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11. Telemetry, Tracking & Commanding

11.1 Introduction

In order for any satellite to be useful, a communications system must be placed on board. The system can be as simple as a radio frequency (RF) beacon which Just puts out a beeping sound on a particular frequency. This example of communication would be one-way (downlink only) since no uplink could be performed from the ground. The early OSCAR series satellites, produced by the Amateur Satellite Corporation (AMSAT), had communications systems of this nature. Most modem satellites have complex communications systems that allow command and voice uplinks as well as voice and data downlinks. These types of communications satellites typically operate in multiple modes and utilize several frequencies to provide worldwide communication.[1]

For project SPARTNIK, the Telemetry, Tracking and Commanding (TT&C) subsystem is divided into two hardware categories: the spacecraft and the SPARTNIK Ground Station (SGS). Interaction between these two nodes, via software and communications links, will enable the Project SPARTNIK Team to receive telemetry from the spacecraft, track the orbit, and send commands to the vehicle.

The following presentation is a review of the final design for the Project SPARTNIK TT&C Subsystem. First, the purpose behind each of the two hardware nodes (spacecraft and ground station) is presented. Then the design drivers are reviewed for each node. Following that is a step-by-step design of the TT&C system, to include an analysis of the baseline hardware choices. Next, the testing and operations plans are discussed. Finally, recommendations are made on the future integration of the TT&C system.

11.2 Purpose

11.2.1 Spacecraft Communications Subsystem

The SPARTNIK spacecraft was designed for completely autonomous operations. However, contact must still be made with the vehicle periodically in order to keep it flying and execute its payload functions. This means the spacecraft bus must have some type of communications capability. The communications package to be flown on board SPARTNIK is faced with the same design constraints as the rest of the vehicle. This means the hardware design must fit in the smallest space possible, using little power, creating little thermal and electromagnetic disturbance, and costing as little as possible. A delicate balance of all of these drivers must be met while at the same time flying a communications package that will provide reliable service in all possible environments the spacecraft may encounter.

11.2.2 Ground Station Communications

The SPARTNIK Ground Station (SGS) also faces many design considerations. Project SPARTNIK does not have the budget nor the resources to emulate commercial spacecraft communications systems. High-power parabolic dish antennas, mainframe processing systems, and worldwide tracking stations are far too expensive to purchase and maintain. Ground communications for SPARTNIK must be scaled down considerably. Communications links must be designed using frequencies which do not have to be leased, which can be accessed through inexpensive low-power equipment and which can efficiently and reliably meet all communications goals. Team SPARTNIK must be able to execute on-orbit operations effectively at a minimum of cost and personnel.

11.3 Literature Search Results

Through an historical analysis of microsatellites with size, orbit, and economic constraints similar to SPARTNIK, it became clear that amateur radio communications has proven to be a very efficient, reliable, and popular method of satellite uplinks and downlinks, People have been communicating with satellites through amateur radio for as long as artificial satellites have been orbiting the earth. In fact, an entire series of satellites have been launched specifically for that purpose. The equipment is fairly inexpensive, reliable, and readily available.[2] Amateur radio adequately fills all of the requirements for the SPARTNIK communications system.

Amateur, or Ham radio is defined as those bands on the electromagnetic spectrum which are specifically set aside by the International Telecommunication Union (ITU) for use by amateur radio operators around the world. Although, this capability is offered to the general public, the ITU and the United States Federal Communications Commission (FCC) still monitor and regulate these frequencies. The following are among the most significant amateur radio regulations[3]:

- One must pass an FCC administered test to obtain an amateur license.
- An FCC license is required in order to transmit from any station in the U.S.
- Amateur radio operators must remain within their assigned frequencies.
- Periodic station identification is required during transmission.
- Operators must follow proper airwave etiquette as defined by the FCC.

What this means, as far as SPARTNIK Ground Station operation, is that an experienced, licensed radio operator, or "Ham," must be responsible for the control station every time two-way contact is made with the vehicle.

The FCC has special rules and regulations governing satellite or "space station" operation. These rules make certain concessions allowing for the dissimilarities between control station and space station operation. For example, space stations are allowed to transmit beacons, transmit encoded signals, use higher data rates, and function without a control operator directly responsible for the transmitter equipment.

Amateur radio frequencies that apply to SPARTNIK communications include[4]:

- The 144.000 - 146.000 MHz Band (2m wavelength)
- The 435.000 - 438.000 MHz Band (70cm wavelength)

Note: the amateur bands are sometimes referenced in terms of signal wavelength.

The OSCAR (Orbiting Satellite Carrying Amateur Radio) series of microsatellites are actually orbiting relay stations, or "bent pipes," for voice and data communications. To simplify this full duplex function, the Amateur Satellite Corporation (AMSAT) has defined various "modes" of satellite communication. A mode is an ordered pair of frequencies which, when used in conjunction with each other, allow duplex operation on the uplink and downlink of the vehicle. The OSCAR satellites carried transponders that would accept communication on one frequency band and relay it on another. Two modes that apply to the SPARTNIK Ground Station include:

- Mode B (70cm uplink, 2m downlink)
- Mode J (2m uplink, 70cm downlink)

The SGS will have the capability to transmit or receive on either wavelength. However, Mode J is better suited for SPARTNIK communications because it has been proven effective for low-altitude orbits. Also, the higher frequency downlink will be more efficient for telemetry and mission data communications. Therefore, Project SPARTNIK will employ Mode J for communications, or more specifically, Mode JD, which signifies digital packet data transmission[6]. The spacecraft will not carry transponder equipment, so it will not function as a repeater.

11.4 Design Drivers

11.4.1 Spacecraft Communication Requirements and Constraints

11.4.1.1 Spacecraft Requirements

There are three communications requirements for the design of the TT&C system:

- Receive command and control data from the ground station
- Transmit telemetry and mission data to the ground station
- Allow full duplex operation

To accomplish these requirements, the spacecraft communications system needs to be equipped with receiving and transmitting systems with independent antennas, a demodulator/amplifier, a transmitter, a receiver, and a software terminal node controller (TNC) housed in the main CPU. After the satellite receives a transmitted signal from the ground station, the signal is immediately sent to a demodulator to strip off the RF carrier. The down converted signal is then processed through the receiver. If the signal contains command and control data, it is sent to the CPU to decode the data bit stream and distribute the information to other systems within the spacecraft. Outgoing signals such as processed telemetry and experimental payload data are first sent to the CPU to combine all the data into a single bit stream of information. The signal is then placed on a RF carrier frequency by an amplifier and transmitted to the ground station.

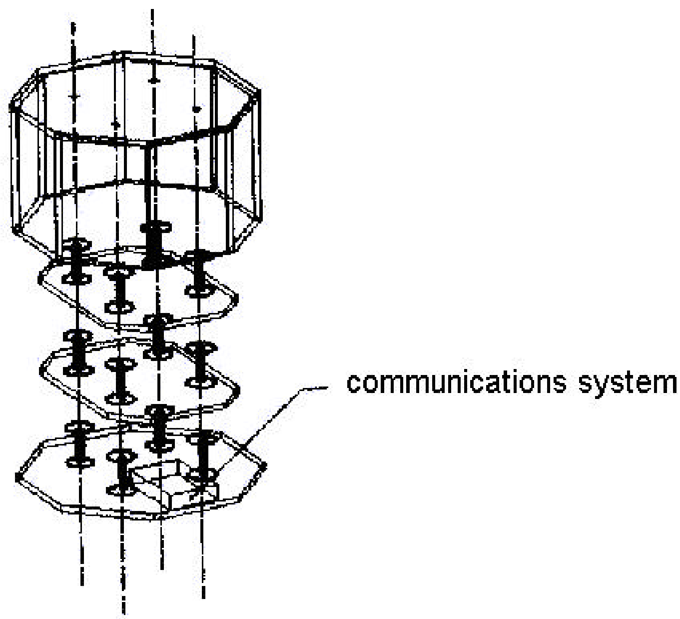


Figure 11. 1: Location of Onboard Communications Electronics

Since physical volume on SPARTNIK is limited, the size of the onboard communications electronics, when completed, will be no larger than the motherboard of an average PC. As shown in Figure 11 - 1, the RF deck has been placed on the bottom tray of the satellite.

The onboard communications system must:

-- Send and receive voice communications using the following amateur band frequencies:

144.000-146.000 (uplink)
435.000-438.000 (downlink)

-- Downlink approximately 80 kilobytes of compressed digital images from the Kodak camera at a user selected throughput of 1.2 - 57.6 kilobaud. The data rates above 9.6 kilobaud will be experimental based on the operational capabilities of the satellites power.
-- Downlink collection data from the on-board radiation sensor.
-- Downlink telemetry from all onboard sensors:

-- Thermal sensors
-- Infrared horizon sensors
-- Voltage and current sensors located throughout the spacecraft
-- Micro-meteorite impact data in the form of a voltage intensity reading.

-- Handle uplink commanding from the ground station using the 144.000-146.000 MHz frequency band.
-- Handle the uplink of new CPU programming code and firmware.

11.4.1.2 Spacecraft Constraints

During the design of the SPARTNIK communications system, three project constraints were considered in order to ensure the success of the project: low cost, minimal available power onboard the satellite, and the small structure of the microsatellite. From the project standpoint, the communications system must provide the best quality RF signal at the lowest cost possible. To satisfy these constraints, the amateur radio field and industry contributions were pursued for parts and equipment. The hardware components for the onboard RF communications system were donated by Philips Semiconductors and Motorola, with engineering dependent on the SPARTNIK Team.

A major concern for the on-orbit satellite is available power. As determined from researching previous microsatellites' communications system power consumption data, one watt of power has been determined as the necessary amount of power needed to generate the necessary RF carrier from a worse-case low Earth orbit of 1000 kilometers altitude. Since SPARTNIK falls within the microsatellite category, defined as being less than 50 kilograms in mass, this limits the relative size and mass of the entire onboard communications system.[8] Including wiring and antenna arrays, the current design for the communications system has been constrained at 7.5 kilograms.[9]

11.4.2 Ground Station Requirements

The ground station can be thought of as the lifeline of the satellite. A standard amateur radio ground station is composed of several essential components: the receiving and transmitting antennas, the RF amplifier, a transmitter, a receiver, a multi-mode packet data controller, and a computer terminal. The function of each of these components is described in the Ground Station Configuration Section. Through the interaction of these components, the ground station must accomplish certain tasks as follow.

-- Send and Receive data and voice communications with SPARTNIK and other amateur satellites using the following amateur frequency Modes:

-- Mode J:
144.000-146.000 MHz (uplink)
435.000-438.000 MHz (downlink)

-- Mode B:

435.000-438.000 MHz (uplink)
144.000-146.000 MHz (downlink)

-- Receive and process telemetry from the thermal, power, and ADAC sensors.
-- Receive and process all experimental payload data:

-- Camera - color digital images (jpeg format)
-- Radiation Sensor - particle collection data
-- MMD - particle impact data

-- Send commands to SPARTNIK.
-- Determine, maintain, and Utilize Keplerian elements for tracking.

11.5 Design and Analysis

11.5.1 Spacecraft Communications System Design

11.5.1.1 Link Budget Theory

Any communications link design between a satellite and a ground station must account for all power losses between the transmitting and receiving nodes. The link budget involves the multiplication and division of large numbers ranging over many orders of magnitude, conveniently simplified as logarithms and expressed in decibels (dB).[10] In order to calculate power in decibels of gain, the power ratio is introduced. This ratio is based on the power generated from an ideal isotropic radiator, which by definition radiates in all directions. The value of an isotropic radiator is accepted as 1miliwatt, giving meaningful units (dBm) to the power ratio. The power ratio can then be expressed as the generated power in miliwatts over the ideal isotropic radiator power with the units of dBm (dB above 1 milliwatt).[11]

$$G = 10 \log_{10} \textit{(Power Ratio)}$$

$$\text{Power Ratio} = \frac{P_1}{P_2} \qquad \text{(Equation 11.1)}$$

where, G = gain in dBm

P_1 = 2 milliwatts (design parameter)
P_2 = 1 milliwatts (ideal isotropic antenna reference value)

A +3 dB gain corresponds to twice the power of an isotropic antenna. This is shown by Equation 11-1 in the following example:

where, P_1 = 2 milliwatts
P_2 = 1 milliwatt (ideal isotropic antenna reference value)

Using this property, a linear relationship can be found. The relationship can be surmised as, "If you double the power you will obtain +3.0 dB of gain." Since this is a linear relationship, the converse is also true.

