DATA LINKS
COMMUNI SATELLITES
RADIO FREQUENCIES
FREQUE. ASSIGNMENT
ANTENNA DESIGN

CONTINUOUS RADIATION
SIGNAL TO NOISE RATIO
FREQ. MODULATION
FREQ. SHIFT KEYING
DOPPLER EFFECT
CODERS
DECODERS

RADIO RECEIVER
+ TRANSMITTER

DY-32
8P

8957

N86-27301

THE NORTHERN UTAH SATELLITE (NUSAT) COMMUNICATIONS LINK

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INTRODUCTION

During the planning stages of the NUSAT satellite, an obvious issue to be discussed was the method of communications to be used. The frequencies would have to be high enough to pass through the atmosphere relatively unattenuated but low enough that antennas and transmission lines would not be so critical in length and properties that unexperienced students would have difficulty with handling them. In conversations with the Federal Communications Commission (FCC) in Washington D.C., the frequencies of 450.000 MHz and 137.900 MHz were decided upon and applied for licensing. The 450.000 MHz up-link is used on a "non-interference" basis to control the satellite while the 137.900 MHz frequency down-links data from the satellite.

A reasonable amount of time was spent discussing the mode of transmission to be used in communication with the satellite. Representatives of the amateur radio satellite organization, AMSAT, were contacted for ideas. This organization seems to favor AM types of emissions such as CW to control their OSCAR series of satellites and also the current Phase III unit. NUSAT personnel felt, however, that there would be merit in the improved signal to noise ratio usually obtained in an FM mode. Doppler shift of the transmitted information on the NUSAT also had to be considered. The final decision was to use Audio Frequency Shift Keying (AFSK) modulated on an FM carrier. In this mode the audio tones used would not shift frequency with Doppler - only the carrier would shift in frequency. If necessary, the receivers could be fitted with a form of AFC control or simply have enough bandwidth to handle the Doppler shift with an acceptable increase in noise.

DATA ENCODER/DECODER

Initially a data rate of 2400 baud was planned. This high speed of data transmission created no small design problem for the communications group. In the worst case where every alternate bit is high and then low in the data stream, the fundamental frequency of the data rate will be half the baud rate or 1200 Hz. The length of a bit is then:

$$t=1/f$$

where:
t= time in seconds
f=frequency in Hertz

therefore:

$$t=1/1200\ \text{Hz} = 833\ \mu\text{s}$$

It was felt that at least three cycles of the lowest AFSK tone would be needed to decode a data bit correctly. Applying the above equation in reverse:

$$f=1/t=1/(833\ \mu\text{s}/3)= 3600\ \text{Hz}$$

A stable frequency source was needed to produce the AFSK tones. Both mechanical and temperature stability had to be considered. The first attempt was to use a color-TV 3.579545 MHz crystal in an oscillator circuit and divide the frequency by 600 and 400 to develop the audio frequencies. In this way, any drift of the oscillator would also be so divided. The frequencies of 5966 Hz and 8949 Hz resulted from the divisions and met the minimum 3600 Hz tone criteria for bit recognition. The lower tone was designated as the Mark (or binary 0) tone. The upper tone was the Space (or binary 1) tone.

The first encoder circuit simply gated the outputs of the two divider chains on or off with the respective logical input. The initial decoder used two "Biquad" active filters - one tuned to each of the respective tones. The filter outputs were rectified and applied to a comparator to regenerate the logical signal.

Severe aliasing problems were encountered with this encoding/decoding scheme. Several decoders were tested with minimal improvement in error output - including dedicated LC circuits. The best results were achieved with a Phased Locked Loop (PLL). The next step was to examine the encoding technique.

If a coherent method of detection was to be used, then it made sense to pay attention to the phase of the encoder signals. The encoder was modified to allow a change in logical input to change the AFSK tone only at a zero crossing of the tone. This seemingly simple change improved the error rate in decoding dramatically. It was further discovered that if even multiples of half the baud rate (the baud fundamental frequency) were used as AFSK tone frequencies, the error rate was further reduced an insignificant level.

