturbances.
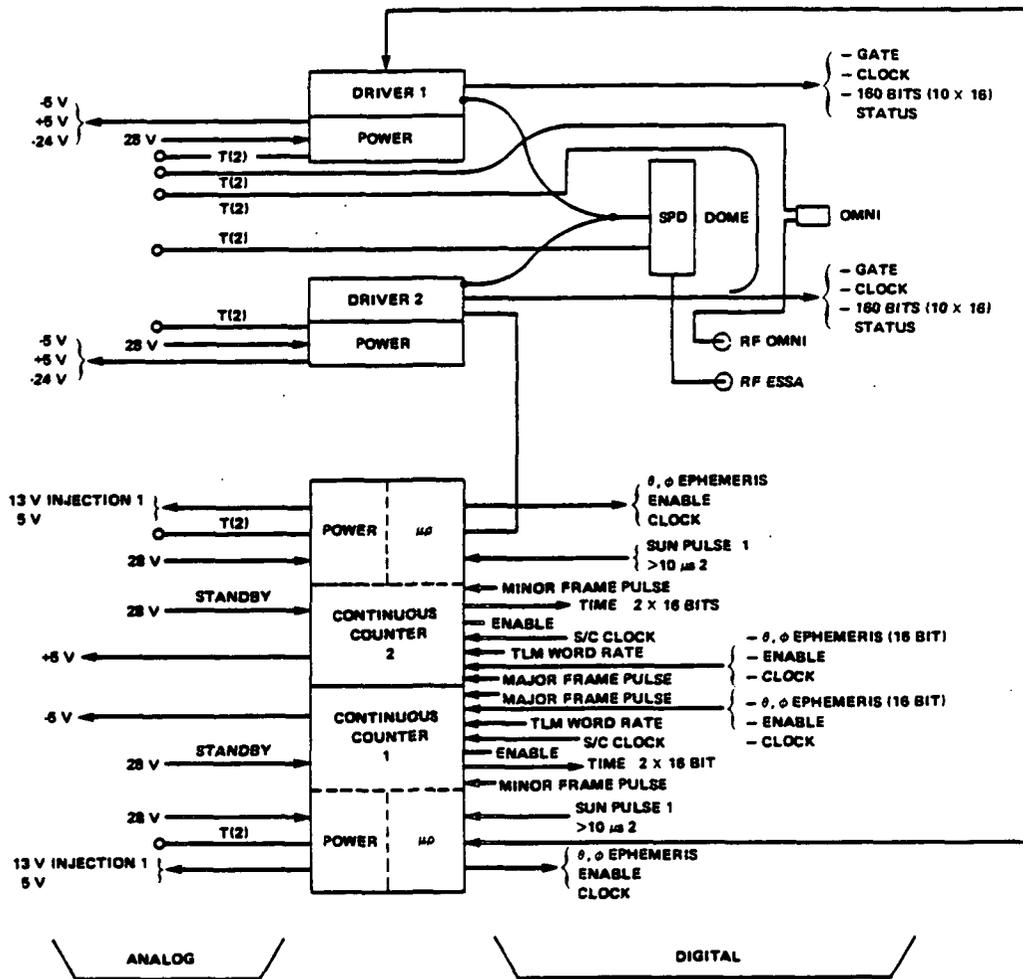
Figure 13. COBE Interface

Table 4
Power Interface Estimates for Various
S—Band ESSA Configurations

| Diameter (in) | No Compensation | 1-Bit Compensation | 2-Bit Compensation |
|---|---|---|---|
| 10 | 22.7 W | - | - |
| 15 | 22.8 W | 23.2 W | 23.5 W |
| 20 | 22.8 W | 23.2 W | 23.5 W |
| 25 | 23.4 W | 25.9 W | 28.3 W |
| 30 | 23.4 W | 25.9 W | 28.3 W |
| 35 | 24.0 W | 27.3 W | 30.5 W |
| 40 | 24.0 W | 27.4 W | 30.7 W |
| 80 | 24.14 W | | |

# APPENDIX A

## ELECTRONIC SWITCHING SPHERICAL ARRAY (ESSA) ANTENNA

## FOR THE

## EARTH RADIATION BUDGET SPACECRAFT (ERBS)

# ELECTRONIC SWITCHING SPHERICAL ARRAY (ESSA) ANTENNA
## FOR THE EARTH RADIATION BUDGET SPACECRAFT (ERBS)

## ABSTRACT

The electronic switching spherical array (ESSA), a microprocessor-controlled S-band antenna for low-orbiting spacecraft is used for telemetry and command relay through the Tracking and Data Relay Satellite System (TDRSS). The array is of hemispherical shape covered with disk-radiating elements. A group of radiating elements are continuously selected by the microprocessor controller to form a beam in the direction of a TDRS. A radial switching power divider uses PIN diodes to select the desired radiating elements.

The antenna gain is a function of the size of the hemispherical dome. At present, a 30-in diameter dome has been built for the Earth Radiation Budget Spacecraft (ERBS). Gain of this antenna over a hemisphere is nominally 12 dBi and polarization is left-hand circular. See "Measured Performance" section. Improvements are in process to have more constant gain of 13 dBi or greater. There are 145 radiating elements with 12 being used at one time to form a beam. The ESSA subsystem antenna, and control electronics weighs 76 pounds and power consumption is 20 W. Radio frequency (RF) power handling capability is 30 W. The S-band radiating elements have a 10-percent bandwidth which allows simultaneous transmission and reception.

## INTRODUCTION

The ESSA is a general class of antenna having medium gain throughout a large coverage region, typically $2\pi$ steradians. An ESSA type antenna can be used for several different applications; however, the system described herein is used for transmitting and receiving data on the ERBS through the TDRSS. This application involves a TDRS at synchronous altitude that relays data for a low-Earth orbiting satellite ERBS.

Ball Aerospace Systems Division (BASD) involvement with the ESSA dates back to 1976. A National Aeronautics and Space Administration (NASA) contract for the development of an ESSA was awarded to BASD during that year and the work continued into 1978. Another NASA contract to BASD resulted in the development of an ESSA controller by mid-1979. The ESSA, a controller, and a NASA standard TDRSS user transponder were combined to demonstrate a closed loop automatic acquisition and track function during another NASA contract ending in 1981. The ERBS contract built, tested, and qualified the first ESSA antenna for space use.