In addition to the radiated power from antennas, receivers, and transmitters the free space path loss must be considered in a link design. The free space path loss is defined as the loss of gain between two isotropic antennas due to the distance (p) between them at a particular frequency (f in megahertz). [12] Before the free space path loss can be calculated, the frequency must be expressed in terms of wavelength through the following equation:

$$\lambda = \frac{c}{f} \qquad \text{(Equation 11.2)}$$

where, f = frequency in megahertz
λ = wavelength in meters
c = speed of light (3×10^8 m/s)

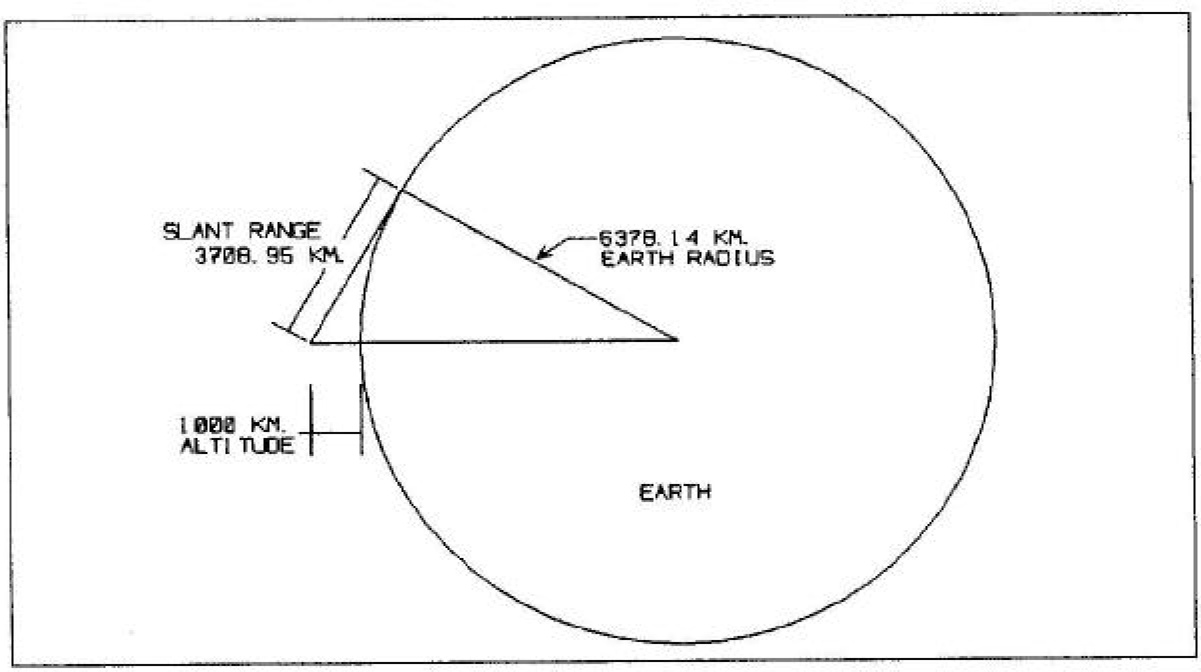


Figure 11.2: Worse Case Slant Distance for-an Orbit of 1000 km.

Figure 11.2 is a depiction of the slant range (distance) of a satellite in a circular 1000 km low Earth orbit. The figure shows a worse case transmitting distance of 3708.95 km to a tracking ground station on the surface of the Earth. The free space path loss is then determined by the following equation, which accounts for frequency and the inverse square law of power density vs. distance: [13]

$$L = 10\log_{10}\left(\frac{4pr}{l}\right)^2 \quad \text{(Equation 11.3)}$$

where, ρ = slant range distance in meters
L = free space path loss in dB

The third step in a link design is to analyze noise that can drown out a transmitted signal. Noise can originate from a variety of sources, but the most detrimental forms of signal noise come from cosmic radiation and from atmospheric conditions. In space, cosmic rays, such as solar radiation emitted from the Sun, can interfere with a transmitted signal. The Earth itself can reflect some solar radiation thereby causing additional noise in space. Within the Earth's atmosphere, noise can be generated by weather conditions such as electrical storms. To calculate the amount of noise, temperature is the parameter analyzed. To compute the received noise power, the following equations are used: [14]

$$T_R = 290(10^{F_T/10} - 1) \quad \text{(Equation 11.4)}$$

where, T_R = Received temperature in Kelvin
F_T = System noise figure

$$T_e = T_R + T_S \quad \text{(Equation 11.5)}$$

where, T_e = Effective system temperature
Ts = Sky temperature in Kelvin = 150K (worse case)

$$W_n = kT_eB \quad \text{(Equation 11.6)}$$

where, Wn = is in milliwatts of power
k = Boltzmann's constant = 1.38 * 10^{-20} mW/(Hz* Kelvin)
B = receiver bandwidth in hertz

$$N_O = 10\log W_n \quad \text{(Equation 11.7)}$$

or

$$N_O = 10\log k + 10\log T_e, + 10\log B \quad \text{(Equation 11.8)}$$

where, N_O = Total noise density in dBm within receiver bandwidth, B

The receiving and transmitting antenna gain are the two other parameters that must be taken into consideration in order to compute the signal to noise ratio. Depending on the type of antenna used the calculation of gain can vary. The gain value of commercially available antennas is documented in the specifications for each antenna. For link calculation purposes, the antenna system for the SPARTNIK satellite was assumed to have isotropic characteristics, but the typical gain for the dipole antennas that will actually be used is about 1.64 dB.

Table 11.1: Typical antenna gain[15]

Type of antenna	Typical gain
Isotropic (reference)	0
Half-wave dipole	1.64

To compute the signal to noise ratio the following equation is used:

$$SNR = (G_{TRANSMITTER} + G_{TRANSMIT\_ANTENNA} + G_{RECEIVE\_ANTENNA} - L) - N_O$$

(Equation 11.9)

where, SNR = Signal to noise ratio (S/N) in dB

$G_{TRANSMITTER}$ = Transmitter gain in dBm

$G_{TRA.NSMIT\_ANTENNA}$= Transmit antenna gain dB

$G_{RECEIVING\ ANTFNNA}$= Receiving antenna gain in dB

Table 11.2 is the trial RF downlink budget for the SPARTNIK satellite in a 1000-km circular low earth orbit for 436 MHz. The calculations for this table are provided in Appendix 11-A. The 1000-km LEO is a worst-case scenario for the SPARTNIK spacecraft, and 436 MHz is a medium-range frequency. Since power is a driving design constraint, the communications system link was based on I watt of power (30.0 dBm), a convenient reference for assessment. Within the spacecraft the internal cabling and connectors will have some associated losses. Although this loss is small and may not adversely affect the transmitted signal, it is still accounted for and assumed to be -0.5 dB. [16] Any transmitting antenna will have some minimal value of gain. By definition, an ideal isotropic antenna has no gain and is therefore the worse case antenna. For calculation purposes the transmitting antenna is assumed to be an ideal isotropic antenna. The free space path loss is the parameter that contributes the most loss to the signal due to the slant range distance and can be calculated using Equation 11.3. The value for the ground station receiving antenna, of + 15.2 dB, was obtained from the manufacturers specifications. Assuming a sky temperature of 150 K, the noise density can be calculated using Equations 11.4 through 11.8.[17]

Table 1 1.2: Trial -RF Downlink Budget For SPARTNIK at 436 MHz

ITEM	SOURCE	GAIN
TRANSMITTER POWER (1W)	Design Parameter	+30.0 dBm
SPACECRAFT CABLE AND FILTER LOSS	Assumed	-0.5 dB

SPACECRAFT ANTENNA GAIN	Worse case isotropic assumption	+0.0 dB
FREE SPACE PATH LOSS	Calculated	-156.6 dB
GROUND STATION ANTENNA GAIN	Manufacturer Specifications	+15.2 dB
RECEIVED POWER	Calculated	-112.9 dBm
NOISE DENSITY (T_S=150K)	Calculated	-128.7 dBm
SIGNAL TO NOISE RATIO	Calculated	+16.8 dB

For the 436 MHz frequency, the received signal has + 16.8 dB of gain going into the receiver. Variation within the 435.0 - 438.0 MHz frequency range does not change this value significantly. However, the link budget was calculated based on a downlink frequency bandwidth of 30 kHz. This should be sufficient to downlink data at 9600 baud, and possibly even up to the desired data rate of 57.6 kbaud. This will have to be experimentally determined. If the downlink bandwidth must be doubled, this will cause a 3.0-dB loss in the SNR, and so forth. The bandwidth necessary for a high-speed downlink is not anticipated to cause much of a problem because the original calculations were based on worst-case assumptions in altitude, bus power, and line losses. Even taking all of these factors into account, the SNR was still calculated to be a 16.8 dB gain. For comparison, anything above a 10-dB gain typically suggests an adequate link.

11.5.2 Hardware Design

Since the main constraining factors are power, size, and mass, the communications system must be designed around those key elements while still fulfilling the system requirements. The International Telecommunication Union (ITU) has allocated several frequencies which can be used by amateur radio operators. On orbit, the SPARTNIK communications system will use the amateur Mode JD for uplink and downlink of data (2m uplink, 70cm. downlink)

The size and mass of the main communications system is similar to that of a PC motherboard. The compact size allows for easy mounting in a specially designed tray within the spacecraft bus. Although the normal operating power required is anticipated at 3 watts, the board will operate on an SGS selectable power level of 0.5 - 5.0 watts. This feature serves as a transmitter gain control. The communications system requires a regulated 5 volts DC for transmitting and 3 to 5 volts DC for receiving from the power bus. The communications system is a RF deck designed by Team SPARTNIK with components donated to this project by Philips Semiconductor and Motorola. It will be required to have a data throughput of 1.2 kbaud to 9.6 kbaud. To expedite downlink transfer of large camera tiles, data rates between 9.6 kbaud and 57.6 kbaud will be examined on an experimental basis.[18]

Physically the RF deck is on a standard two-layer circuit board co-located with the CPU and measures approximately 26 cm. in length by 13 cm. in width. The board will be mounted to the bottom computer tray of the satellite and connected to the antennas by SMA connectors via 50 Ω semi-rigid coax cable.[19] The spacecraft hardware is currently in the breadboard prototype design phase. Once this design is tested and validated, the schematic will be submitted to volunteers at Philips Semiconductor who will manufacture the printed circuit boards to be flown aboard SPARTNIK.

The RF deck can be broken down into two components, the receiver and the transmitter and will be capable of both full and half-duplex operation. The receiver portion of the RF deck is functionally depicted in Figure 11.3. It is a double-conversion superheterodyne system with the first intermediate frequency at 45 MHz and second intermediate frequency at 455 kHz. A Phase Lock Loop (PLL) is used to maintain lock on the incoming frequency, and a quadrature detector is used to demodulate the Binary Frequency Shift Keyed (BFSK) FM digital bit stream. The result is a demodulated binary bit stream to be sent to the on-board CPU.[20]

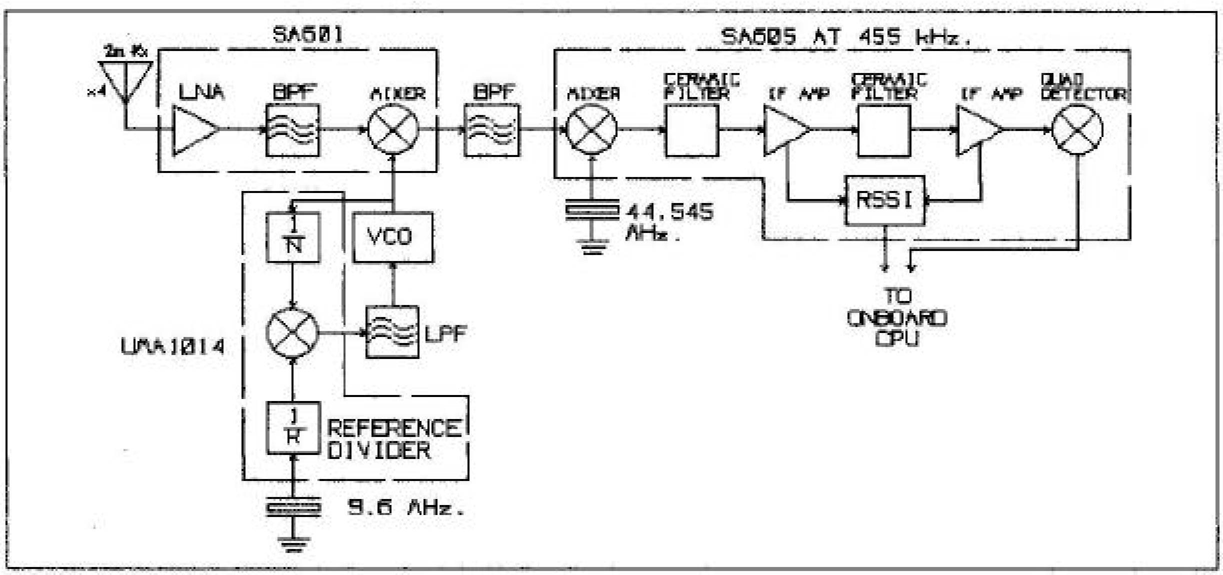


Figure 11.3: SPARTNIK Receiver Block Diazram

Two unique features characterize this receiver. First, the second intermediate frequency conversion stage employs a Received Signal Strength Indicator (RSSI). This is a chip originally designed for cellular telephones, which provides an output indicator proportional to the received signal strength from a ground station over approximately a 90dB range. This indicator will be modulated into all downlinked telemetry and will be used to assess the uplink and SPARTNIK Ground Station performance.

