SOESAT LOW COST TELEMETRY GROUND STATION

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5th Annual AIAA/Utah State University
Conference on Small Satellites

By

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1 August 1991
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Appendices

A: 6-Turn Helix Antenna
ABSTRACT

SOESAT LOW COST TELEMETRY GROUND STATION

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The School Of Engineering SATEllite (SOESAT) will be fabricated and donated by American Microsat Inc. of Sunnyvale, California. SOESAT will carry a radiation sensor that will measure the secondary emission internal to the satellite caused by the impinging of external primary radiation. At the time of this abstract SOESAT has not been manifested on a launch vehicle. A fourth quarter '92 launch into a geotransfer orbit on a European Space Agency Ariane is being investigated. Low earth orbit launch alternatives on various boosters are also being investigated. Command and control of SOESAT will be accomplished using the telemetry ground station built and operated on site at San Jose State University. The total cost of this system is less than $8000.

The telemetry ground station will also be compatible with various currently on orbit satellites. Spacecraft telemetry will be received and processed/displayed for instructional purposes. The ground station will operate in a passive receive only mode when conducting these operations.

The telemetry ground station will consist of three major subsystems: ground antenna, telemetry front end, and data processing/display. A steerable 13 dB gain circular polarized helix antenna will amplify and transmit packetized commands at 149 MHz and 170 W. The helix antenna will also receive telemetry files transmitted by SOESAT at 136 MHz and 4-10 W. The telemetry front end will consist of a commercial VHF FM transmitter and receiver. Command and telemetry ASCII files will be formatted and error checked by an off the shelf terminal node controller. The terminal node controller will be compatible with the SOESAT 1200 bps uplink and 9600 bps downlink. A command pool will reside on an IBM compatible personal computer (pc). The pc will also store telemetry files during the satellite pass and process/display the measurands postpass. SOESAT orbital vectors will be acquired from NORAD and propagated on the pc by commercial software to produce vehicle ephemeris with visibility times and local look angles.
INTRODUCTION

The School Of Engineering SATellite (SOESAT) low cost telemetry ground station was designed with the idea of maximizing the use of "off-the-shelf" inexpensive commercial products coupled with the self fabrication of antenna hardware in order to minimize total ground system cost. The system described can transmit commands and receive telemetry in a "packetized" format using standard data transfer protocols. The total system cost is less than $8000.00. This ground system will be used to command and control the SOESAT spacecraft on-orbit and passively receive telemetry from a variety of currently on-orbit satellites.

SOESAT SPACECRAFT DESCRIPTION

SOESAT is hexagonally shaped with each side of the hexagon being 11 inches (Figure 1). The spacecraft will be powered by eight solar arrays attached directly to the outer surface of the spacecraft and by internal batteries both non-rechargeable cells and rechargeable nickel-cadmium cells. An onboard multitasking computer will govern internal spacecraft functions as follows (Reference 1):

- Monitor all subsystems and payload and assess their state of health
- Format and generate telemetry files
- Perform onboard attitude determination and antenna selection (requires ephemeris upload from ground station)
- Receive, interpret, and store commands for the spacecraft and payloads
- Receive, store, and forward message files from ground station
- Transfer data to/from an onboard data recorder
- Perform power management functions
- Coordinate activities of all subsystems

The spacecraft has redundant FM transmitters and receivers. A terminal node controller with an internal modem operating AX.25 version 2 protocol will modulate telemetry at 9600 baud and demodulate command files at 1200 baud. There is no onboard attitude control system. Two 5 dB gain omnidirectional VHF quadrifilar helix antennas fixed to the top and bottom panels will transmit at 136 MHz and receive at 149 MHz.
SOESAT DESCRIPTION

[ ] TT&C
  - UPLINK
    149 MHz
    1200 baud
    AFSK
  - DOWNLINK
    136 MHz
    9600 baud
    AFSK
  - 2 QUADRIFILAR HELIX ANTENNA 5dBi