The following paragraphs describe the ERBS/ESSA and its performance.

## ESSA Description

The ERBS/ESSA shown in Figure A-1 has 145 radiating elements on a 30-in diameter, spun-aluminum dome. The elements are spread over the dome to approximately 6° below the upper hemisphere. Twelve of the 145 elements are selected to form a beam having approximately 13 dB of gain. The beam is steered by selecting appropriate groups of 12 elements. The element distribution is determined by icosahedron geometry. Elements are placed at the vertices of equilateral triangles resulting in element spacing of from 0.61 to 0.68λ.



12 INCH DIAMETER
7 dBic GAIN
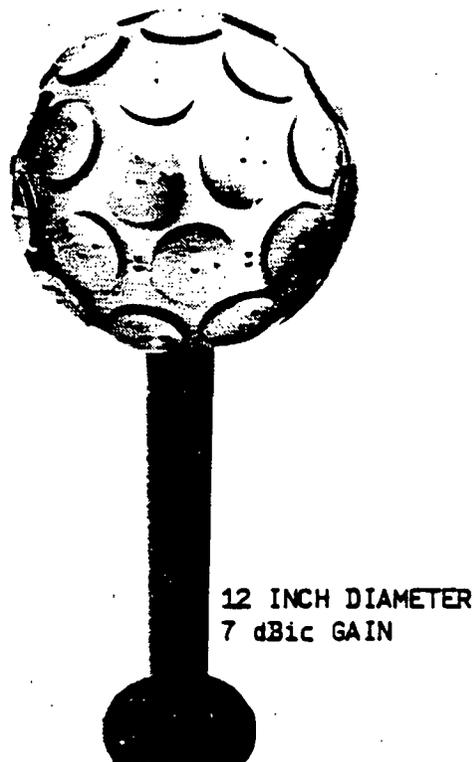
Figure A-1.   Low Gain ESSA

Elements are selected with a switching power divider (SPD) that is located in the center of the equatorial support ring (Figures A-2 and A-3). The SPD is basically a 145-way power divider with 12 outputs being activated at a time with PIN diodes. Each of the 145 SPD outputs is connected to a radiating element with a low loss coaxial cable. The cables are held in place with a cable support assembly.

The PIN diodes in the SPD are biased on or off with a electronics drive assembly located inside the dome and below the equatorial support ring. The driver assembly is shown in Figure A-2 and a bottom view is shown in Figure A-3. The driver is standby redundant and
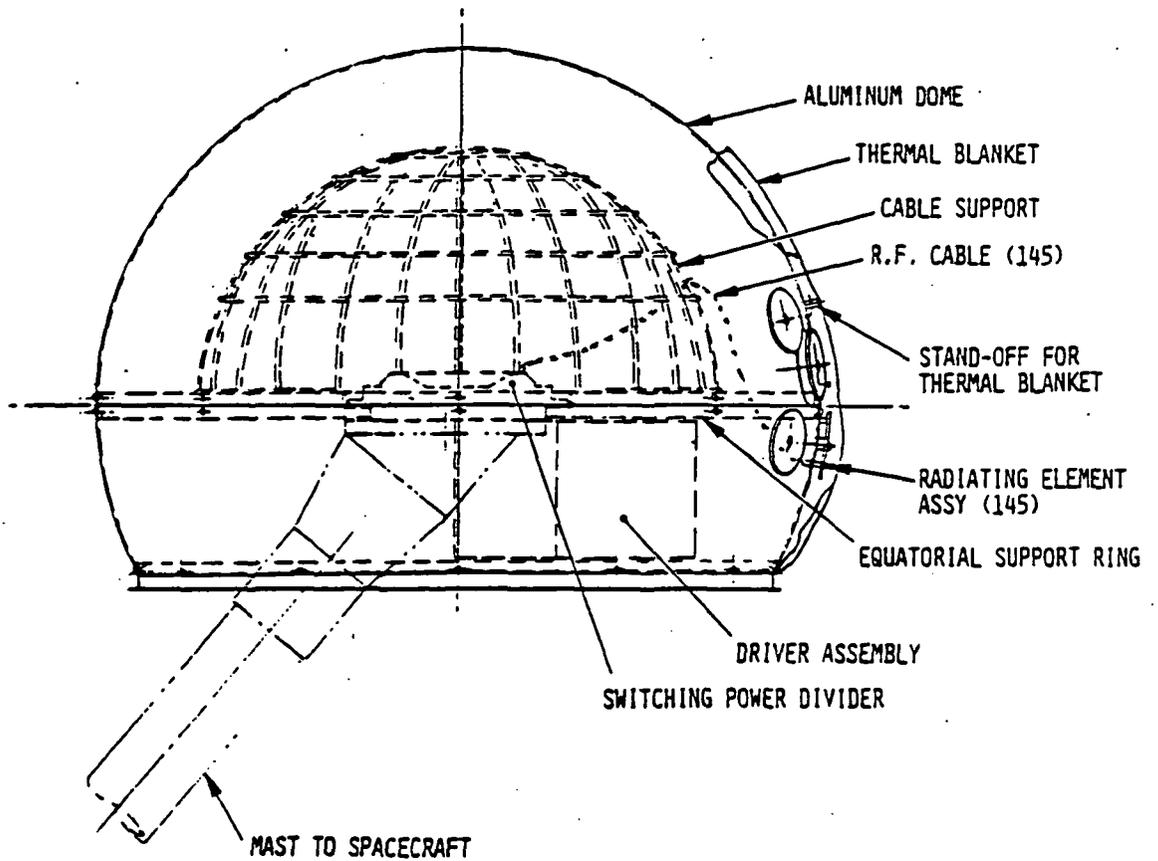
Figure A-2.   ESSA Antenna
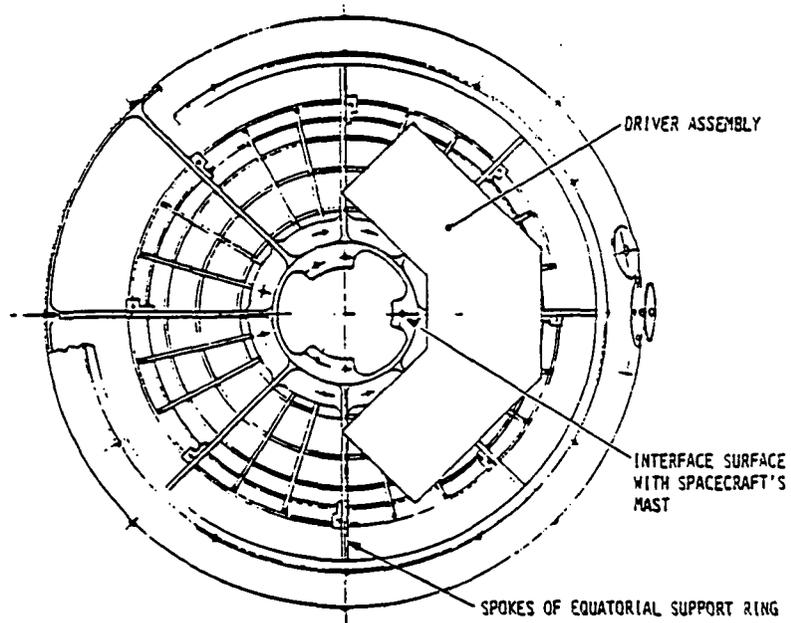