The second unique feature is the fact that the receiver is frequency agile. It is capable of receiving signals anywhere within the 144.0 - 146.0 MHz range in 5 kHz steps. This feature will be command uploadable with one particular frequency assigned as the reboot/default.[21] Once contact is made with the vehicle on its default frequency, it can be commanded to another frequency within the given range. The advantage of this feature is that if the default frequency is noisy or has a great deal of

Ham traffic, the ground station will be able to search for another, more facilitating channel. This is accomplished by varying the reference voltages in the phase lock loop (PLL).

The satellite transmitter is shown in Figure 11.4. It consists fundamentally of a voltage-controlled oscillator PLL and an RF power amplifier feeding the four 70 cm spacecraft transmit antennas. Like the receiver, this unit will be frequency agile, commendable to any frequency in the range of 435.0 - 438.0 MHz. Additionally, output power is variable, from 0.5 - 5.0 W, and can be set by commanding from the ground. This will allow the transmitter to consume only that power which is necessary to maintain a reliable downlink, a significant feature when spacecraft power is such a valuable commodity.

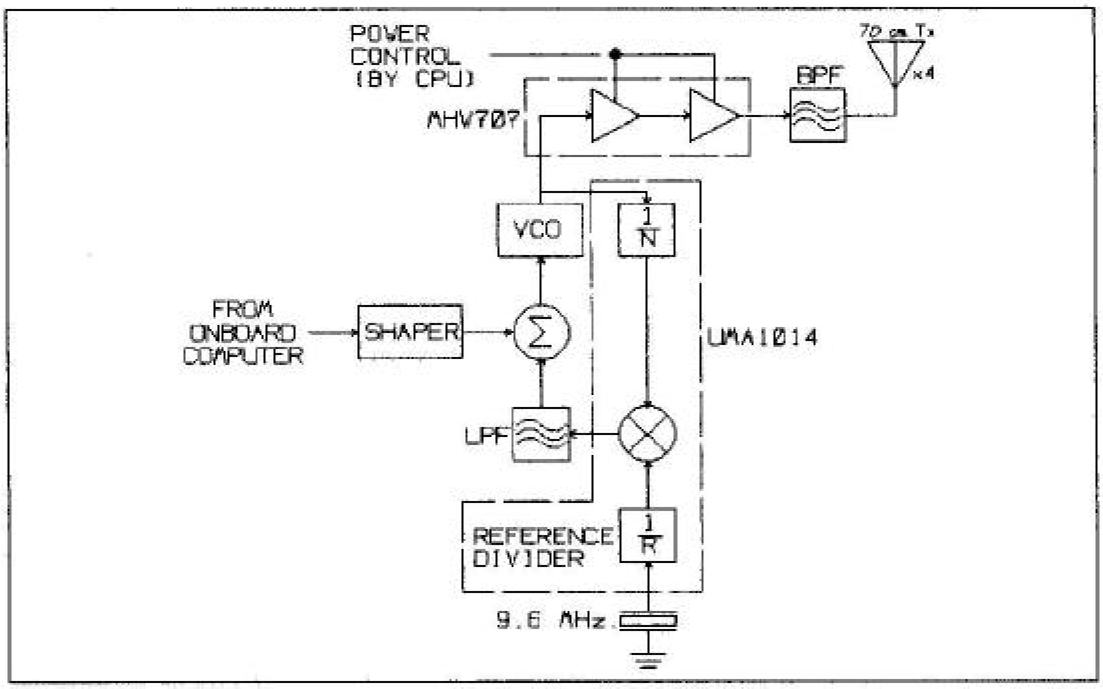


Figure 11.4: SPARTNIK Transmitter Block Diagram

11.5.3 Baseline Hardware Choices

To simplify the design of the communications system, state of the art, direct synthesis will be used. The receiver will employ the Philips SA601 mixer and LNA, the SA605 low power mixer, and the UMA 1014 frequency synthesizer. For transmitting, a second UMA1014 will be used to modulate the data at the carrier wave frequency. The Motorola MHW707 power amplifier will also be used to increase the transmitting signal strength. The following is a general description of the components along with a table of general operational data.

UMA 1014 Low-power frequency synthesizer:[22]

The UMA1014 is a low-power universal synthesizer that has been designed for use in channelized radio communication. The IC is manufactured in bipolar technology and is designed to operate at 5 to 100 kHz channel spacing with an RF input from 50 to 1100 MHz. The channel is programmed via I^2C-bus. A low-power sensitive RF divider is incorporated together with a dead-zone eliminated, 3-state phase comparator. The low-noise charge pump delivers 1mA or 0.5mA output current to enable better compromise between fast switching and loop bandwidth. A power-down circuit enables the synthesizer to be set to idle mode.

Table 11.3: Philips Semiconductors UMA1014
Low-power Frequency Synthesizer Data

PARAMETER	MIN.	TYP.	MAX.	UNIT
Supply voltage range	4.5	5.0	5.5	V
Supply current	---	13	---	mA
Supply current in power-down	---	2.5	---	mA
Power required	---	65	---	mW
Power required in power-down	---	12.5	---	mW
Phase comparator reference frequency	5	---	100	kHz
RF input frequency	50	---	1100	MHz
Ambient temperature	-40	---	+85	°C

SA605 High-performance low power mixer FM IF system:[23]

The SA605 is a high performance monolithic low-power FM IF system incorporating a mixer/oscillator, two limiting intermediate frequency amplifiers, quadrature detector, muting, logarithmic received signal strength indicator (RSSI), and voltage regulator. The SA605 features a high mixer input intercept point, an IF bandwidth of 25 MHz. and temperature compensated RSSI and limiters permitting high performance application.

Table 11.4: Philips Semiconductors SA605
High-performance Low-power Mixer FM IF System Data

PARAMETER	MIN.	TYP.	MAX.	UNIT
Supply voltage range	4.5	5.0	8.0	V
DC current drain	4.55	5.7	6.55	mA
Power required (at 5.0 VDC)	22.8	28.5	33	mW
Ambient temperature	-40	-----	+85	°C

SA601 Low voltage LNA and mixer: [24]

The SA601 is a combined RF amplifier and mixer designed for high-performance low-power communication systems from 800-1200 MHz. The low-noise preamplifier has a 1.6dB noise figure at 900 MHz with 11.5dB gain and an IP3 intercept of -2 dBm at the input. The gain is stabilized by on-chip compensation to vary less than ±0.2 dB over -40 to +85°C temperature range. The wide-dynamic-range mixer has a 9.5 dB noise figure and IP3 of -2 dBm at the input at 900 MHz. The nominal current drawn from a single 3V supply is 7.4mA. The Mixer can be powered down to further reduce the supply current to 4.4mA.

Table 11.5: Philips Semiconductors SA601
Low voltage LNA and mixer Data

PARAMETER	**MIN.**	**TYP.**	**MAX.**	**UNIT**
Supply voltage range	2.7	3.0	5.5	V
DC current drain	-----	7.4	-----	mA
DC current drain in power-down	-----	4.4	-----	mA
Power	-----	22.2	-----	mW
Power required in power-down	-----	13.2	-----	mW
Ambient temperature	-40	-----	+85	°C

MHW707 UHF Power Amplifier:

The MEW707 is a voltage controlled power amplifier which can generate a gain of +38.5 dB and which operates in the 403 MHz - 470 MHz frequency range.

Table 11.6: Motorola Semiconductor MHW707
UHF Power Amplifier Data

PARAMETER	**MIN.**	**MAX.**	**UNIT**
supply voltage range	---	9.0	V
power required	---	3.0	mW
control voltage range	0.0	7.0	V
power gain at 25'C	---	+38.5	dBm
frequency range	403	470	MHz
Ambient temperature	-30	+80	°C

11.6 Software Interface

Like most amateur microsatellites, SPARTNIK will incorporate standard AX.25 software for onboard communications use. However, due to the high cost, Team SPARTNIK will not be able to purchase a commercially available package. Taking the place of this commercialized software will be a custom-designed interrupt driven system that will emulate the AX.25 protocol in all aspects, as it will be written based on AX.25 specifications. Team SPARTNIK plans to develop this software and make it available as shareware for future amateur microsatellite endeavors.

For transmitting, the onboard software must control the transmitter power amplifiers and the baud rate at which data is to be downlinked. These values will be uploaded from the ground. In addition, the onboard software will emulate the operations of a terminal node controller (TNC) unit to allow packet communications. Put simply, a packet is a method for moving data in an efficient and reliable manner. For the RF deck to interface with the onboard CPU via the I^2C bus, a special driver program will be written. This driver program will center around the phase lock loop (PLL), a feedback voltage control portion of the Philips UMA14 frequency synthesizer.[25] The program will operate both synthesizers in one of three modes:

-- Full programming and initialization mode
-- Scan mode
-- Read mode

The programming and initialization mode will be implemented when the satellite is deployed into its orbit. This mode will also be used in emergency situations when the synthesizer has signaled an *out of lock* condition. The scan mode will be used to change themaindividerratiowithinaparticularUMA1014. The read mode occurs in an *out of lock* and is used to reset a hardware interrupt flag internal to the UMA1014 prior to reprogramming.

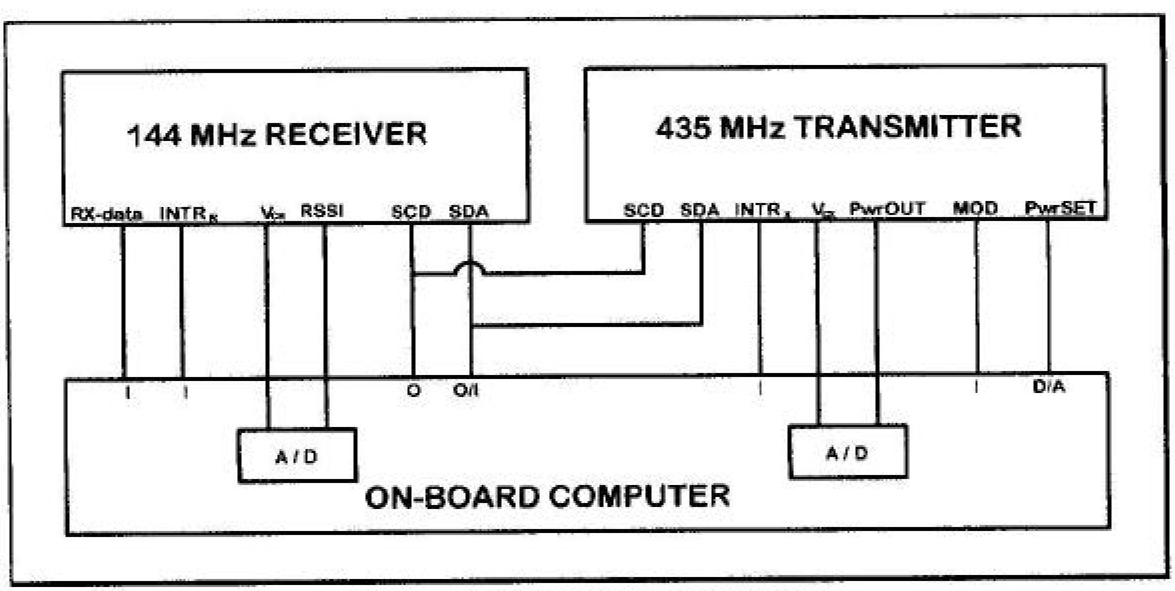


Figure 11.5: Onboard Computer and Communications Deck Interface

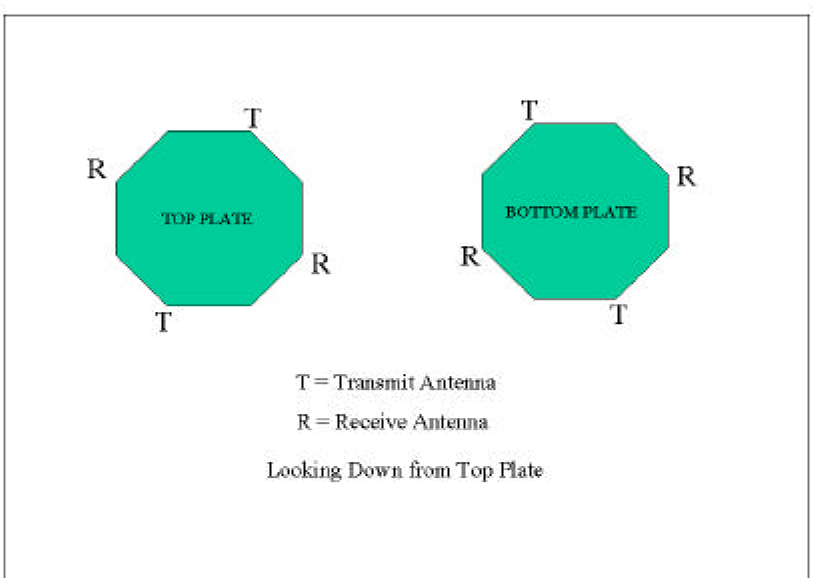
Figure 11.5 summarizes the interface between the spacecraft computer and communications systems. It shows a simple block diagram of the functional interface between the on-board CPU and the receiver and transmitter decks. Within the on-board CPU: I indicates a digital input line, O is an output line, while O/I can flow in either direction; A/D designates an analog-to-digital input port while D/A identifies an analog output port.