[ ] EPS
  - 8 SOLAR ARRAYS
  - NiCd BATTERIES
  - NON-RECHARGEABLE BATTERIES
### SOESAT

#### ORBIT PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Inclination</td>
<td>4 Deg</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.73</td>
</tr>
<tr>
<td>Apogee</td>
<td>33567 Km</td>
</tr>
<tr>
<td>Perigee</td>
<td>205 Km</td>
</tr>
<tr>
<td>Period</td>
<td>9h 55m</td>
</tr>
</tbody>
</table>
SOESAT will be launched from Kourou, French Guiana into a 200 \times 35000\text{ Km} geotransfer orbit of 4 degree inclination. The period of the SOESAT orbit will be approximately 9.92 hours (Figure 2). SOESAT will only be visible around apogee from the ground station at San Jose State. The maximum look angle elevation for this mission will be 51 deg.

**DESIGN GUIDELINES**

The design of the telemetry ground station is forced by numerous inputs. One of the first considerations is the spacecrafts antenna. Since SOESAT has no attitude control subsystem, the spacecraft will be in an uncontrolled tumble throughout its on orbit lifetime. Directional antennas, common with spacecraft at these altitudes, cannot be used because the downlinked signal strength would vary drastically due to the changing antenna orientation with respect to the ground station antenna. A quadrifilar helix antenna was chosen for the spacecraft antenna because it provides an omnidirectional radiation pattern perpendicular to its z-axis and a 5 dB gain along the z-axis (Reference 2). It has a circular polarized waveform which helps in decreasing signal attenuation due to antenna mismatch. If a linearly polarized antenna were used the random tumbling would create maximum attenuations of 30 dB for a linear polarized ground station antenna and 3 dB for a circular polarized ground station antenna. There is no attenuation between two circular polarized antennas with the same sense (Reference 2).

All SOESAT contact visibilities with the San Jose State ground station only occur when the spacecraft is near apogee. The typical slant range from ground station to spacecraft will be in the neighborhood of 42,000 km. The spacecraft is limited to 10 watts maximum for its downlink. This rules out an omnidirectional antenna for the ground station because with no gain the ground station antenna would be unable to collect enough RF to overcome cosmic and receiver noise at that frequency. Therefore a high gain circular polarized antenna must be used for the ground station. Because the ground station antenna will have relatively high gain a method of pointing the antenna must be improvised.

The ground station must be compatible with the VHF "packetized" telemetry FM carrier. It must operate at the same frequencies as the spacecraft and allow enough passband to compensate for maximum frequency shifts due to doppler and still be narrow enough to filter undesired RF. It must be compatible with the receivers mod index requirements. It must utilize the same AX.25 protocol for data transfer that will be used onboard the spacecraft. It must also use a modulation technique compatible with the onboard modem.
The ground station will be tested and utilized prior to the launch of SOESAT to passively receive RF telemetry from various currently on-orbit satellite programs. Special interest will be focused on receiving Automatic Picture Transmission (APT) signals transmitted by various US, Soviet, and Chinese spacecraft. These APT direct readout transmissions of weather photographs can be processed and displayed. Other satellite transmissions can be received and tracked across the sky to verify ground station receiver operations but not processed/displayed without special modifications required for each unique downlink. VHF voice transmissions from Mir and the Space Shuttle can also be received and recorded on audio tape.

SYSTEM OPERATIONAL REQUIREMENTS

Ground Station Antenna
-Requirements:  
  transmit 149 MHz  
  receive 136 MHz  
  high gain (13dB)  
  circular polarized  
  low cost (<$1k)  
  steerable (360 AZ; 180 EL)  
  slave capability

Telemetry Front End
-Requirements:  
  transmit 170W at 149 MHz  
  receive at 136 MHz  
  display signal strength  
  compensate for doppler effects  
  low cost (<$1.5k)  
  modulate/demodulate AFSK  
  internal bit error correction scheme  
  configurable data packet size  
  low cost (<$400)

Data processing/display subsystem
-Requirements:  
  store, format and transmit commands  
  receive/store spacecraft telemetry files  
  generate ephemeris load for spacecraft  
  generate slave bus to drive antenna  
  process telemetry post pass  
  limit check state of health measurands  
  display telemetry post pass  
  archives telemetry
FUNCTIONAL ANALYSIS

The telemetry ground station looked at as one system interfacing with the spacecraft will be required to receive RF telemetry, strip the information signal from the carrier and store that data in a telemetry file for later processing. It must also receive typed commands, modulate the commands onto a carrier and uplink those commands. In order to perform the above functions it will need vehicle ephemeris to generate local look angles and format ephemeris loads to be uplinked to SOESAT to assist the spacecraft with attitude determination and antenna selection (Figure 4).