The final encoder was constructed to produce phase coherent keying at tone zero crossings. Following the earlier argument about having enough cycles to decode for bit recognition, the AFSK frequencies were chosen to be 7200 Hz and 9600 Hz - both multiples of the 1200 Hz fundamental baud frequency for a data rate of 2400 baud. It was found that the varactor modulator of the FM transmitter to be used would not modulate 9600 Hz properly due to circuit capacitances. Rather than change the oscillator circuit and risk frequency instability in the transmitter, the tone frequencies were reduced to 4800 Hz and 7200 Hz. A 2.88 MHz crystal was used in a high speed C-MOS oscillator circuit and then divided to provide the desired frequencies. The remainder of the circuit was also designed using C-MOS gates to keep power consumption low. The final encoder circuit is illustrated in Figure 1.

The decoder used was based on the LM565 PLL. Audio from the receiver was sampled directly after the ratio detector and fed to the decoder circuit board. The original low pass filter in the receiver was disabled and replaced on the new circuit board with an RC filter with a sufficiently high cutoff frequency to allow the 7200 Hz AFSK tone to pass unattenuated.

Following the RC filter, a single bipolar transistor, with a gain of roughly 100, was used to hard limit the audio input against the positive voltage supply and ground to remove AM type noise. The limiter then drives a "Biquad" active filter with a Q of about 5 centered on 5879 Hz - the geometric mean frequency of the two AFSK tones. This active filter band limits the input signals to the region of interest.

The filter output was next connected to the LM565 PLL input. The free running frequency of the Voltage Controlled Oscillator (VCO) in the PLL was also adjusted to the 5879 Hz geometric mean frequency. A silvered mica capacitor was used to set the VCO frequency for temperature stability.

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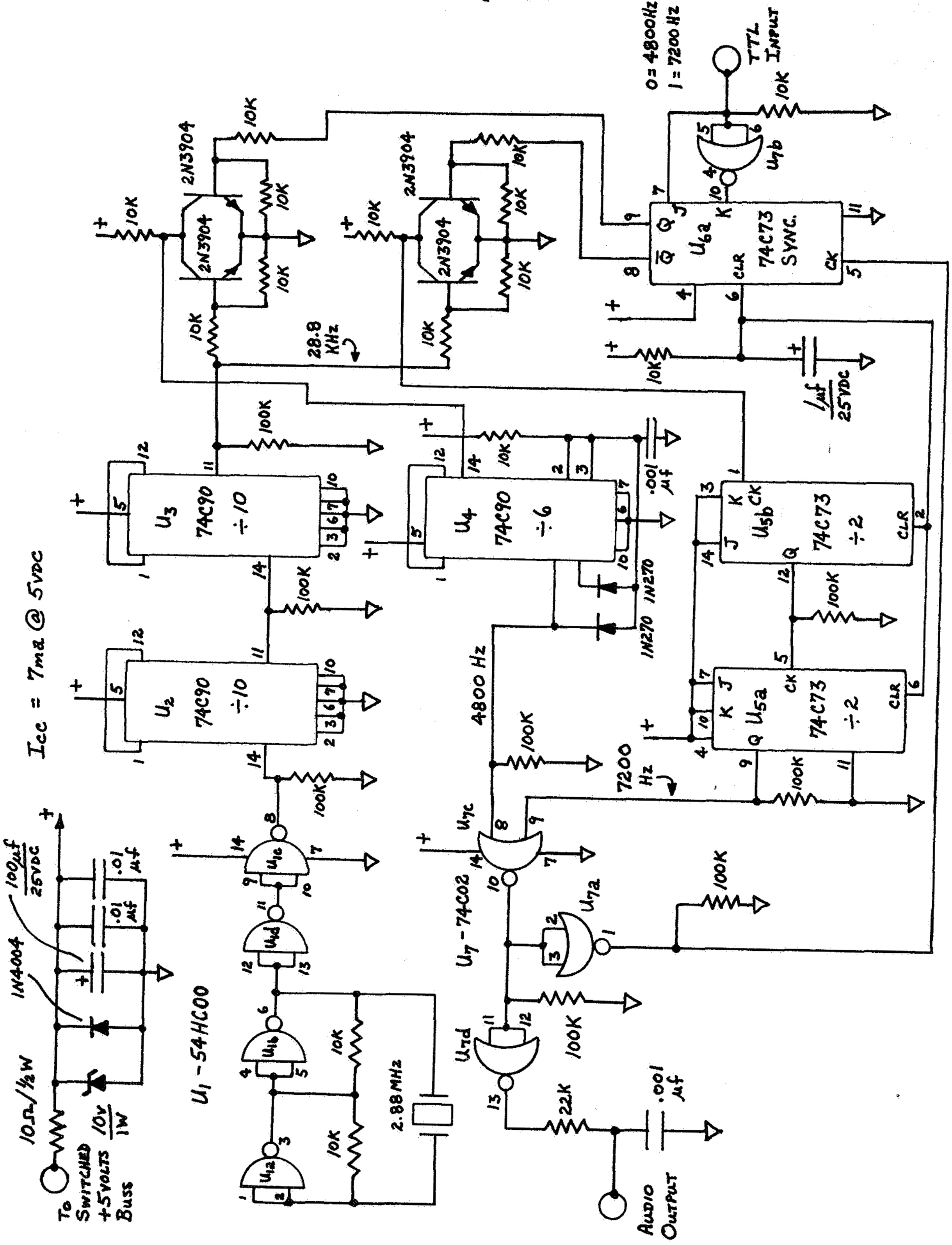