The transmitter and receiver units on the spacecraft both employ one phase locked loop (PLL) each for RF frequency control. The on-board CPU uses sub-carrier discriminator (SCD) and Serial DAta line (SDA), a two-wire synchronous bus (I^2C), to program and monitor these PLLS. In the event either PLL loses lock on its intended frequency, an interrupt is sent to the CPU via the relevant "INTR" pins. The interrupt service routine (ISR) called by this action will subsequently determine, through software, which PLL(s) is/are unlocked and will take appropriate action to re-initialize them. Additionally, the control voltage (which varies with programmed frequency) on each PLL is sampled through two AJD ports to assess incipient aging and frequency drift problems. These are shown in Figure 11.5 as "V_{CR}" and "V_{CX}" for the receiver and transmitter, respectively.[26]

The demodulated bit-stream from the receiver is shown as "RX-DATA" in Figure 11.5 while the out-going digital stream data modulates the RF carrier at the transmitter's "MOD" input. Received Signal Strength Indicator ("RSSI") provides a telemetry voltage giving an indication of the ground station's received signal over a range of about 90 dB. One D/A port on the onboard CPU is used to set the transmitter's RF carrier output power. This may be adjusted from the ground station based on a received signal strength indicator used on the downlink. A corresponding A/D port samples a fraction of the actual adjusted RF carrier output power to ensure the unit is functioning correctly and to observe incipient failure and general aging.[27]

11.6.1 Antenna Placement and Design

There are two antenna systems on the satellite for receiving and transmitting data communications. The first system is the 144 MHz receiving antennas which are to be mounted on the top and bottom face of the spacecraft alternating on every other corner with the second antenna system which are the 435 MHz transmitting antennas. The four antennas of each system, transmitting and



receiving with a total of eight antennas, are quarter-wave monopoles which are to be mounted in a turnstile fashion on the structural vertices of the satellite. The satellite will therefore have an antenna mounted on every other corner on both top and bottom plates (see Figure 11.6). The four receiving antennas measure 50 cm. in length and 2 cm. wide and will be placed at a 45° angle to the plane of the top and bottom face with the free end pointing away from the center of the satellite. The four transmitting antennas measure 17.5 cm. in length by 2 cm. wide.[28]

Figure 11.6: Approximate Antenna Placement on SPARTNIK

Both antenna systems will be made of spring steel, which is similar to a roll up tape measure. When in launch position, the antennas will be rolled up and stowed. Once the satellite has cleared the launch vehicle, an electrical charge will melt a nylon line that holds the Antenna Deployment Mechanism (ADM) and each antenna in the stowed position. When the line has melted, the ADM will spring open allowing the antennas to deploy into their operational positions. If the antennas do not deploy due to an unavoidable malfunction, the nylon line will degrade from exposure to ultraviolet rays to deploy the antennas. This fail-safe measure was implemented to ensure deployment.

11.6.2 Ground Station System Design

11.6.2.1 Hardware Design

The SPARTNIK Ground Station is located in the School of Engineering building at San José State University. It is in the Space Engineering Laboratory on the north end of the second floor. The main antennas are located three stories above the ground station on the roof of the building. The antenna array has been affixed to a tower that stands about 30 feet tall. Appendix 11-B details the antenna tower structure along with the approval of a professional civil engineer.

The roof antennas are connected to the equipment in the Space Systems Engineering Laboratory by Belden 9913 RG-8 low loss coax cable. The loss due to distance for this coax cable is about -3.0 dB per 100 feet in the 435 MHz range. The distance from the main antenna array on the roof is estimated at 150 feet, so a -4.5 dB loss of the signal going into the transceiver is expected for the 435 MHz antenna. The 144 MHz signal is expected to have 3.0 dB of loss because of the lower frequency.

Table 11.7: Belden 9913 Low Loss VHF-UHF
Attenuation Specifications[29]

Nominal Attenuation	
MHz	**DB/100ft**
1	0.1
10	0.4
50	0.9
100	1.3
200	1.8
400	2.7
700	3.6
900	4.2
1000	4.5
4000	11.0

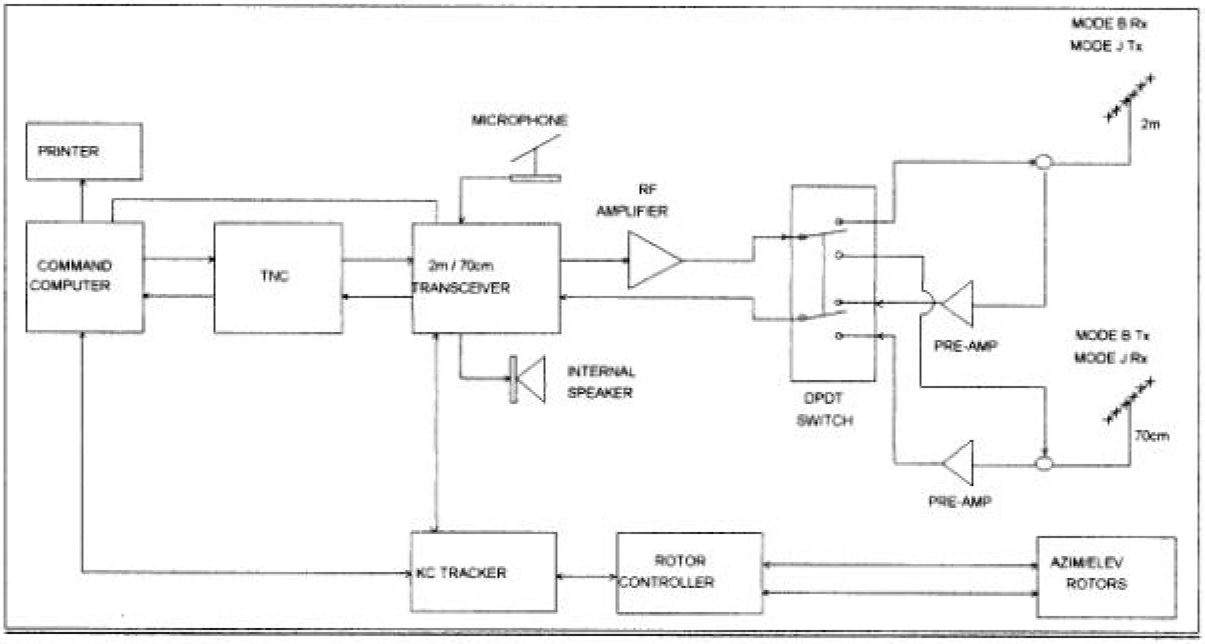


Figure 11.7: SPARTNIK Ground Station System Configuration

Figure 11.7 is a signal flow block diagram of the ground station setup. Shown are the two roof antennas, both of which are capable of receiving a signal. The 2 meter and 70 centimeter antennas will also have the ability to transmit depending on the Mode being used. This configuration allows the ground station to communicate not only with SPARTNIK but also with other amateur satellites. The design takes advantage of the duplex feature offered in the selected ground station transceiver by allowing simultaneous uplink and downlink of data.

The baseline configuration will be implemented for Mode J operation. This is transmitting (uplink) on the 2m wavelength, while receiving (downlink) on the 70cm wavelength. A 2m RF Amplifier has been incorporated in this configuration for more gain on the uplink. The ground station will also be capable of operating in Mode B, which is a reversal of the uplink and downlink wavelengths. This will be accomplished by throwing a switch that connects power only to the pre-amplifier on the receive antenna.

For command and control functions, the user would enter a command at the computer terminal. The command is then sent to the packet data controller (TNC for the ground station). The TNC processes the command into a signal that is then sent to the transmitter. The signal is then modulated onto an RF carrier frequency and sent out through the transmitting antenna to the satellite. When receiving voice or data communications from a satellite, the signal passes from the antenna through a preamplifier to augment a weak incoming signal. The signal is then demodulated down to the data and voice frequencies by the demodulator before it reaches the receiver. Any telemetry and experimental payload data is passed to the TNC which then separates the data for processing by the computer. The processing computer then displays telemetry data from the various onboard sensors.

The ground station is capable of operating fully autonomously through the use of the WISP (ver. 3215) software through the Kansas City Tracker with the Tuner option interface which drives the Azimuth and Elevation motors as well as tune the radio's receive and transmit frequencies while compensating for Doppler shift. The software package also stores downloaded data. All these operations can be accomplished without user intervention. The user simply turns on the equipment, opens the previously configured program, and updates the orbital elements to assure accurate tracking. When Spartnik is overhead, the ground station will autonomously track the spacecraft.

The computer terminal calculates satellite orbit, and therefore, antenna position using archived orbital element sets. It then periodically sends signals to the antenna rotor controller. The rotor controller in turn sends signals to the antenna rotors, driving them to the correct angles. The rotors send current position information back to the computer terminal.

Other possibilities, as depicted in the figure, are multiple mode use, frequency commanding and Doppler Shift update. The antenna pair can be switched from Mode J to Mode B by reversing the transmit and receive antenna frequencies. This is accomplished using the double-pole, double-throw (DPDT) switch, as explained above.

11.6.2.2 Ground Station Baseline Hardware Choices

The goal for the design of a good ground station is to eliminate the noise generated by the system itself so even very weak signals in the 145 and the 435 MHz frequencies could still be received. Although this goal can never be ultimately achieved, careful selection of equipment can minimize the system noise. To fulfill the system requirements for SPARTNIK several baseline choices were made for the ground station equipment. All of the communications equipment is of the amateur radio variety. Table 11.8 is the cost breakdown for the communications equipment purchased for the permanent ground station.

Table 11.8: Cost of San Jose State University Ground Station

Quantity	Manufacturer	Model Number	Description	Cost
1	Yaesu	FT-736R	25W 2m/70cm Transceiver	$1729.95
1	AEA	DSP-2232	2 Channel Data Controller	$879.95
1	Mirage	B-1016-G	2m 160W Amplifier	$329.95
1	KLM	2M-22C	22 Element 2m Antenna	$219.95
1	KLM	435-40CX	40 Element 70cm Antenna	$249.95
1	Yaesu	G5400B	Azimuth / Elevation Antenna Roter	$499.95
1	KLM	FM 7.5	7.5’ Fiberglass Mast	$59.95
1	Landwehr	2m	2m Pre-Amp	$199.95
1	Landwehr	435	70cm Pre-amp	$249.95
600 feet	Belden	9913	RG-8 Low Loss Coax Cable	$0.69/foot
300 feet	Belden	9405	Rotor Control Cable	$0.69/foot
30	Various	Various	Cable / Connectors	$88.00
1	Astron	RS-35A	DC Power Supply: 13.8 V, 25 A	$197.95
			Subtotal	$5326.5
			Sales Tax (8.25%)	$439.44
			Grand Total	$5765.94

11.6.3 Ground Station GUI (Graphical User Interface)

The Spartnik Ground Station GUI is designed in order to provide the user with the complete ability to control and monitor satellite activities and data. This Windows based software runs on machines running the Windows NT operating system and has been written in C++ using MFC (Microsoft Foundation Classes) for the interface components. The GUI uses a serial port to communicate with the TNC in order to transmit and receive data streams to and from the satellite.

The three primary features of the Ground Station GUI are:

1. Display of incoming information for the Power, Thermal, ADAC and Payload units: A separate view panel is dedicated to each subsection mentioned above and users can easily switch between views at any time. In addition, the GUI also has a main window that provides an integrated view of all the important data fields of each subsection.

2. Command Transmission: The Ground Station GUI allows for users to transmit commands and requests to the satellite either by piecing them together using drop down menus or simply by typing complete commands in a text box. Different levels of users (Super Users, administrators, etc) are allowed access to different sets of commands.

3. Interactive Chat Sessions: The Ground Station software also provides users with interactive satellite chat capabilities allowing them to communicate, in real time through the satellite, with other users using the same GUI software. A chat window displays the session contents.

In addition, the GUI restricts unauthorized access by requiring the user to login before the start of every session. User accounts can be created and maintained by the administrator.

11.6.4 Orbit Determination Code[30]

Necessary to the ability to track Spartnik is a capability to determine and maintain an accurate knowledge of the satellite orbit. The solution of the spacecraft orbit determination problem is highly dependent upon the type of tracking data available at the ground station. Many algorithms exist for different types and combinations of tracking data. Well-funded tracking stations are typically able to supply six or more observed parameters simultaneously, enabling explicit solution of the orbit determination problem via a large number of initial orbit determination algorithms. The low-cost ground station under development at SJSU, however, will initially be able to measure only Doppler shift as a function of time, thereby providing range rate as the single observable parameter, measured at a single ground station. An algorithm enabling explicit solution of the orbit determination problem using range rate data exclusively was not found, but orbit estimate *improvement* is still possible via differential correction. The algorithm described herein provides for state estimate improvement via differential correction using range rate data exclusively.