Figure A-3.   Bottom View of ESSA

is shaped in the form of a vee to fit around the mast to the space-craft. The driver receives ESSA pointing commands from a micropro-cessor based controller assembly located in the spacecraft. The controller automatically generates pointing commands to keep the ESSA pointed at either of the TDRS's and will also accept uplinked commands. Dual beam performance has been demonstrated and could point simultaneously at both TDRS's when in the ESSA coverage region.

The entire dome is covered with a beta-cloth blanket for thermal control. This blanket improves the uniformity of dome and element temperature.

Figure A-4 shows the electronic configuration. Pointing commands are generated by the controller and sent to the driver. The driver outputs 12 forward bias signals and 133 reverse bias signals to the SPD, which results in a group of 12 elements on the dome to be active for receiving uplinked data and transmitting downlinked data.

SUBASSEMBLY DESCRIPTION

All radiating elements are identical. See Figure A-5 for this configuration. The radiating element is a metallic disk approxi-mately $0.5\lambda$ in diameter. This disk is grounded at its center to a ground plane with a standoff. The disk is fed at two points with equal power but differing in phase by 90° which produces circular polarization. The equal power and 90° relationship is accomplished with a microstrip branch line hybrid which is bonded to the ground plane. The two feed points to the disk from the branchline hybrid are done with spring contacts. The branchline hybrid has two remaining ports, one of which is terminated with a chip resistor and the other is an RF connector that is connected to one of the 145 outputs on the SPD. The spacing between the disk element and its ground plane is about 0.25 in. This wide spacing in addition to the branchline hybrid allows for wide-band operation at two operating frequencies with good axial ratio. The two frequencies are 2106 MHz for receiving and 2287 MHz for transmitting.