Figure 1. NUSAT AFSK Encoder

Baud rate is also a consideration in the low pass filter network of the PLL. The cutoff frequency of the filter had to be higher than 1200 Hz - the fundamental frequency of the 2400 baud rate. Following the filter, a high gain comparator was used. The comparator made use of an operational amplifier operating at open loop gain. A capacitor in the feedback loop was used to slow the slew rate of the comparator to prevent oscillations with inputs close to the switching point.

The comparator output was applied to a buffer transistor which interfaced with the computer. To prevent open squelch noise from driving the computer input randomly, a second transistor was connected to incorporate the receiver's built in noise squelch with the data circuit. When the receiver squelch is closed, the data line to the computer is held low (at a logical 0). The data line only follows the comparator output when the receiver squelch is open.

The final circuit for the decoder is shown in Figure 2. Tests on the encoder/decoder circuits demonstrated that a data rate as high as 4800 baud produced very few errors. At 2400 baud the circuits were tested extensively with no apparent errors occurring. The only abnormality worth mentioning has to do with "jitter". Jitter in the output wave form was observed because the AFSK tones derived from the crystal oscillator in the encoder were not exact multiples of the baud rate fundamental frequency. As a result, a beat note between the AFSK frequencies and the fundamental baud rate frequency occurs causing a cycle of the AFSK tone to "slip" between the data bits at the same rate as the beat note. The output data bits are then pulsewidth modulated at the beat note rate and one AFSK tone cycle in width. However, since the computer samples the data bit at the center of the bit frame, this pulsewidth modulation or jitter was not significant. One way to avoid jitter in future projects would be to use the computer data clock to generate the AFSK tones.

All data levels on the satellite are TTL while those in the ground station are RS-232.

SELECTING A TRANSMITTER AND RECEIVER

The next task was to select a transmitter and receiver to handle the selected data rate of 2400 baud. The main concern with the selection was the required bandwidth to handle such a data rate. Several sources indicate that in the transmission of Pulse Code Modulation that a deviation of (.7 X data rate) yields an acceptable signal to noise ratio on an FM carrier. If this criteria can be applied to the AFSK data to be applied to the FM carrier, then a deviation of only 1680 Hz is needed. It was decided to use twice the required deviation or 3.4 kHz. Using Carson's rule for FM bandwidth, the following relationship developed:

$$BW=2(Fm+\Delta F)$$

Where: Fm= the highest modulation frequency

ΔF= the instantaneous carrier deviation

therefore: $BW=2(7200\text{ Hz}+3400\text{ Hz})=21.2\text{ kHz}$

Several narrowband transmitter and receivers are commercially available with the capability of this modulation index and bandwidth.