The ground station can be broken down into six functional areas: telemetry reception, telemetry demodulation, data processing and display, command modulation, antenna pointing, and command transmission (Figure 5). RF telemetry radiated from SOESAT at 136 MHz with Frequency Shift Keying (FSK) modulation is captured and the modulation stripped from the carrier (Figure 6). Next, the modulation is converted from an analog signal into a digital signal. The digital signal is then verified as being accurately received using AX.25 version 2 file transfer protocol (Figure 7). The digital data is then passed into a buffer for storage and later retrieval (Figure 8).

The ground station must also receive typed commands, identify the file to be transmitted, and retrieve that file from a command pool (Figure 8). The command files are passed along to a digital to analog converter where the commands are "packetized" according to AX.25 protocol and FSK modulated (Figure 9). A carrier wave of 149 MHz is formed and modulated with the command tones and radiated towards the spacecraft (Figure 10). In order to radiate the commands in the proper direction, vehicle ephemeris must be converted into local look angles (Figure 8). The local look angles must then be converted into servo commands in order to drive the antenna (Figure 11).
0. TELEMETRY GROUND STATION

RF TLM 136 MHz CARRIER W/ MODULATION

RCV TLM -1.1-

TLM AFSK TONES

DEMODULATE TLM -1.2-

TLM FILES (ASCII)

PROCESS DATA -1.3-

CMD FILES (ASCII)

MODULATE CMDs -1.4-

RF CMDs 149 MHz CARRIER W/ MODULATION

XMT CMDs -1.5-

CMD AFSK TONES

POINT ANTENNA -1.6-

LOOK ANGLES

VEHICLE EPHEMERIS

TYPED CMD

TLM DATA FILES
RF TLM
136 MHz

CAPTURE RF AND DELIVER TO RCVR
-1.1.1-

RF TLM

TUNE TO 136 MHz AND FILTER ALL OTHER FREQUENCIES
-1.1.2-

136 MHz (only)
RF TLM

STRIP MODULATION FROM 136 MHz CARRIER
-1.1.3-

AFSK TONES

1.1 RCV TLM

Figure 6
1.2 DEMODULATE TLM

CONVERT TONES INTO BITS -1.2.1-

BITS

ERROR CHECK DATA -1.2.3-

ASCII

RECOVER DATA AND ASSEMBLE ASCII WORDS -1.2.2-

TLM FILES (ASCII)
1.4 MODULATE CMDs

CMD FILES (ASCII) -> ENCODE ASCII FILES INTO BITS -1.4.1- -> BITS -> CONVERT BITS INTO TONES -1.4.2- -> CMD AFSK TONES
1.5 XMT CMDs

MODULATE TONES ONTO 149 MHz CARRIER
-1.5.2-

RF CMD

DELIVER FROM XMTR AND RADIATE RF
-1.5.3-

RF CMDs
149 MHz CARRIER W/ MODULATION

CMD AFSK TONES

UNMODULATED CARRIER

GENERATE CARRIER
-1.5.1-
FUNCTIONAL ALLOCATION OF HARDWARE AND SOFTWARE

1.1 RCV TLM
   1.1.1 13 dB helix antenna
          RF Concepts 2-417 amplifier
          50 Ohm transmission line
   1.1.2 ICOM IUX-R96 Receiver
   1.1.3 Same as 1.1.2

1.2 DEMODULATE TLM
   1.2.1 AEA PK-88 TNC
   1.2.2 Same as 1.2.1
   1.2.3 Same as 1.2.1

1.3 PROCESS DATA
   1.3.1 H/W: IBM PC (386 or 486)
          S/W: PROCOMM+
   1.3.2 H/W: Same as 1.3.1
          S/W: Same as 1.3.1
   1.3.3 H/W: Same as 1.3.1
          S/W: GrafTrack II