It is assumed that the initial orbit estimate will be supplied by the launch service provider. It is further assumed that this initial estimate will contain a higher level of error than will estimates given by subsequent improvement via differential correction, due to typical accuracy variances associated with launch and orbit injection. Additionally, the levels of noise and bias induced by the ground station equipment and the spacecraft transmitter are presently unknown, although estimates of these quantities have been computed. It is believed these items will induce a level of noise and bias higher than those typically seen at better-funded ground stations. Accordingly, methods were studied by which both the allowable error in the initial estimate and the tolerable level of systematic error could be increased without degrading the accuracy of the resulting solution. Extreme precision knowledge of the spacecraft position and velocity was not a requirement of the Spartnik project. Rather, the requirement was simply to provide a method whereby the orbit may be determined well enough to provide correct tracking estimates to within a few degrees in antenna azimuth and elevation for the lifetime of the spacecraft.

A least squares filter utilizing a modified Marquardt technique has been implemented at SJSU as the software package "Spartnik Orbit Determination Application" (SODA), and is expected to serve the needs of the Spartnik team for the lifetime of the vehicle. Additionally, improvements are expected to be implemented in the future. Improvements include outfitting the ground station to measure azimuth and elevation angles, as well as their time derivatives, and implementation of appropriate software algorithms for initial orbit determination using these data. A sequential filter may be implemented should the characteristics of the measured data show this to be an allowable pursuit.

11.7 The Transceiver: [31]

The Yaesu FT-736R Base Station transceiver is the heart of the ground station setup. The unit is a solid-state, frequency-synthesized VHF and UHF amateur radio transceiver incorporating the 144 and 430 MHz. amateur bands. The unit's 8-bit CMOS main microprocessor and 4-bit 1/o coprocessor provide digital integration and control: including selectable tuning rates or mode-dependent channelized tuning in selectable steps for each mode. The unit has ten memory settings with the capability of operating in a full duplex mode meaning it can receive and transmit at the same time. In special memory setting, a user can retain twelve satellite uplink / downlink modes at all times. Because of the wide frequency range covered by the FT-736R, this unit was the logical candidate for the ground station. Some basic characteristics of the Yaesu FT-736R are as follows:

General:

- Operating frequency ranges (MHz.):
  - 144.000 - 147.999
  - 430.000 - 449.999
- Power consumption:
  - Maximum: 250 VA
  - Receive: 1.5 A
  - Transmit: 8 A
- Antenna impedance: 50 ohms, unbalanced
- Dimensions (WED): 368 x 129 x 286 mm
  - Weight: 9 kg
- Transmitter:
  - Power input: 60 watts DC at 144, 430
  - Modulation methods:
    - Single Side Band (SSB) Balanced, filtered carrier
    - FM Variable reactance
- Receiver:
  - Circuit type:
    - 144 MHz.: double-conversion
    - Others: triple-conversion superheterodyne
  - Intermediate frequencies:
    - 13.69 MHz.
    - 455 kHz.
    - 47.43 MHz. on 430 MHz.
  - Audio output power: 1. 5W into 8 ohms

This unit is also commendable from a personal computer terminal using a built-in feature called the Computer-Aided Transceiver (CAT) System. The documentation provided with the unit details the entire operating protocol and instruction code chart. This feature may be integrated into the SPARTNIK Operations Control Software to be incorporated at the SPARTNIK Ground Station.

The transceiver had to be modified somewhat to interact with the Terminal Node Controller at the higher data rates necessary for SPARTNIK and other satellite operations. The unit was modified internally by SPARTNIK Team members, and additional RCA jacks were installed in the chassis for Tx input and Rx output. The Tx input was inserted directly into the Tx unit, bypassing all of the Mic filters and enhancers. The Rx data was tapped on the Rx unit, immediately after the discriminator. The 15 kHz bandwidth filter provided with the unit should be sufficient to receive data rates up to 9600 baud. However, for the SPARTNIK experimental data rate of 57.6 kbaud, a 30 kHz or larger filter may need to be designed and inserted in place of the factory issue.

11.8 The Terminal Node Controller:

The Terminal Node Controller (TNC) to be used at the SPARTNIK Ground Station is the Advanced Electronic Applications (AEA) DSP-2232. A TNC is an interface between the computer terminal and transceiver and is the amateur radio equivalent of a modem. The unit itself in fact has numerous user-selectable ROM modems within it ranging in data rates from 300 to 9600 baud, with multiple modulation techniques including Frequency Shift Keying (FSK) and Binary Phase Shift Keying (BPSK).[32]

The principle behind packet communications is simple. The TNC breaks down a data stream into many small, easy to handle "packets" of information. Along with the information from the computer, each packet contains addressing, error-checking, and control information. The addressing information is used to ensure there is a secure link between the TNC at the transmitting node and the TNC at the receiving node. The error checking information is used by the receiving node to determine if there are any errors in the packet of information just received. If there are errors, the TNC on the receiving end asks for re-transmission of that particular packet until it obtains an error-free copy. The transmitting TNC does not send the next packet until receipt of the previous one is confirmed. This method of operation ensures a reliable and secure means of data exchange.[33]

11. 9 The Power Supply:

A common power supply is employed at the ground station to supply voltage to all components that cannot be connected to standard 120 VAC outlets. This includes the TNC, 2m RF Amp, masthead pre-amps, and polarity relays. Most amateur radio equipment was designed to operate off of a marine battery, which nominally provides 1214 VDC. For SPARTNIK Ground Station purposes, an ASTRON RM-35A power supply is employed. This converts 120 VAC outlet voltage to a 13.8 VDC voltage supply at up to 25 A continuous current or 35 A intermittent use. The driving factor behind this unit was the 2m RF Amp, which can consume up to 25 A of current.

All of the above components are connected to the power supply and will draw various amounts of power based on need. Only one pre-amp is connected at a time, according to which "Mode" the switch box is set. The polarity relays will draw a minimal amount of current and only when voltage is applied to them through the switch box. When powered up, the TNC draws about 1 A continuously.

11.10 The Antennas:

The 144 and 435 MHz. antennas were purchased at a local amateur radio retailer and were manufactured by KLM Antennas, Inc. Both are circularly polarized, high-gain yagi antennas, capable of left or right hand circular polarization. The KLM 2M-22C is a 144 MHz (2m) antenna with 22 crossed yagi elements, while the KLM 435-40CX is a 43 5 MHz (70cm) antenna with 40 elements. Reference Figures 11.8 and 11.9.

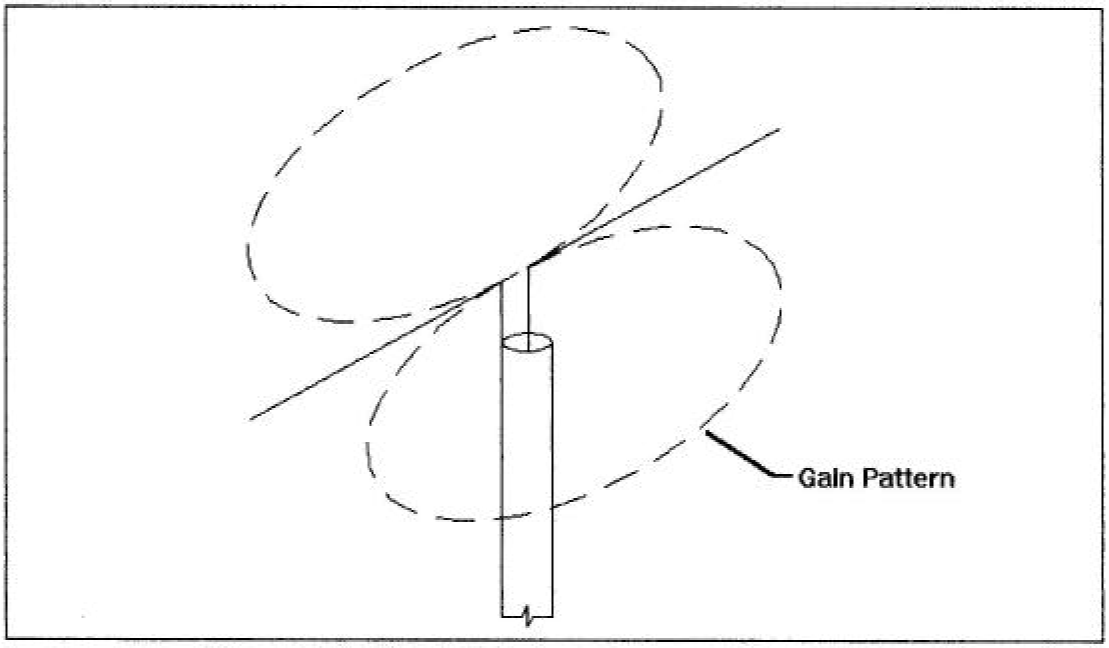


Figure 11.8: Simple Dipole Antenna and Gain Pattern

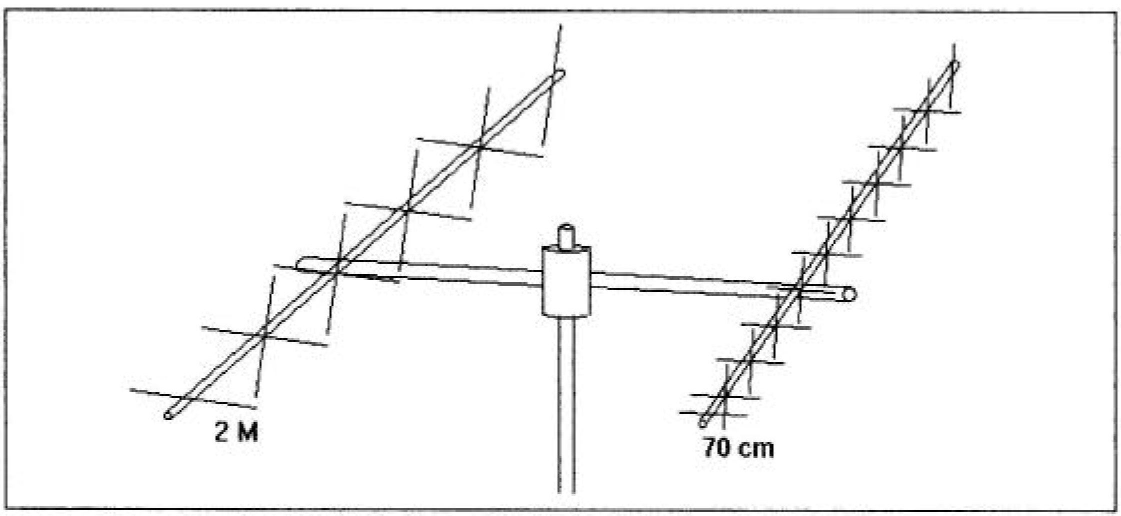


Figure 11.9: Crossed Yagi Antennas of High Gain

When properly spaced, centered, and crossed, the half-wave dipole yaggi elements are phased 90° from each other. This configuration allows the antenna to receive or transmit a circularity-polarized radio wave.

Each antenna has a polarity control that can alternate RF polarity between left and right circular. Applying a voltage to the polarity control relay causes the antenna polarity to change direction. This is accomplished using a switch box located at the ground station. Polarity control may be used on an experimental basis in an attempt to improve transmission or reception.

The aluminum booms are tapered to yield low windload yet retain strength where required. These antennas are the primary transmitting and receiving antennas for the ground station. They are mounted to a 7.5-foot horizontal mast that is in turn placed on the 30-foot antenna tower on the roof of the San José State University Engineering building. Tables 11.9 and 11.10 are partial listings of the manufacturer's specifications for the 144 MHz. (2 m) antenna and 435 MHz. (70 cm) antenna respectively. Both tables include the usable bandwidth, measured gain, and beamwidth (See Figure 11.10) for the particular antenna. The tables also list the overall boom length, windload, turning radius and weight of the antennas.