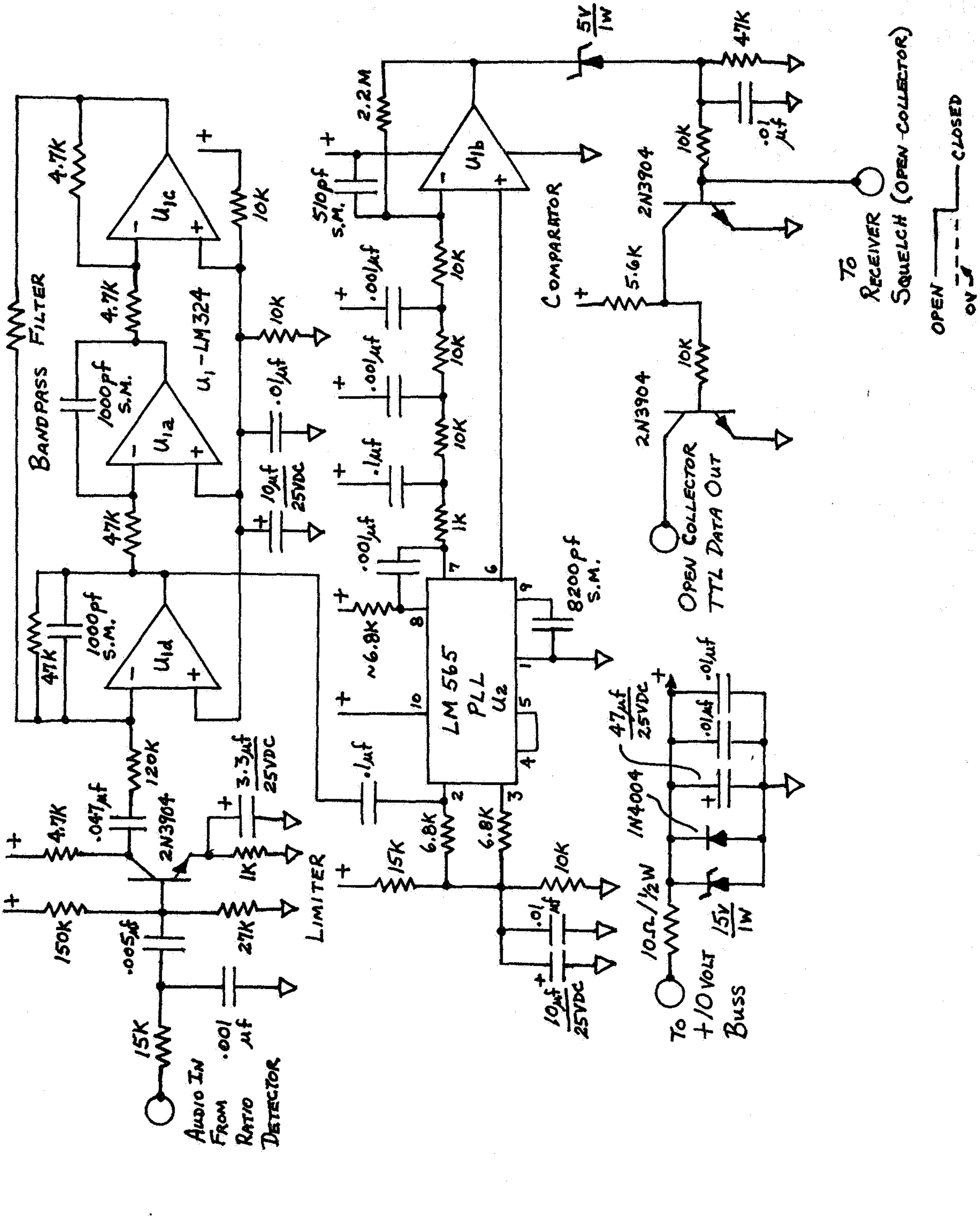

Figure 2. NUSAT AFSK Decoder

The ground transmitter and receiver along with the satellite transmitter were all purchased from Spectrum Communications Corporation, Norristown, PA. Because of size constraints in the satellite, a smaller receiver had to be purchased. A handheld transceiver was purchased from ICOM Corporation, Bellevue, WA, for this purpose.

The Spectrum Communications transmitter, model SCT110, was ordered for 137.9 MHz. The circuitboard was physically too big to fit in the satellite at first. The transmitter was carefully cut in half and the two halves were stacked to allow for mounting. The speech clipper and microphone preamplifier were eliminated and the AFSK encoder was wired to drive the transmitter directly through a level setting resistor network. In final configuration, the spacecraft transmitter had an output of 10 watts using the onboard 10 volt power buss. Only minor tuning was required to achieve this output.

The ICOM transceiver, model IC-4AT, was purchased for the receiver onboard the satellite. The transmitter section was completely disabled and many of the components were removed. The IC-4AT is synthesized in frequency by means of thumbwheel switches. The switches were disabled and removed while the synthesizer was hard wired for the 450 MHz frequency. As mentioned previously, a data squelch transistor was added to the original receiver noise squelch to prevent random receiver noise from driving the computer when no carrier signal is received. The receiver had a final sensitivity of .35 µV for 20dB quieting of the audio output. The squelch threshhold was .3 µV. The receiver was tested for bandwidth before distortion. At a 10 µV input level, the receiver will work to +5.7 kHz and -6.4 kHz. The receiver can, therefore, accept a reasonable amount of Doppler shift and still function.

All electrolytic capacitors on the spacecraft radios were replaced with tantelum capacitors to prevent possible damage while exposed to the vacuum of space.

The station on the ground employs a model SCR200, 137.9 MHz receiver and a model SCT410, 450.0 MHz transmitter - both manufactured by Spectrum Communications. The two units are mounted in individually shielded boxes to prevent broadband noise interference from the transmitter into the receiver during duplex operation. Each have separate power supplies. The transmitter speech clipper and microphone preamplifier were also removed in this application and the AFSK unit was again wired directly in. A 100 watt output, in line power amplifier was added to boost the transmitter's 7 watts to a usable level on 450 MHz.