Figure A-6 is a schematic of the SPD. The SPD is basically a 150-way radial power divider with the RF input at the center of a hub and the 150 outputs extending radially from the center. Five out-puts are spares and are bundled for future use if required. At the end of each radial is a PIN diode that can either be forward or reversed biased. A blocking capacitor is used for preventing the dc bias from being connected to the radiating element which is at dc ground. A two-turn inductor is used for tuning out the PIN diode capacitance which improves the isolation and resulting loss of power from 133 back-biased diodes. Dc bias is connected to each diode through a high impedance $0.25\lambda$ line which is RF grounded with a feedthrough capacitor. This arrangement "chokes off" RF from traveling on the dc bias lines.
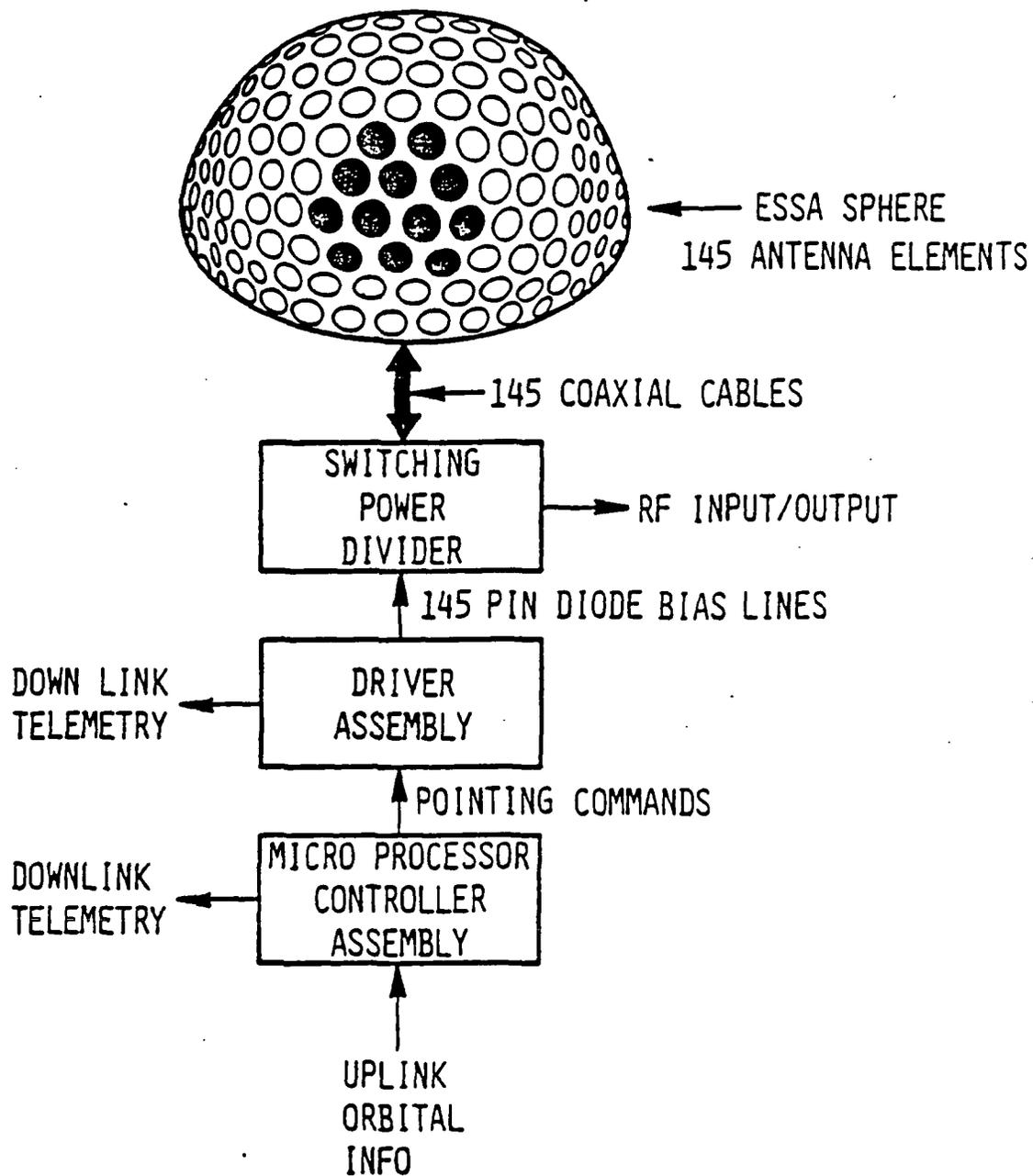
Figure A-4. ESSA Configuration
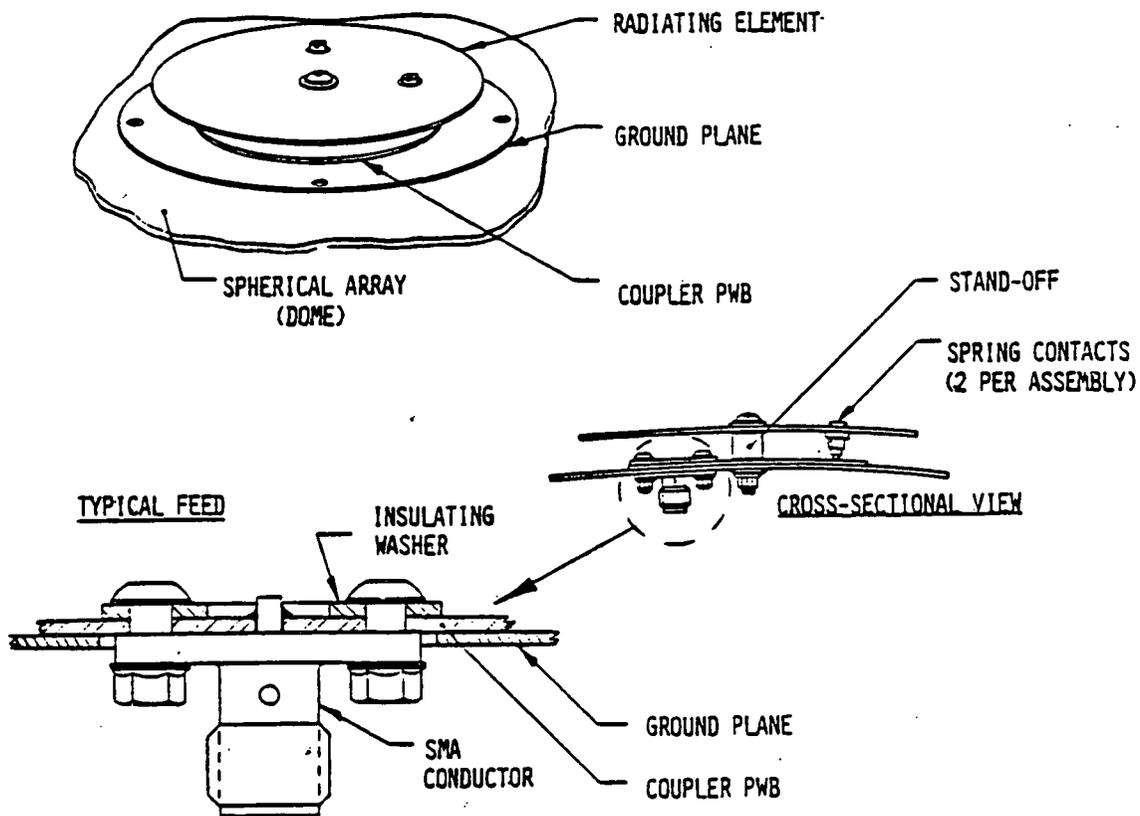
**Figure A-5. Radiating Element Assembly**

The driver assembly, which produces the bias for the PIN diodes in the SPD, is shown in Figure A-7. The pointing command from the controller is a 145-bit word that is clocked into a shift register. If this command is valid, it contains 12 ones and 133 zeros. This feature is then checked with the valid data verify counter which results in the 145-bit word being transferred to a latch that causes 12 outputs to have forward bias and the remaining outputs to have reverse bias.

The ERBS controller uses a now discontinued Texas Instrument's 9900 Series microprocessor. Future units will use a Texas Instrument 9989. The function of the controller (Figure A-8) is to calculate the relative position of the TDRS's and the host satellite, to generate the appropriate pointing command to direct an antenna beam at a TDRS, and to uplink commands to the controller. The following uplink commands are used to:

● Update Ephemeris data

● Direct the antenna to point to a discrete azimuth and elevation angle
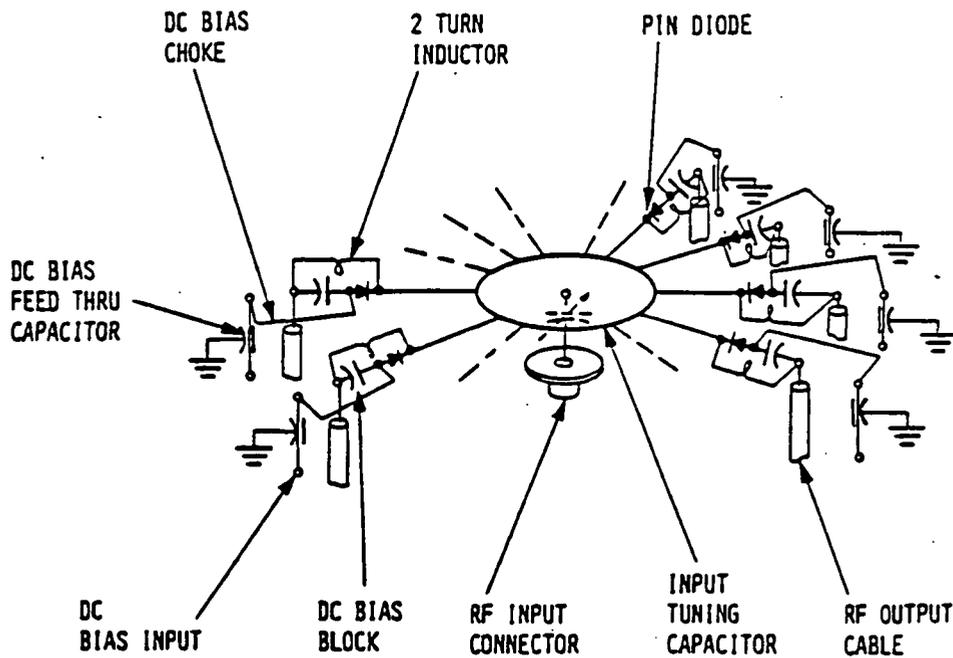
Figure A-6. Switching Power Divider Schematic