Table 11.9: 144 MHz. Antenna Specifications[34]

Bandwidth:	(Spec.) 144-146 MHz.
	(Usable) 144-148 MHz.
Gain:	13 dB
Beamwidth:	34 degrees
Boom Length:	19 feet 1 inch
Windload:	1.85 sq. ft.
Turning Radius:	135 inches (typical)
Weight:	11 pounds

Table 11.10: 435 MHz. Antenna Specifications[35]

Bandwidth:	(Spec.) 420-440 MHz.
	(Usable) 410-450 MHz.
Gain:	15.2 dB @ 436 MHz.
Beamwidth:	25 degrees
Boom Length:	14 feet 7.5 inches
Windload:	1.85 sq. ft.
Turning Radius:	109 inches (typical)
Weight:	10 pounds

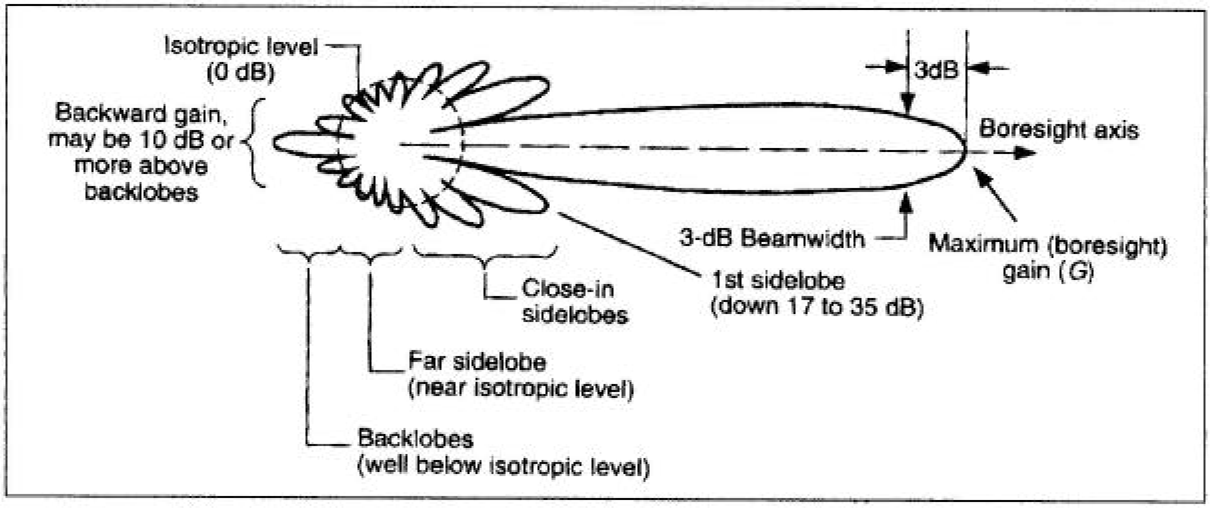


Figure 11.10: Typical High Gain Antenna Pattern[36]

11.11 The Amplifiers:

The SPARTNIK Ground Station will make use of two pre-amplifiers to increase the power output of the antennas, and an RF amplifier to increase the power output of the transceiver. A 70cm pre-amplifier and a 2m Landwehr GaAs pre-amplifier will be attached to the respective antennas on the mast assembly to help compensate for line losses, etc. Both pre-amps run off of a supplied voltage of 12-14 V DC on 100 mA and offer a 17-19 dB gain. The 2m pre-amp has a maximum transfer power of 750 W, and the 70cm pre-amp has a maximum transfer power of 350 W. These pieces of hardware are necessary for satellite communications because most receivers are only designed to compensate for the less-stringent sensitivity requirements (noise factor) of terrestrial communications. The use of a pre-amp on our receive antenna will improve reception significantly.

An RF amplifier does for transmission what pre-amps do for reception. This piece of equipment is essential for quality transmissions to an on-orbit satellite. For transmission on Mode JD, a power amplifier must be located between the transceiver and the 2m transmit antenna. For convenience purposes, the unit will be connected at the ground station rather than the antennas. The amplifier to be used is a MirageB-1016-G 2m 160 W unit. For proper operation, the pre-amp must be connected (power supplied) on the receive line, and the power amplifier must be connected on the transmit line.

11.12 **The Junction Boxes:**

To enhance and improve ground station operation, the Project SPARTNIK Team employs two custom-designed junction boxes in the ground station configuration. The first of these boxes is located on the antenna mast and is a simple junction box. Its purpose is to minimize the number of cables that need to be fed to the antenna mast. This box feeds the power and control for the pre-amps and polarity relays on the 2m and 70cm antennas. One eight-conductor cable may be run up the mast to the junction box. The box splits the circuits into four separate wires feeding the components listed above. There are no electrical components within the junction box, just wires and connectors. The entire box has been weatherproofed for outside use.

The switch box located at the ground station is used for Mode and Polarity control. When the Mode switch is in the "Mode J" position, it grounds (activates) the 70cm pre-amp for clear reception of 435 MHz signals. In the "Mode B" position, the 2m pre-amp is grounded. The Polarity switches are connected to the polarity relays on the antennas as indicated. Throwing a Polarity switch will either supply or remove positive voltage from the relay, reversing the direction of the antenna polarity. The polarity when voltage is applied depends on what the default polarity was. The actual direction (left or right circular) is unimportant. The switch should be in the position that promotes the best reception or transmission at the time.

11.13 The Ground Station Computer Equipment:

In order to control the onboard systems of the satellite efficiently from the ground, a computer system is necessary. The choice of the computer system was based on the following criteria:

-- User familiarity
-- Applications used
-- Ease of an upgrade
-- Cost

In preliminary investigations into a computer system, two classes of computer systems were considered. The first was the UNIX based workstation. The second was the common IBM compatible personal computer (PC).

Workstations differ from PCs in several ways. When compared to a PC a workstation has more raw processing power since they are designed to be operated on a network, and with multi-tasking operations. Since the workstation is much more sophisticated than a PC, the workstation costs a great deal more. When considering the workstation avenue, two manufacturers were considered. A new DEC3000-m400 as well as the SUN Sparc 20/40 costs about $18,000 which is out of reach because of current budget constraints. As a compromise reconditioned workstations were also considered. The SUN Sparc 10/30 and 10/40 workstations offered a comparable price to that of a PC, but they had three major drawbacks:

--The software for a workstation is UNIX oriented, and the majority of the users who are working on SPARTNIK are PC oriented. To maximize the contributions of all the users, they must be accommodated with a user-friendly environment.
-- The majority of the available software that will be used is oriented toward the PC world.

-- Software upgrades and licensing for the UNIX environment cost a great deal more than PC software. To run Alpha OSF/l, it would cost about $2,500 plus licensing.

Since the cost of maintaining UNIX workstation could exceed the cost of the entire project, the workstation avenue was impractical and was, therefore, abandoned in favor of the personal computer.

Once the type of computer system was selected, the process of determining the needs of the system began. The central processing unit (CPU) was chosen to be the Intel 486 DX2 because of its speed and reliability. Since the system would have to incorporate several command and processing functions, it would require several megabytes of random access memory (RAM). The plan from the payload subsystem is to download sets of color digital images from the on-board camera. When uncompressed, the pictures would take several Megabytes of space, which prompted the decision to purchase a large capacity hard disk drive so an archive file of these images could be kept. A high-resolution color video card and a 17-inch monitor were also chosen for display of the photographs to be downloaded. Table 11.11 is a listing of the current computer configuration for the ground station computer:

Table 11.11: Baseline Computer Configuration for the SPARTNIK Ground Station

CPU:	Intel 486 DX2 at 66 MHz
Memory:	16 Megabytes RAM on four 4 Megabyte Simm boards
Motherboard:	Intel 486-33 VESA Local Bus w/ 256 Kbytes cache
Disk Drives:	1 - 3.5" 1.44 MB floppy drive (TEAC)
	1 - 5.25" 1.2 MB floppy drive (TEAC)
	1 - 1.08 GB SCSI hard drive (Quantum)
Interface Card:	IO card w/ 2 serial ports and I parallel port
Video Card:	VESA Local Bus with 2 MB VRAM (Diamond Stealth 64)
Monitor:	17 inch SVGA .31 dpi (Samsung 17GL)
Power Supply:	250 watts w/ tower

11.14 Testing

The testing of the SPARTNIK TT&C Subsystem will be accomplished in four phases. These phases are listed below accompanied by a brief description of what each phase entails.

11.14.1 Phase One: Ground Station Hardware Checkout

The SPARTNIK Ground Station configuration will be operationally tested by attempting uplinks and downlinks with existing satellites. The test satellites will be selected based on the similarity between their communications packages and SPARTNIK's communication payload. Also, links will be attempted on satellites in orbits similar to all of the potential SPARTNIK orbits.

In order to accomplish this, the SPARTNIK Ground Station will run commercially available software on the SGS computer terminal. The orbit tracking software will be the same package used for SPARTNIK operations. The telemetry processing software, however, is a commercially available product obtained from the Amateur Satellite Corporation (AMSAT). The title of this package is "TLMDCII" and was designed to allow amateur radio satellite operators to decode telemetry from various existing OSCAR microsatellites.

Current Keplerian Orbital Element Sets (elsets) must be obtained from AMSAT or another source for the OSCARs we intend to contact. These element sets can be imported into the antenna tracking software to ensure accurate pointing angles during the satellite passes. We will track these vehicles using the SGS and attempt to establish valid communications links with them. We will also use these opportunities to gain experience with the orbit determination task.

Based on the data obtained from these tests, we can adjust our system configuration as necessary. This may entail reconfiguring the antennas, implementing an impedance-matching network on the antenna system, adjusting the amplifiers, finding RF sources, correcting the equipment location, or other methods of troubleshooting.

11.14.2 Phase Two: Vehicle Communications Checkout

Checkout of the vehicle communications package will entail verifying all aspects of data flow within the vehicle up to, but not including the receiver and transmitter. This means that diagnostic equipment will be connected directly to the onboard CPU inputs and outputs, and emulate signals to and from the communications equipment. The purpose of this test is to ensure all telemetry and mission data is reaching the CPU correctly, and this data is then sent out through the proper channels to what would be the transmitter. Also, a command stream would be sent from the simulated receiver so it could be verified that all commands are reaching their proper destinations. Finally, all other interaction between the CPU and transmitter/receiver would be verified.

11.14.3 Phase Three: System Integration

In this phase of testing, on-orbit operations would be examined with the only simulated factor being the actual communications links. Instead of standard transmission and receiving of data, physical cables will carry the data between the SGS and the SPARTNIK Flight Model. All modes and manner of operations will be tested during this phase.

11.14.4 Phase Four: Alpha Test

In the final test, the entire system will be checked out under conditions as close to actual as can be obtained. This may entail transporting the SPARTNIK Flight model and/or ground station equipment off-site. The actual ground station antennas may not be used due to the fact that they are permanently installed, they are oriented for space-based communications, and area obscura limits their use in terrestrial-based test communications.

The testing team will, however, want to use an antenna system that, when in use, will simulate the attenuated communications links to be faced by the SPARTNIK TT&C on-orbit system. Significant distance, RF interference, sidelobes and other hazards to be faced in the space environment will also need to be simulated as closely as possible. Even thermal, stress, and vacuum environment characteristics will want to be examined as they apply to the communications system.

11.15 Operations

This section will examine standard operations of the spacecraft once it is in orbit. First the design considerations behind the SPARTNIK Operations Control Software will be detailed. Then a typical spacecraft contact scenario will be presented in a chronological sequence, following the data flow and hardware interactions with close scrutinization.

11.15.1 SPARTNIK Operations Control Software

The SPARTNIK Operations Control Software (SOCS) is a project that is currently under development by a group of dedicated computer programmers. The intent behind this software is to have it installed on the SGS computer terminal, and it will be THE central resource as far as spacecraft operations are concerned. It will be utilized in and data reduction. The software engineers designing the package will be allowed great leniency as far as constraints because creative ideas are welcome in the design of this software. However, the Project SPARTNIK Team will provide some guidelines in the form of a software specifications document. A detailed description of the status of this software design may be found in that associated documentation. However, the general idea of the software requirements is presented below.

SOCS will allow an authorized user to run a SPARTNIK support unassisted, It must interact with the antenna driving system via software as explained below. It must interact with the SGS communication equipment via the computer hardware interface cables and serial/parallel ports. Finally, it must interact with the other components of the SGS computer station such as the video card, disk drives, math coprocessor, and printer.

SOCS will run in the foreground of a multi-tasked interrupt-driven system. In the background, a commercially available antenna driver will be executing. SOCS must be able to toggle between these functions as well as other software applications, such as a spreadsheet. It must be able to exchange information with these other programs based on their respective software input/output specifications.

Prior to contacting the vehicle, SOCS must be able to access a Zulu time standards database to update the internal clock. It will maintain a command database that will be user-selectable during a contact. Also, it will ensure security by implementing a password-type system for authorized users.

During a real-time contact, SOCS will process and display the telemetry data stream in a user-friendly format. A separate display for each subsystem has been suggested. The software must demonstrate the capability to control the transceiver using the controls provided in the transceiver specifications. It will display and archive MMID and Rad Sensor Payload mission data upon request and archive telemetry and Camera Payload mission data for analysis by other software. Finally, SOCS will maintain secure control over all data archives, but will allow read-access for analysis.