1.4 MODULATE CMDs
   1.4.1 Same as 1.2.1
   1.4.2 Same as 1.2.1

1.5 XMT CMDs
   1.5.1 ICOM IC-970H Transceiver
   1.5.2 Same as 1.5.1
   1.5.3 Same as 1.1.1

1.6 POINT ANTENNA
   1.6.1 Antenna Operator (ie. ops crew)
   1.6.2 Yaesu G-5600B Antenna Controller
# TELEMETRY GROUND STATION HARDWARE LIST

## Helix Antenna (make)

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</tr>
<tr>
<td>2</td>
<td>U bolt spacers</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>U bolt nut with lock washer</td>
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<td>1</td>
<td>Reflector mounting plate, Al, 19&quot;x7&quot;x.2&quot;</td>
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<tr>
<td>1</td>
<td>Coaxial receptacle, N type</td>
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<tr>
<td>1</td>
<td>1&quot;x2&quot; heavy wire mesh, 5'x5'</td>
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<tr>
<td>2</td>
<td>Boom 2&quot;x2&quot; redwood 13 feet long</td>
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</tr>
<tr>
<td>6</td>
<td>Boom spacer 2&quot;x2&quot; redwood 12 inches long</td>
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<tr>
<td>12</td>
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<td>Elevation boom, 1 5/8 in dia, steel pipe 24&quot; long</td>
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<td>Antenna mast, 2.5&quot; dia, steel pipe 8' long</td>
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<td>Helix coaxial cable, 40'</td>
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<td>Transmission line, 913 Beldon 1dB/100' loss line</td>
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<td>1</td>
<td>Amplifier, 45W in 170W out, 2-417 by RF Concepts</td>
<td>$280</td>
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<td>1</td>
<td>Antenna rotator, AZ/EL, Yaesu G-5600B</td>
<td>&lt;$400</td>
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<td>Antenna rotator control line, twisted pair 300'</td>
<td>$75</td>
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## Telemetry Front End (buy)

| 1        | Transceiver, ICOM IC-970H                  | $2499  |
| 1        | Aux Receiver, ICOM IUX-R96                 | $389   |
| 1        | TNC, AEA PK-88                             | $400   |

## Data Processing/Display

| 1        | 4' RS-232 cable                           | $10    |
| 1        | PC, IBM compatible,                       | $2500  |

TOTAL: $7015

## NOTE:
Total does not include software (GrafTrack II and Procomm +) and/or installation costs.

### Additional Hardware/Software Required For APT Processing

| 1        | Interface Board, A&A Engineering          | $70    |
| 1        | Multifax software, David Schwittek        | $50    |

### Additional Hardware Required for VHF Audio Recording

| 1        | Audio Tape Recorder, GE                   | $100   |
GROUND STATION DESCRIPTION

The telemetry ground station will consist of three major subsystems: ground antenna, telemetry front end, and data processing/display (Figure 11). A steerable 13 dB gain circular polarized helix antenna will amplify and radiate packetized commands at 149 MHz and 170 W. The helix antenna will also receive telemetry files transmitted by SOESAT at 136 MHz and 4-10 W. The telemetry front end will consist of a commercial VHF FM transmitter and receiver. Command and telemetry ASCII files will be formatted and error checked by an off the shelf terminal node controller. The terminal node controller will be compatible with the SOESAT 1200 bps uplink and 9600 bps downlink. A command pool will reside on an IBM compatible personal computer (pc). The pc will also store telemetry files during the satellite pass and process/display the measurands postpass. SOESAT orbital vectors will be acquired from NORAD and propagated on the pc by commercial software to produce vehicle ephemeris with visibility times and local look angles.