The ground receiver is fully metered for deviation level, signal strength, and center frequency. The sensitivity of the receiver is .3 µV for 20dB audio quieting.

There was an original concern about whether or not there would be sufficient signal at the 10 watt power level of the spacecraft to establish reliable communications. Independent studies by NUSAT personnel using both the standard space loss and the radar equation methods of signal strength predictions confirmed that a good signal should exist. These calculations were further confirmed by one of the shuttle missions in which an amateur radio operator communicated easily with the ground with similar power and antenna. Communications with the NUSAT subsequent to its launch have also confirmed good signal levels exist.

ANTENNA CONSIDERATIONS

The final pieces of the communications puzzle were the antenna designs. Because the antenna orientations would not be known because of the unpredictable attitude of the satellite, the decision was made to use circular polarization on the satellite.

The first plan was to use a common pair of vertical antennas for both frequencies. The verticals would use the satellite chassis as a groundplane. A microstripline filter and matching network was designed and built but there was inadequate room for the unit in the satellite. To solve the problem, a second set of vertical antennas were added to the satellite and the matching was done using coaxial transformers and phasing sections.

Each vertical is mounted on a triangular panel of the satellite. All of the antennas are at right angles to each other. As a result, there should be no mutual coupling between them because they are in orthagonal planes. Two of the antennas are tuned to the 450.0 MHz frequency and the other two are tuned to the 137.9 MHz frequency. Because each pair of antennas are space separated by 90 degrees already, it is only necessary to shift the phase of the feed point signal another 90 degrees to produce circular polarization. Essentially the array is half of a turnstile antenna. In this configuration, a ground station should see at least one linear polarization or circular depending on the spacecraft orientation.