11.15.2 Chronology of a Real-time SPARTNIK Contact

The following chronology demonstrates data flows and physical actions that will take place during a standard contact. Items highlighted in **bold print** indicate actions occurring on the spacecraft. The following Figures may prove useful when reviewing this section:

Figure 11.3: SPARTNIK Receiver Block Diagram
Figure 11.4: SPARTNIK Transmitter Block Diagram
Figure 11.5: Onboard Computer and Communications Deck Interface
Figure 11.7: SPARTNIK Ground Station System Configuration

11.15.2.1 Orbit Prediction

-- Obtain latest SPARTNIK orbital elements from an on-line database, or NORAD, if this is the initial few contacts. Otherwise, elements generated at SJSU will be used.
-- Input these elements into tracking routine
-- Update Zulu time using on-line service
-- Initiate Tracking and Antenna Driver routine
-- Use this software to predict rise/set times, maximum slant range, and support duration
-- The tracking routine will automatically send signals to the antenna drivers, as well as provide current azimuth and elevation to the screen.
-- **Beacon is constantly generated by the CPU and transmitted using low power on the downlink**

11. 15.2.2 Establishing Contact

-- Power-on SGS equipment
Initialize SOCS
-- Power-up receive antenna pre-amp
-- Power-up transmit power amplifier
-- Set default transmit and receive frequencies on the transceiver. Ensure tracking routine is pointing antennas according to azimuth and elevation data provided
-- Acquire audible beacon as the vehicle rises above the horizon/obscura. Ensure antennas are tracking properly
-- Initiate "hand-shaking" sequence through SOCS
-- Once command capability is obtained, command the spacecraft transmit antenna to high power using the command sequence described below, enacted on **the transmitter powerset.**
-- Vehicle may be commanded to different frequencies as needed, **using the control voltages,** to obtain a clear channel.
-- **Phase lock loops provide feedback on the SCL and SDA to maintain lock on the transmit and receive frequencies. Re-initialization will occur as necessary, based on interrupt input.**
-- Monitor the uplink signal via the **RSSI,** and the spacecraft transmitter via **the power output.**
-- A telemetry stream is initiated via the avenue described below.

11.15.2.3 Receiving Telemetry

-- Voltage/current levels originate at the transducers located throughout the spacecraft
-- These values are sent to the onboard CPU
-- The digital signals are converted to packets using a TNC emulation software protocol within the on-board CPU -- This data is modulated with an RF carrier at the transmitter's MOD input and sent to the 70cm transmit antenna
-- **The data is downlinked at 9600 baud on 435 MHz**
-- The bit stream is received at the 70cm antenna, then flows through the pre-amp and cable to the transceiver, where the signal is demodulated
-- Next stop is the TNC, where the data packets are decoded, reassembled and sent through the computer's serial port to SOCS for processing and display
-- The **onboard telemetry log** may be commanded down in a similar fashion as payload mission data (See below)

11.15.2.4 Sending Commands

-- The command is selected by an authorized user from SOCS' command database
It is sent through the serial port to the TNC where it is encoded and packetized
--The packets travel through the transceiver, where they are modulated on an FM carrier for transmission
-- The data flows through the power amplifier and cables to the 2m transmit antenna

-- The data is uplinked at 9600 baud on 145 MHz

-- It is received at the spacecraft 2m antenna and processed through the double-conversion superheterodyne, with the first intermediate frequency being 45 MHz and the final I.F. being 455 kHz. The signal is then demodulated from the FM carrier.

-- The bit stream is sent to the onboard CPU via the RX-DATA port, the packets are processed, the command is validated, and it arrives at its final destination as determined by the CPU

-- **A command verification courtesy is returned via the telemetry channels**

11.15.2.5 Mission Data

-- The requests for mission data and telemetry logs are transmitted through the command channels

-- **All mission and telemetry data will be time-tagged**

-- The spacecraft memory registers will duplicate their telemetry log contents through the telemetry channels

-- SOCS places this data in secure data files on the SGS computer

-- **The spacecraft memory registers are reset by command from the SGS**

-- This applies to Rad Sensor, MMID, and archived telemetry data

-- The only difference for the camera images is that they may be transmitted at a user-selectable higher data rate (up to 57.6 kbaud if power is available)

11. 15.2.6 Data Analysis

-- Data analysis will be completed at the SGS in-between vehicle contacts

-- SOCS will manipulate data files to include making them read-only, allowing back-up capability, and block transfer of sections of data

-- Data files will be imported into commercial software packages, such as spreadsheets, for the purpose of trend analysis

-- Camera images will be imported into the Koala software for processing.

11.16 Conclusion

Based on the above design, analysis, hardware selections, and software selections, the Project SPARTNIK Team should have no trouble communicating with the vehicle from launch separation until bum-in. Telemetry and Payload data should be received and processed, the vehicle should be tracked, and commanding should be transmitted, all without any problems. The validated design of the communications package will facilitate TT&C design for future San Jose State microsatellite projects. The SPARTNIK Ground Station will be adaptable for use with other vehicles and the SPARTNIK Operations Control Software will be upgradeable for different missions.

An operable ground-based communications link is the only means by which the satellite engineers will be able to observe the culmination of their efforts. Successful satellite operations under this TT&C design will be a reward for a considerable amount of hard work on the part of Team SPARTNIK. More importantly, however, it will be a building block for future projects and a stepping-stone for future engineers.

11.17 Recommendations

The SPARTNIK TT&C Subsystem team has two recommendations for future study and integration of the SPARTNIK communications package: implementation of a SPARTNIK Mobile Ground Station and electromagnetic modeling of the spacecraft antennas. These suggestions are detailed below along with the preliminary work that has been accomplished on them.

11.17.1 SPARTNIK Mobile Ground Station

The Spartan Mobile Ground Station (SMoGS), is similar to the permanent ground station but in a compact form. This unit's primary function **is** to serve as an educational and community outreach tool. The main usage of SMOGS is targeted at the primary and secondary school level. The unit could be taken to a school and demonstrate the usefulness of mathematics, science, and engineering as applied to the Aerospace field. The basic setup of the SMOGS unit consists of a quadrifilar antenna, a down converter, a receiver, a TNC, and a portable laptop computer. The unit will be able to downlink and process all the information from a satellite, but unlike the permanent ground station, SMOGS will not have a transmitting capability.

11.17.1.1 Design Drivers

The SMOGS unit must:

-- Receive data and voice communications from SPARTNIK, other amateur satellites, and other amateur radio control stations on the 435 MHz amateur frequency.
-- Receive and process telemetry from the thermal, power, and ADAC sensors. Receive and process all experimental payload data:

-- Camera - color digital images (bit map format)
-- Rad Sensor - particle collection data
-- MMID - impact data

-- Maintain and Update Keplerian elements for tracking.
-- Provide educational support for primary and secondary school students in the fields of mathematics, science, engineering, and Amateur Radio as they apply to the Aerospace industry.
-- Contain all necessary equipment housed in a transportable configuration.

11.*17.1.2 Design and Analysis*

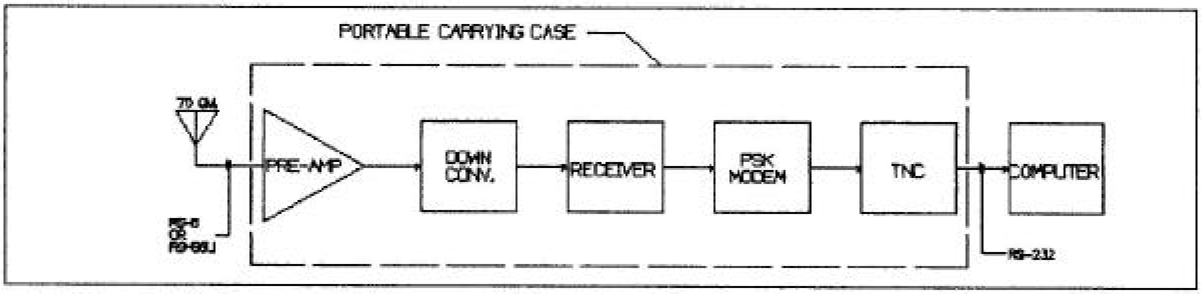


Figure 11. I 1: Spartan Mobile Ground Station Preliminary Design

Although the system is still in its preliminary design stages, Figure 11.11 shows a potential SMOGS unit in its block diagram form. The SMOGS unit is intended to be a three pieces portable system that can be transported by one person in an average-sized automobile. The basic pieces are a portable computer, a carrying case with the pre-amp, receiver, demodulator, and TNC pre-wired, and a small quadrifilar helix antenna (Figure 11.12). The SMOGS unit will have a receiving capability of 435 MHz and is therefore capable of downlinking all the telemetry information that the permanent ground station can. As a result of the 435 MHz antenna, the digital pictures from the Logitech Pixtura can only be received at 9600 baud.[37] The quadrifilar antenna consists of four 1/2 turn helices equally spaced around the circumference of a common cylinder. The antenna has a maximum gain of about 5 dB and a beamwidth of 114°.[38]

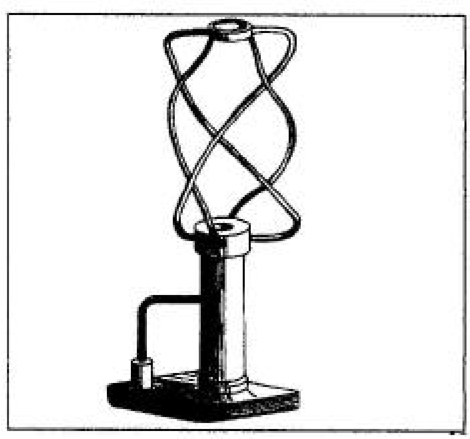


Figure 11.12: Quadrifilar Antenna[39]

As a teaching tool, the SMOGS unit provides excellent hands-on experience and excellent exposure to the Aerospace industry for primary and secondary school students.

Since the SMOGS unit will depend on available funding, only the design phase of this unit can be pursued at this time.

11.17.2 Electromagnetic Modeling

The overall antenna gain pattern can be estimated by simulating the antenna placement on the satellite with a computer. Once the modeling is completed, the gain pattern for the entire satellite can be applied to the link budget calculations for any orientation of the satellite. Once the antenna system is built, the gain can then be measured under laboratory conditions and compared to the computer model.

Electromagnetic modeling on this scale requires vast amounts of time and computational resources that were not readily available during the initial design of the SPARTNIK spacecraft. However, if it becomes a possibility in the future, this modeling could provide significant information on how to improve the TT&C Subsystem.

11.17.2.1 Modeling Theory

One of the more challenging tasks of the communication subsystem is antenna design modeling. Many satellite programs of this size and budget are not able to do real design modeling of their antennas simply because the task can not be achieved on conventional computers or workstations. San José State University's SPARTNIK program will need to use donated high speed computer accounts to meet the computational high power computer needs of electromagnetic field modeling.

Without the use of a computational high power computer, such as a Cray, a satellite program of this size and budget would be limited to isotropic antenna theory. An isotropic antenna is one that radiates equally in all directions maintaining spherical symmetry. Although this is a good starting point to estimate field patterns for an initial link budget, it is important that the antenna configuration be modeled to obtain maximum radiation intensity.

The goal of electromagnetic field modeling is to accurately predict the actual antenna performance in free space. To predict antenna performance, far field antenna ranges must be determined. Far field antenna ranges or radiation patterns are the radiated fields a long distance away from the antenna sufficient to be considered a plane wave.

There are two methods used in electromagnetic field modeling. The first method for electromagnetic field modeling uses an analytical technique. This would involve using a mathematical model of the satellite structure and then deriving and solving electric field integral equations. The SPARTNIK satellite structure is too complex to solve for a closed form integral solution. The second approach to electromagnetic field modeling is numerical analysis. Numerical analysis entails modeling the satellite structure into many elements in which closed form analytic solutions are known. By applying the method of superposition, a process of taking the vector sums of a linear system, the far field radiation pattern can be determined.

The second method, numerical analysis, will need to be employed by the SPARTNIK communications subsystem to accomplish electromagnetic field modeling. There are many computer codes that have been developed over the last forty years that can compute the electromagnetic properties for antennas. The SPARTNIK satellite program will need one such code for the antenna simulations. Numerical Electromagnetic Code is a powerful computer program for analyzing electromagnetic interactions with wire structures and conducting bodies.

Developed by Livermore National Laboratory, Numerical Electromagnetic Code (NEC) is applicable to typical antennas at lower frequencies. NEC uses the method of moments, a finite element electromagnetic computation technique, to compute mutual impedances of wires that have been divided into segments of less than 0.1 wavelengths. The method of moments is then determined by the following equation:

$$M*J, = F \qquad \text{(Equation 11.10)}$$ [40]

where, $\mathbf{J_s} =$ Surface current density
M = magnetic current density
F = Matrix representation

A matrix equation relating the impedance matrix of the structure, the excitation voltages applied to the structure from the transmission lines connected to the antenna or plane waves incident on the antenna, and the individual segment currents can be written.

$$[z] * [I] = [E] \qquad \text{(Equation 11.11)}$$ [41]

where, z = Impedance matrix
I = Current vector matrix
E = Electric field matrix

This equation then can be solved for unknown currents in the segments. The solution of the segment currents then can be used to calculate the far field radiation pattern.

When using the method of moment's solution, surfaces of a modeled structure are approximated by small flat patches or facets. Therefore, the individual patch shape is not used, only its area. NEC also takes advantage of matrix symmetry that permits structure modification without complete recalculation. The NEC code returns output as a listing of numerical data. This data will then be run through a filter, code that plots numerical output to obtain visual charts of the far field energy pattern for the antenna configuration being modeled.