- Track only TDRS east/west

- Rotate azimuth 180°

The updating of Ephemeris data command is to correct for TDRS and ERBS small orbital drifts. The discrete azimuth/elevation angle command allows a backup operational mode in case of controller problems or an unusual ERBS orbit. The track-only TDRS east or west command disables the automatic handover from one TDRS to the other during a data dump. The rotate azimuth 180° command corresponds to a planned 180° ERBS yaw maneuver every 34 days to keep the solar arrays properly oriented to the Sun.

PERFORMANCE SUMMARY

Figure A-9 shows a typical antenna beam from a group of 12 elements. The peak gain is 14 dB and the 3-dB beamwidth is 25°. Axial ratio is better than 3 dB at both operating frequencies. Using 145 elements in groups of 12 results in 1807 unique beams that are distributed as indicated in Figure A-10. The beams are so densely distributed that the effective gain over the scan region is nearly the same as that of the peak gain of 14 dB. A group of adjacent beams is recorded on Figure A-11 which shows the variation in gain being 1 dB. A computer-generated radiation distribution plot (RDP) for a 145-element ESSA (Figure A-12) also shows gain variations of 1 dB. Some degradation of the ideal RDP is expected
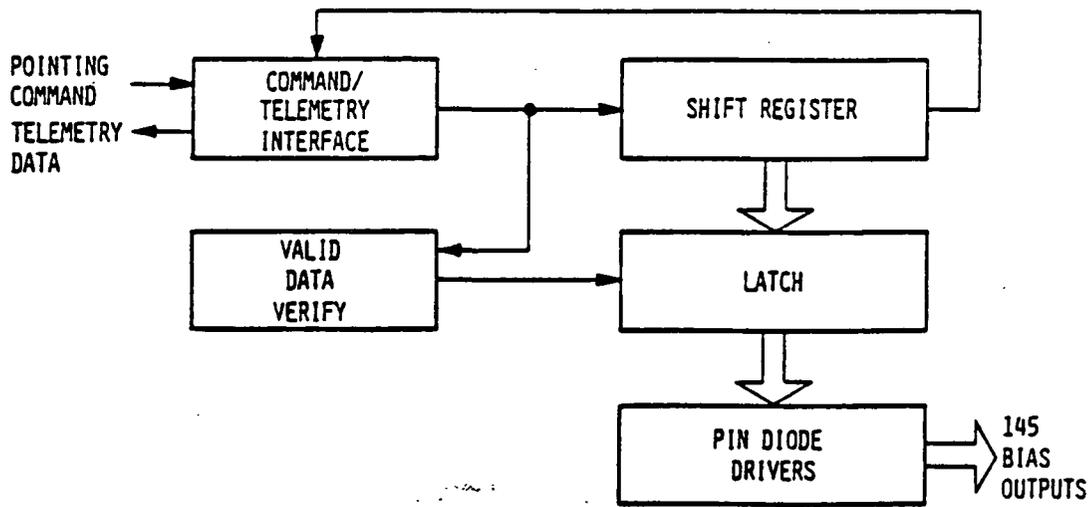
**Figure A-7. Driver Assembly**
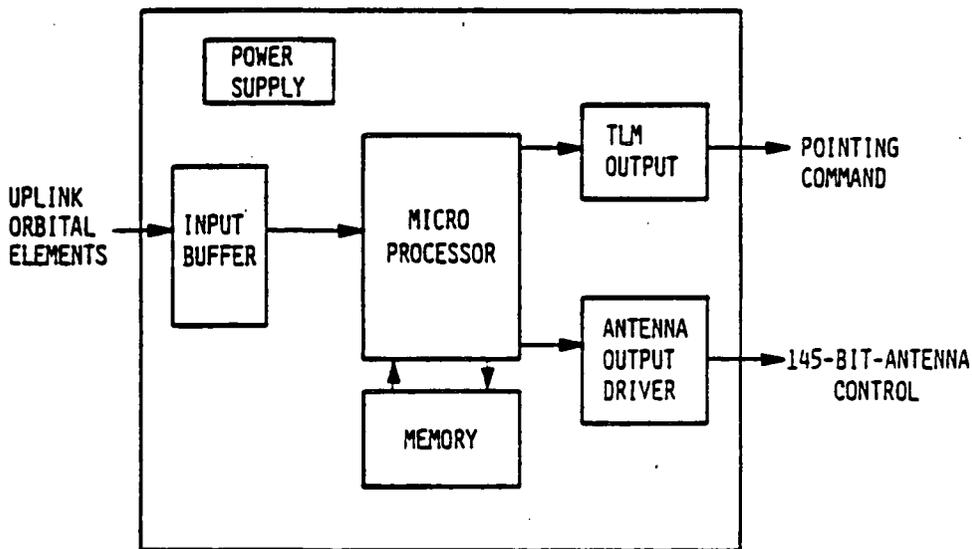


**Figure A-8. Controller Assembly**

because the SPD will not provide perfectly equal power division and phase matching to the 12 elements. These data are shown in Figures A-13 and A-14.

The weight of the ESSA antenna, including the controller and thermal blankets, is 74 lbs. Approximately 30 lbs of the weight can be attributed to redundant driver and controller assemblies. Power consumption is 20 W from a 28 Vdc satellite bus.