SYSTEM LAYOUT

The helix ground antenna will be located on top of the engineering building at San Jose State University. A site survey has been completed. The antenna will be attached to an existing railing with standard television type U-bolts. The preamp and high power amplifier will be attached to the antenna mast and enclosed in a weatherproof housing. The amplifier will be powered by utility power existing along the railing or through the coaxial cable transmission line. The Az/El rotators will be powered by utility power existing along the railing. The twisted pair Az/El rotator control lines will run along with the transmission line into the lab. The low loss transmission line will run approximately 100 feet down the antenna mast, along the railing, down the side of the engineering building and into the lab through a drilled hole. The transmission line will be secured to the mast and the railing with steel ties and secured to the building with television cable u-nails. The transmission line will then be attached to the transceiver using an N-type connector. The transceiver will be attached to the auxiliary receiver by an 8-pin connector. The transceiver push-to-talk (ptt) port will be connected to the terminal node controllers (tnc) ptt-out port. The transceivers mike audio port will be connected to the tnc data out port. The transceivers automatic frequency control (afc) port will be connected to the tnc afc port. The transceiver to tnc cables are provided with the tnc. The tnc will be connected to the personal computer (pc) with a 4 foot RS-232 cable. The transceiver, receiver, tnc, and pc will all run on utility power with common ground.

For APT receiving the interface board should be installed in the pc and directly connected to the receiver using the vendor supplied cable. During this mode of operation the tnc should be disconnected. For the reception of audio FM signals from Mir or
SOESAT LOW COST TELEMETRY GROUND STATION

AZ/EL Rotator

6-Turn Helix Antenna

Amp/Preamp

Twisted Pair

Transmission Line

Antenna Controller

Transceiver w/ Aux Rcvr

PTT

AFC

XMT

RCV

Terminal Node Controller

RS-232

Personal Computer

Ground Controller

Mission Controller

149 MHz

136 MHz
the space shuttle the audio out port of the receiver should be connected to a speaker and/or audio recorder.

Two crew members are required during a satellite contact. The ground controller will sit in front of the antenna controller and track the spacecraft during the contact. The ground controller (gc) will use a table of azimuth/elevation angles versus time values generated prior to the pass to guide the antenna manually. He will be able to see the helix antenna and monitor the received signal strength from his position. This manual task can be eliminated by converting the local look angles into electronic servo commands using another pc. Various vendors produce the software and hardware required for this task. The gc will also be responsible for all transceiver and receiver modifications during the contact. The mission controller will sit in front of the pc and have visual contact with the tnc when required. He is responsible for commanding the spacecraft and receiving/storing the downlinked telemetry during the satellite contact.

PRE-PASS OPERATIONS

Pre-pass operations consist of three major tasks; look angle generation, command pool and pass plan generation, and pre-pass check out test. Look angles are generated using software hosted on the pc. GrafTrack II or any compatible commercial or personally written software will do. The software must be able to accept a vehicle state vector in \( x, y, z, \dot{x}, \dot{y}, \dot{z} \) format or classical Keplarian orbital elements with its associated time tag and local geographic position and altitude of the ground station. It should be capable of modeling all major orbital perturbations especially atmospheric drag (for satellites below 1000 nm), nonspherical earth, solar radiation pressure (for high altitude satellites) and third body effects. State vectors must be acquired from NORAD USSPACECOMM. On site orbit determination is not possible. Procedures for acquiring a state vector from NORAD have not been developed. Using the orbit software, local time tagged look angles can be generated and printed for on console use. Look angles printed at one minute intervals during a pass should do (SOESATs velocity at apogee will be small enough that this should suffice).

Command pool generation is accomplished by creating the command files on the pc or importing them by disk. Command files will be loaded using commercial tnc software. Commands will be one of seven different types: Ephemeris uploads, Payload cmds, stored payload cmds, spacecraft cmds, stored spacecraft cmds, spacecraft software changes, and store-and-forward messages. Spacecraft and payload command formats have not yet been defined. Pass plans describing all pass objectives and expected spacecraft status at turnon should be drawn up and verified.

Pre-pass checks of all hardware and software prior to the transmission of the turnon command is essential to the efficient operation of the ground station and spacecraft. Three pre-pass
checks will be made before each contact: track test, command test and telemetry test. The track test consist of the ground controller slaving the antenna in azimuth and elevation in order to visually confirm full mechanical operation. The command test consist of transmitting a test command into a dummy load and verifying proper pc, tnc and transceiver operation. The telemetry test consist of receiving a telemetry file and ensuring proper storage of the file.