11.17.2.2 Analysis

Once a computer model of the spacecraft is generated and the synthesizer interface driver has been written and coded, electromagnetic modeling and software testing can begin. The electromagnetic modeling will begin with known antenna patterns that will lead to the antenna gain pattern for the entire satellite. The synthesizer driver program will test each of the three operational modes.

11.18 Onboard Software

The Onboard Software for Spartnik interfaces with the Onboard Hardware. Without the software the hardware would serve no useful purpose. Figure 11.11 shows a basic flow diagram for Spartnik's onboard software. The onboard software manages and interfaces with the Kodak Digital Camera, with the RF deck (Tx/Rx in Figure 11.11) that is used for communications, and the Analog Board that takes readings from the onboard sensors including the MMID. The OS also incorporates Spartnik's version of the PACSAT and AX.25 protocols and also will allow users to chat during a pass as discussed previously.

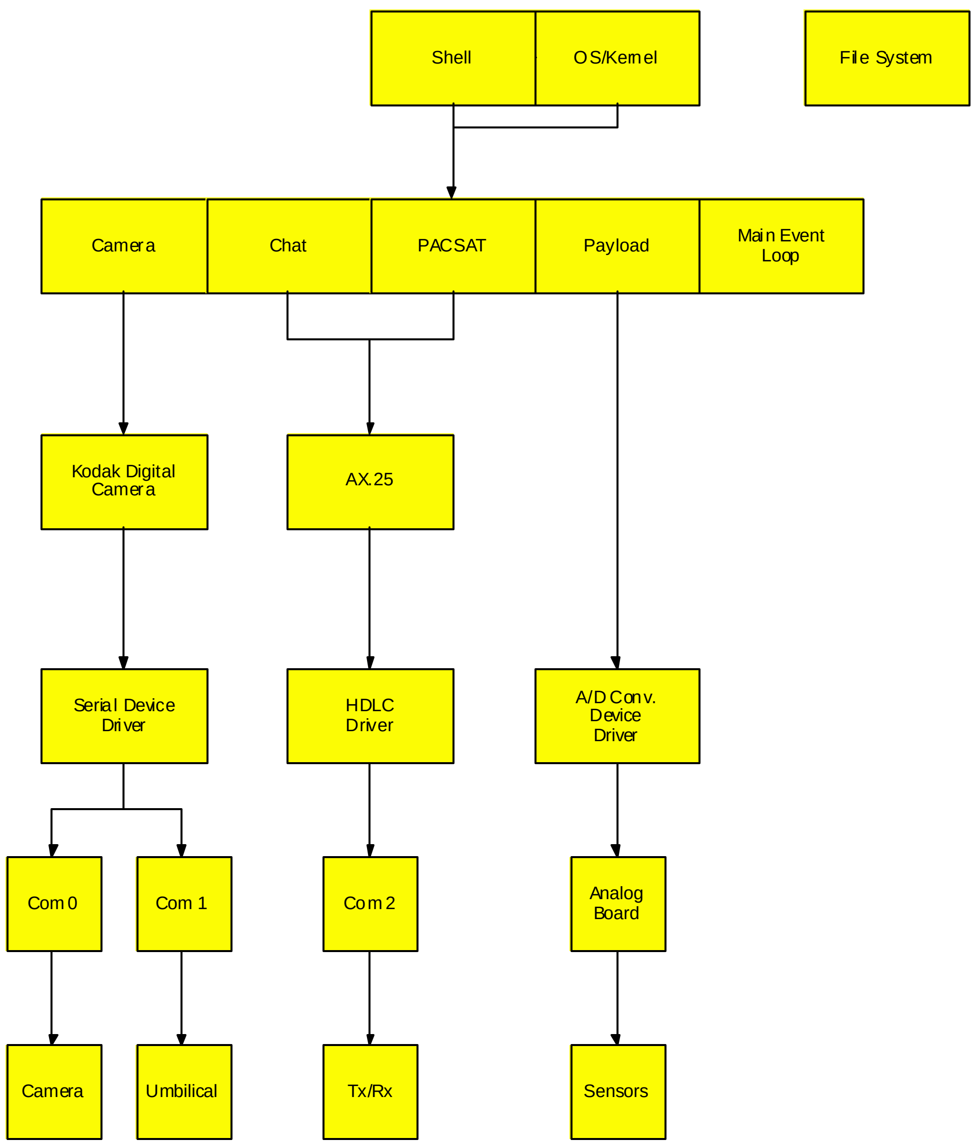


Figure 11.11: Onboard Software Flow Diagram

11.19 Onboard Hardware/Onboard Computer

the onboard computer or OBC will be a four to six layer circuit board designed to fit within the computer box aboard Spartnik. The entire onboard hardware including the OBC can be considered as three separate boards. The OBC is one board onto which the RF Deck and Analog board are interfaced with. The RF Deck is the communication hardware that Spartniik will use to communicate through the HAM Radio frequencies discussed in the previous sections. The Analog board or the sensor board is used to interface with all of the onboard sensors. The onboard sensors, including the MMID, have analog outputs so an analog to digital or A/D converter is necessary for the OBC to process the data. The OBC has three communication ports labeled COM 0, COM 1, COM 2 where COM 0 and COM 1 are RS-232 ports and COM 2 is a HDLC. The RF Deck is connected through an RS-232 on the COM 0 port and the umbilical utilizes the RS-232 COM 1 port. The OBC uses an Intel 80C188EC 16 MHz, 8-bit microprocessor with 20-bit address space and has 256 KB PROM, 756 KB RAM, 8 MB of RAMDISK space expandable to 16 MB, two A/D converters, can support up to 128 sensors, utilizes an Error Detection and Correction (EDAC) circuit, and as mentioned before, two RS-232 and one HDLC Communication Ports. See Figure 11.12 for a simple diagram of the OBC memory.

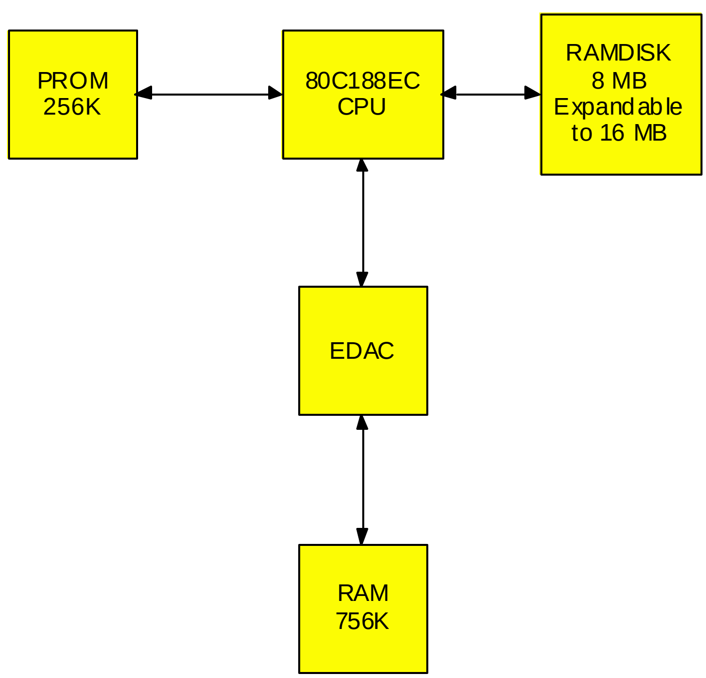


Figure 11.12 OBC Memory

The OBC development is divided into three phases:

Phase 1: Prototype OBC Up and Running
Phase 2: OBC Final Design and Fabrication (4-6 Layer Board)
Phase 3: RF Deck Design and Integration

At the conclusion of Phase 3 the OBC including the RF deck should be ready for integration into the spacecraft.

11.20 Reference List

1). Fundamentals of Space Systems, edited by Vincent L. Pisacane, Oxford University Press, 1994.
2) Robert Twiggs, Director Satellite Systems Development Laboratory, Stanford University.
3) Jim Prass, SPARTNIK Structures Group Manager, Worse Case Mass Budget, San José State University.
4) The Satellite Experimenter's Handbook, Martin Davidoff, The American Radio Relay League, 1990.
5) Numerical Electromagnetics Code; NEC Overview, G.J Burke, Lawrence Livermore National Lab.
6) Stephen Petersen, professor of Electrical Engineering, University of California at Santa Cruz.
7) RF/Wireless Communications Data Handbook, 1994.
8) Belden Wire and Cable Master Catalog, 1989.
9) Yaesu Operating Manual FT-736R, Yeasu Musen Co., LTD.
10) AEA Operating Manual Model DSP-2232, Advanced Electronic Applications, INC., 1994.
11) KLM 2M-22C Installation Guide, KLM Antennas, INC., 1990.
12) KLM 435-40CX Installation Guide, KLM Antennas, INC., 1990.
13) Now You're Talking, Larry D. Wolfgang ed., The American Radio Relay League, 1993.
14) Landwehr 2m and 70cm GaAs Pre-Amplifier Specifications, Landwehr Electronic GmbH, 1992.

11.21 Contributors Appendix

Vendors

Amateur Radio Equipment:

The Ham Radio Outlet
510 Lawrence Expressway, 102
Sunnyvale, CA 94086
(408) 736-9496
(408) 736-9499 FAX

Computer Hardware:

NTR Computer Products
2000 Wyatt Drive, Suite 42
Santa Clara, CA 95054
Contact: Clive Yu
(408) 727-4500
(408) 727-4586 FAX

Surplus Connectors and Wire:

Halted Specialties Company
3500 Ryder Street
Santa Clara, CA 95051
(408) 732-1573

RF Electronics:

Philips Semiconductor
81 1 East Arques Avenue
P.O. Box 3409
Sunnyvale, CA 94088-3409
(408) 991-3737

Motorola
5005 East McDowell Road
Phoenix, Arizona 85008
Contact: Fred Schneider

Mentors

Stephen C. Petersen

Amateur Radio
Transceiver Design
(408) 335-3115

Rubin Ramos

Communications Systems Engineer, NASA Ames
(415) 604-5698

Dr. Roger Taur

Communications Systems Engineer Lockheed-Martin
(408) 742-6110

Endnote List

[1] The Satellite Experimenter's Handbook, 2nd edition, Martin Davidoff, The American Radio Relay League, 1990, pages 11-1 through 2-13.
[2] Ibid., pages 1-2 through 2-2.
[3] Now You're Talking, Larry D. Wolfgang ed., The American Radio Relay League, 1993, pages 2-1 through 2-8.
[4] The Satellite Experimenter's Handbook, pages 5-4 through 5-8.
[5] Ibid., page 5-6 through 5-8.
[6] Ibid., page 5-8.
[7] Fundamentals of Space Systems, Vincent L. Pisacane ed., Oxford University Press, 1994, page 539.
[8] Robert Twiggs, Director of Satellite Systems Development Laboratory, Stanford University.
[9] Jim Prass, SPARTNIK Structures Subsystem Engineer, San José State University, 1995.
[10] Fundamentals of Space Systems, page 570.
[11] Ibid.
[12] Ibid., page 571.
[13] Ibid.
[14] The Satellite Experimenter's Handbook, page 13-12 through 13-13.
[15] Fundamentals of Space Systems, page 575.
[16] Ibid.
[17] The Satellite Experimenter's Handbook, page 13-13.
[18] Stephen Petersen, Professor of Electrical Engineering, University of California at Santa Cruz.
[19] Ibid.
[20] Ibid.
[21] Ibid.
[22] RF/Wireless Communication Data Handbook, 1994, page 866.
[23] Ibid., page 436.
[24] Ibid., page 51.
[25] Stephen Petersen, Professor of Electrical Engineering, University of California at Santa Cruz.
[26] Ibid.
[27] Ibid.
[28] Ibid.
[29] Belden Wire and Cable Master Catalog, 1989, page 124.
[30] Orbit Determination at a Single Ground Station Using Range Rate Data, **Daniel Coyle, The Journal of the Astronautical Sciences Apirl – June 2000.**
[31] Yaesu FT-736R Operating Manual, Yaesu Musen Co. Ltd., pages 1 through 4.
[32] AEA Operating Manual Model DSP-2232, Advanced Electronic Applications INC., 1994, page 1-1 through 1-4.
[33] Now You're Talking, page 5-6.
[34] KLM 2M-22C Installation Guide, KLM Antennas Inc., 1990, page 1.
[35] KLM 435-40CX Installation Guide, KLM Antennas Inc., 1990, page 1.

[36] Fundamentals of Space Systems, page 571.
[37] Stephen Petersen, Professor of Electrical Engineering, University of California at Santa Cruz.
[38] The Satellite Experimenter's Handbook, page 8-15.
[39] Ibid.
[40] Numerical Electromagnetic Code; NEC Overview, G.J. Burke, Lawrence Livermore National Laboratories.
[41] Ibid.