Thermal control of the ESSA is achieved by passive means. The entire ESSA dome is covered with a beta-cloth blanket. A multi-layer thermal blanket is used to cover the truncated spherical end. All metallic surfaces inside and outside the dome are black
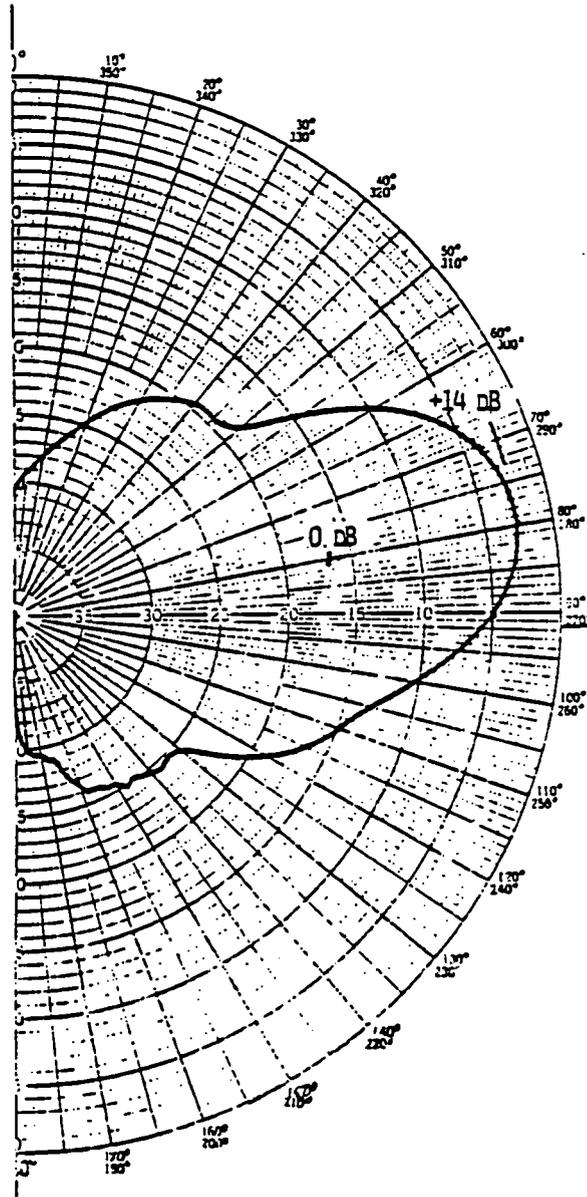
Figure A-9.   Typical ESSA Beam
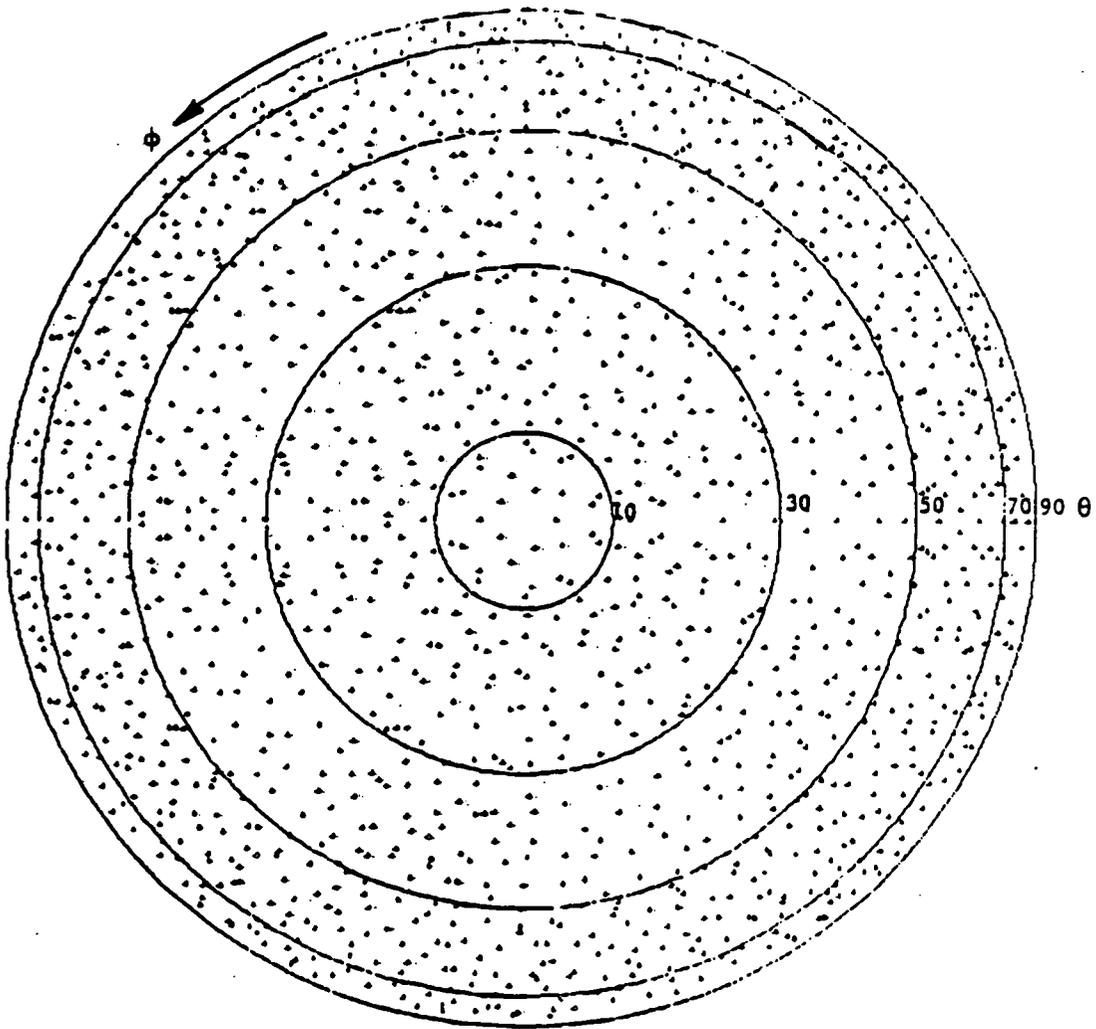
Figure A-10.   1807 Unique Beams
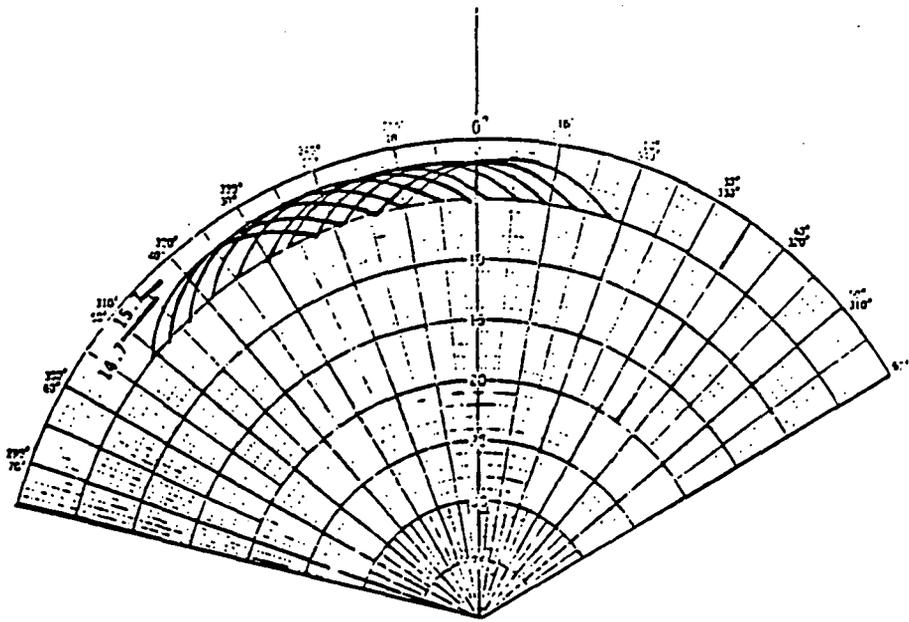
Figure 11.   Beam-to-Beam Gain Variation, Measured
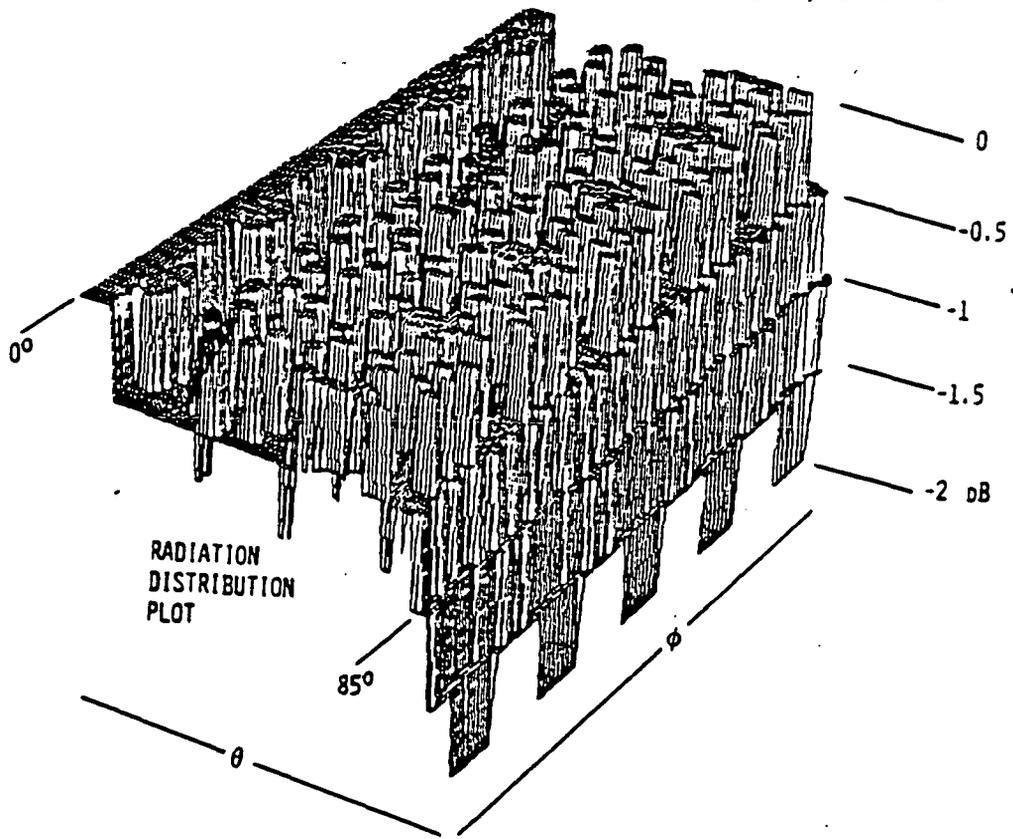