REAL-TIME OPERATIONS

During real-time operations the ground controller will slave to the proper azimuth and elevation for the contact time and the mission controller will transmit the turn-on command. This will initialize the link. The turn-on command will be retransmitted until the link is initialized. Once the link is initialized the tnc should indicate carrier detect (Reference 4). The link will be half-duplex. The mission controller can send seven different types of commands:

- Spacecraft Stored Program Command (spc) load
- Payload spc load
- Spacecraft command
- Payload command
- Vehicle ephemeris load
- Software load
- Store-and-forward message load

When all commanding is complete the mission controller will send the turnoff command. The receiver signal strength should be monitored to functionally verify turnoff.

POST-PASS OPERATIONS

Post-pass operations consist of data analysis and mission planning. The pass should be logged to document all actions during the contact. Data analysis includes processing the telemetry and determining the spacecraft and payload state of health. Payload data should then be formatted according to the payloaders requirements. Data formats and processing requirement have not been defined. Mission planning includes assessment of all on orbit spacecraft and payload requirements and allocating those requirements to specific satellite contacts. First, all visibilities need to be identified. Second, specific pass objectives need to be identified and allocated to specific passes. Checks should be made to ensure that all objectives can be met in the allocated duration of the pass. This will require calculations of command file lengths and communication link data transfer rates.
LINK ANALYSIS

Transmitted space waves are attenuated along its path by a variety of phenomena both constant and variable. Transmission losses are a combination of feeder losses, free-space spreading, atmospheric absorption, antenna misalignment, and polarization mismatch. The weakest link will be the downlink because the spacecraft transmit power will be fixed and the antenna orientation of the spacecraft antenna with respect to the ground station antenna will vary with the tumbling of the satellite. The uplink transmitter power can be increased to such a point that signal reception is guaranteed. With this in mind, a detailed analysis of the downlink follows.

Transmitter feeder losses through the spacecraft antenna are minimal (.01 dB approximately) and can be folded into the transmitted signal power or the transmit antenna gain (Reference 3). Free space spreading is constant and is dependant upon the distance between the transmitter and receiver. A worst case scenario should be used. In the case of SOESAT a slant range of 42000 km will be the worst case experienced when SOESAT is at apogee and the ground station is waxing or waning over the horizon. Atmospheric absorption is a result of energy absorption by the atmospheric gases. At the 2 meter wavelength atmospheric absorption is on the order of 0.03 dB (Reference 3). Rainfall results in attenuation of radio waves by scattering and absorption of the wave energy. Rainfall attenuation is variable and is typically less than 0.2 dB 99% of the time (Reference 3). Antenna misalignment results when the transmit and receive antennas are not aligned for maximum gain. Because the tumbling SOESAT has no attitude control system, omnidirectional antenna will be used. The quadrifilar helix has a gain of 1.76 dB in the plane perpendicular to its longitudinal axis and 5 dB gain along that axis (Reference 2). The half-power beamwidth or the point where there is a 3 dB gain dropoff is 57 degrees from the maximum gain axis, which creates a 114 degree beamwidth (Reference 2). The receiving ground station antenna has a maximum gain of 13 dB and a half-power beamwidth of 45 degrees (Reference 2). Ephemeris generated from NORAD vectors should provide sufficient ground station antenna pointing accuracy to maintain less than 1 dB attenuation due to antenna mismatch.

The received noise is a function of total effective temperature of the receiver and the bandwidth of the transmitted information signal. The effective temperature of the receiver is the combination of sky temperature at the receiving frequency and the receiver temperature. The sky temperature for receiving at 136 MHz is approximately 150 K and is often much better (Reference 3). The temperature of the receiver is a function of the noise figure for the receiver. The noise figure takes into account stage noise including preamp noise and transmission line noise (Reference 2).
The bandwidth of the Frequency Modulated information signal equals: $2*(\text{peak frequency deviation of carrier} + \text{maximum modulation frequency})(\text{Reference 3})$. The maximum modulation frequency is fixed by the modem which is chosen. Most AFSK modems use a 1000 Hz tone for a zero and a 1200 Hz tone for a one. The peak frequency deviation of the carrier is configurable by the transmitter. On board the spacecraft, however, it will be configured prior to launch at the maximum deviation of 5 KHz. This equates to a downlink signal with a bandwidth of 12400 Hz.