Figure 12.   Computer-Generated RDP

Figure A-13. Gain

A-12

Figure A-14. Relative Phase

A-13

in the infrared. Thermal analysis has been conducted for ERBS orbits. Predicted temperatures for all surfaces and subassemblies are well within the qualification temperatures of -45° to +60°C.

ERBS/ESSA Testing Description and Test Results

The electronics that direct the ESSA antenna are diode drivers and a microprocessor controller. The drivers are mounted on the ESSA but the microprocessor is part of the spacecraft system. The microprocessor is simulated during antenna tests by an antenna test unit (ATU) which contains a dome of light-emitting diodes (LED's) that display the elements being activated for visual confirmation of antenna element functioning. A specific feature of the ATU is the ability to "talk" to the antenna test range computer and to accept coordinate instructions from it. This ability allows evaluation of the behavior of the ESSA in a quasioperational manner. In this mode, the ESSA will form a beam to illuminate the look angle set up by the range. This ability is used for producing composite radiation distribution plots (CRDP's) examples of which are shown in Figure A-12.

These data are acquired by use of an antenna range computer and the ATU microprocessor controller. The antenna range computer operates in a standard RDP mode. This master computer sends pointing angles to the ATU controller which instructs the ESSA to form a beam in the appropriate direction. The ATU controller also acknowledges that pointing information was received or the system will shut down. The range then measures and records the signal level that the ESSA is presenting to cover that specific pointing angle. These measurements are repeated for every degree of the hemisphere, with the resulting CRDP printout including every degree in $\theta$ and $\phi$.

Figure A-13 is a reproduction of a 30° by 57° section of this CRDP. Note that the gain is relatively constant. The lower areas in the hemisphere coverage region are caused by the behavior of the SPD. Not all of the 1800 beams can be optimally coupled out of the SPD, and those associated with the less optimum assignments and coupling show up as areas of lower gain. A 12 dB or more gain, however, covers 93 percent of the hemisphere. (An improved SPD that is currently in development will remove these lower gain regions, with expected nearly constant 13-dB gain.)