The receiving filter must allow enough room not only for this information signal bandwidth of 12.4 KHz but also allow for a guard band. A guard band of 2 or 3 KHz is more than sufficient. The ground station receiver therefore will be configured for a 15 KHz bandwidth information signal. The receiver on board the spacecraft will only accept a minimum carrier modulation of 7 KHz (Minimum spacecraft receiver acceptance according to manufacturers specs). This can be configured on the transmitting equipment at the ground station. The ratio of frequency deviation to frequency modulation is called the modulation index or just mod index. The downlinked mod index will be 4.167 and the uplinked mod index will be 5.83 (Reference 3).

The downlink link analysis was completed using both possible power settings available on the spacecraft transmitter. The signal to noise ratio is directly equivalent to the bit error rate. Figure 12 (Reference 5) shows the relationship between the bit error rate and the signal to noise ratio. The bit error rate expected with FSK modulation at 14-18 dB S/N is better than 10E-5.
Spacecraft Characteristics:
Transmit power= 4-10 W
Bandwidth (B)= 15 KHz
Antenna gain= 1.76 dBi - 5 dBi (RHCP quadrifilar helix)
Max slant range (d)= 42,000 Km

Ground Station Characteristics:
Antenna gain= 13 dBi (RHCP 6 turn helix)
Sky Temperature (Ts)= 150 K
Receiver noise= 1.83 dB
Bandwidth (B)= 15 KHz

Signal to Noise ratio (S/N)= \frac{\text{Received signal power}}{\text{Received noise power}} = \frac{W_s}{W_n}

S/N (dB)= 10 \log W_s - 10 \log W_n = Ps - Pn

Signal:
Ps= xmtd signal power (dBm) + xmt antenna gain (dBi) + rcv antenna gain (dBi) - free-space path loss (dB) - antenna misalignment (dB) - atmospheric absorption (dB) - rainfall attenuation (dB)

xmtd signal power (4 W)= 10 \log 4000 \text{ mW}= 36.02 \text{ dBm}

xmtd signal power (10 W)= 10 \log 10000 \text{ mW}= 40 \text{ dBm}

free-space path loss= 10 \log (4\pi d/\lambda^2)= 168.2 \text{ dB}

Ps (4 W)= 36.02 dBm + 1.76 dB + 13 dB - 168.2 dB - 1 dB - 0.03 dB - 0.2 dB = -118.65 dBm

Ps (10 W)= 40 dBm + 1.76 dB + 13 dB - 168.2 dB - 1 dB - 0.03 dB - 0.2 dB = -114.67 dBm

Noise:
Wn= k Te B
where k= Boltzmann's constant= 1.38 \times 10^{-20} \text{ mW/(Hz K)}
Te= Ts + Tr
Tr= rcvr temp (K)= 290(10^E(Ft/10)-1)
Ft=system noise figure= 10 \log f
f= preamp noise+ (coax noise- 1)/preamp gain

f= 1.26+ (2-1)/40= 1.285
Ft= 10 \log 1.285= 1.089 \text{ dB}
Tr= 290(10^E(1.089/10)-1)= 82.65 K
Te= 150 K + 82.65 K= 232.65 K

Wn= (1.38\times10^{-20} \text{ mW/(Hz K)}) (232.65 K) (15000 Hz)= 4.82 \times 10^{-14} \text{ mW}

Pn= 10 \log Wn= -133.17 \text{ dBm}

S/N (4W)= Ps- Pn= -118.65 dBm- (-133.17 dBm)= 14.52 dBm

S/N (10W)= Ps- Pn= -114.67 dBm- (-133.17 dBm)= 18.5 dBm
BER performance of BPSK, coherent FSK, and noncoherent FSK.

Figure 13
List of References


6-Turn Helix Antenna (13 dB)

 prejudiced diameter.

G = 0.8 \lambda or greater.
N = number of turns = 9
P = 0.12 \lambda space from reflector to start of first turn.
S = \frac{1}{4} \lambda space between turns center to center.
\lambda = wavelength in free space.
l(inches) = 11.810
f (MHz)