Another parameter of the ESSA is the relative phase from beam to beam which is measured by the CDRP in the same way that the amplitude was measured. The phase is constantly progressing around the hemisphere in $\phi$, however; this progression is smooth with steps usually less than 10° from point to point over the scan region. Figure A-15 is a portion of the numerical printout.

The ATU has several modes of operation including an AUTO mode that was previously described for running CRDP's. A second mode concerns a value of $\phi$ and $\theta$ that is entered by the keyboard and the

controller selects a group of 12 radiating elements which form a beam nearest to the value of $\phi$ and $\theta$. With a third mode, a single radiating element can be selected by the keyboard. A fourth mode automatically steps through 20 standard beams. These standard beams ensure that every radiating element is used at least once for quick-look testing. The dome on the controller contains an LED for every corresponding radiating element and illuminates those LED's being activated.

## Measured ERBS ESSA Performance

The measured performance of the ERBS ESSA is summarized by the following comments:

a.  Frequency/VSWR*

- 2287.5 MHz--1.4 to 1.6:1 (varies with beam)
- 2106.4 MHz--2.1 to 2.3:1 (varies with beam)

b.  Polarization/Axial Ratio

- 2287.5 MHz--LHC @ 1 to 2 db axial ratio
- 2106.4 MHz--LHC @ 2.5 to 3.5 axial ratio

c.  Gain/Coverage*--0° < $\theta$ < 90°

| 2287.5 MHz At or Above 14 db | Post 2.2% | Pre-Environmental 4.2% At or Above | 2106 MHz At or Above 12.5 dB | Mhz Pre 1.8% | Post 1.3% |
|---|---|---|---|---|---|
| 13 | 25.6 | 55.3 | 11.5 | 2.9 | 5.9 |
| 12 | 81.1 | 92.7 | 10.5 | 7.0 | 38.6 |
| 11 | 97.9 | 99.1 | 9.5 | 20.7 | 97.8 |
| 10 | ≈100.0 | 100 | 8.7 | 79.3 | 99.8 |
| 9.7 | 100.0 | 100 | 7.5 | 96.8 | 99.9 |
| | | | 6.5 | 100.0 | 100.0 |

d.  Beam-to-Beam Steps

- Amplitude*--Majority are 1.2 db or less for both frequencies, with occasional ones to 2.7 db

- Phase*--There are only a few that exceed 10° at either frequencies

- Power handling--Tested to 30 W

e.  Switching Speed

- Off to on--≈500 ns
- On to off--8+ $\mu$s

---

*Improvements expected for future units with improved switching power divider

f. Dc Power

- Turn on--≈700 ma
- Normal-beam pointing--340 ma @ 28 V
- Working voltage range--28 ±7 V

g. Weight (antenna and driver assembly)

- Complete with blankets--57 to 58 lbs

h. Weight (controller)

- 19 lbs

i. Size (antenna)

- With thermal blankets--15.7-inch radius

j. Size Controller

- 10.5-inch length by 8.5-inch width by 9-inch height

## ERBS/ESSA Antenna Environmental Testing

a. Temperature--45° to +65°C

- Tested 42 cps of thermal, ambient pressure
- Tested 8 cps of thermal vacuum

b. Sine Vibration

- 5 to 17.7 Hz @ 0.4" double amplitude
- 17.7 to 200 Hz @ +6.4 g
- All three axis @ 2 octaves/min.

c. Random Vibration

- 20 to 2000 Hz @ 18.9 G acceleration for 2 min.

d. Acceleration

- X + Y axis--30 gs/30 Hz/1 min
- Z axis--20 gs/25 Hz/10 s

e. ERBS/ESSA Controller Environmental Testing Temperature

## OPERATIONAL TEST WITH TDRSS

BASD and NASA performed a ground-to-satellite test with TDRSS using the spacecraft transponder and additional instrumentation. This test was to verify compatibility, gain, and any problems with beam switching.

The results were very positive. The command link, which in orbit would be the uplink, could be measured very accurately and was compared with a parabolic antenna. This link displayed 1 to 2 dB more than anticipated.

Switching exercises were performed where the beams were altered in various sized steps. Small steps changed the array by one or two elements. The largest step changed 8 of the 12 elements. At no time did beam changes cause the transponder to drop lock.

The TDRSS S-band single access mode was used for this test. Usually, ESSA will work with the multiple access part of the system; however, TDRSS had not activated the multiple access system at the time of the test. The difference between the TDRSS SA and the MA systems was considered when evaluating if performance would be satisfactory for in-orbit conditions.

BIBLIOGRAPHIC DATA SHEET

| 1. Report No. NASA Tech. 86127 | 2. Government Accession No. N/A | 3. Recipient's Catalog No. N/A |
|---|---|---|
| 4. Title and Subtitle Electronic Switching Spherical Array (ESSA) Antenna Systems | | 5. Report Date July 1984 |
| | | 6. Performing Organization Code 727.1 |
| 7. Author(s) Richard P. Hockensmith | | 8. Performing Organization Report No. N/A |
| 9. Performing Organization Name and Address Goddard Space Flight Center Greenbelt, MD 20771 | | 10. Work Unit No. N/A |
| | | 11. Contract or Grant No. N/A |
| | | 13. Type of Report and Period Covered Technical Memorandum |
| 12. Sponsoring Agency Name and Address NASA/Headquarters Washington, DC 20546 | | |
| | | 14. Sponsoring Agency Code |

15. Supplementary Notes

16. Abstract

ESSA (Electronic Switching Spherical Array) is an antenna system conceived, developed and qualified for linking satellite data transmissions with NASA's tracking and data relay satellites (TDRSS) and tracking and data acquisition satellites (TDAS). ESSA functions in the "S" band frequency region, cover 2 π or more steradians with directional gain and can operate in multiple selectable modes. ESSA operates in concert with the NASA's TDRS standard transponder in the retrodirective mode or independently in directional beam, program track and special modes.

This document introduces organizations and projects to the ESSA applications for NASA's space use. Coverage gain, weight power and implementation and other performance information for satisfying a wide range of data rate requirements are included.

| 17. Key Words (Selected by Author(s)) antennas electronic switching control space command/telemetry | 18. Distribution Statement unclassified unlimited Star category | | |
|---|---|---|---|
| 19. Security Classif. (of this report) NC | 20. Security Classif. (of this page) - | 21. No. of Pages 34 | 22. Price* |

GSFC 25-44 (10/77)