The antennas were tuned individually to the proper length and match. A phasing and matching harness was built for each antenna pair from coax. Figure 3 shows the method used. The quarterwave 72 Ohm sections transform the 50 Ohm impedances to about 102 Ohms. These impedances are in parallel at the tee connector producing a 50 Ohm match. The additional quarterwave length of 50 Ohm cable from one antenna is only to delay the phase to that antenna by the required 90 degrees without creating a mismatch. The final satellite antennas had a standing wave of 1.5.

The ground station antennas are cross polarized, multiple element yagi antennas. One for each frequency is mounted on an Elevation/Azimuth rotor assembly to point them. The ground antennas exhibit about a 30 degree beamwidth and are pointed by an Apple IIe computer loaded with orbital data. The ground antenna gains are approximately 10dB.

A block diagram of the entire communications link is illustrated in Figure 4.

CONCLUSION

Since the NUSAT launch the communications link has been tested. The concepts have been successfully demonstrated and some weaknesses have been discovered. The 450 MHz antennas on the satellite seem to be more shaded than originally anticipated because of their short size. As a result, the communications have been somewhat geometry sensitive. Currently it is felt that with additional improvements in the ground station such as lower loss cables to the antennas; additional shielding between the ground transmitter and receiver; and perhaps more ground transmitter power that the link can become more reliable and less geometry dependent. It is also possible that the ground station inadequacies have caused some illegal uploads to the computer on the satellite causing undue battery drain. As time goes on these ideas will be validated.

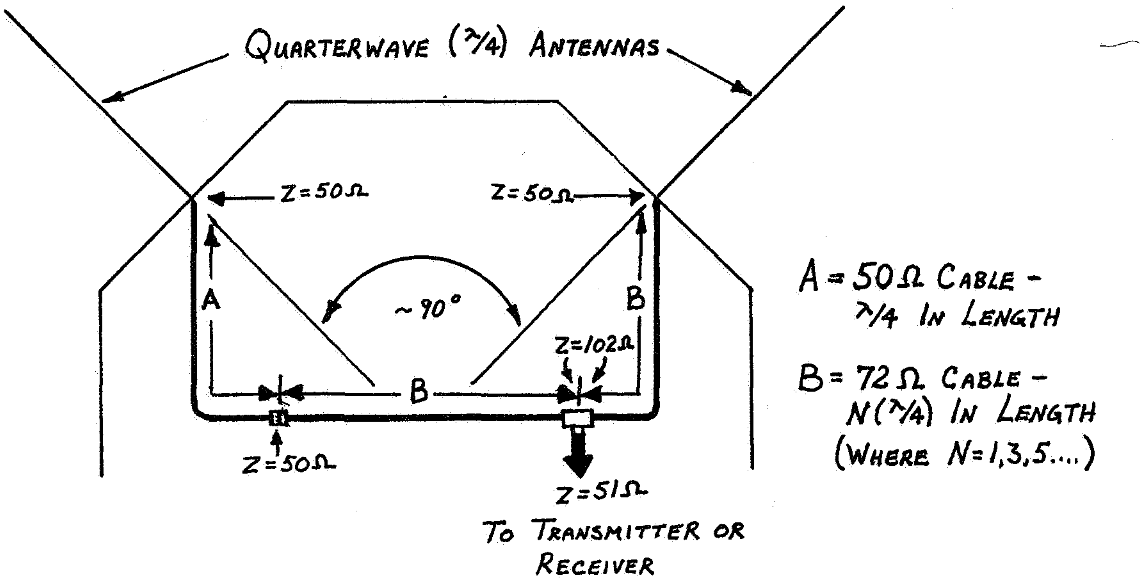

Figure 3. Antenna Matching and Phasing

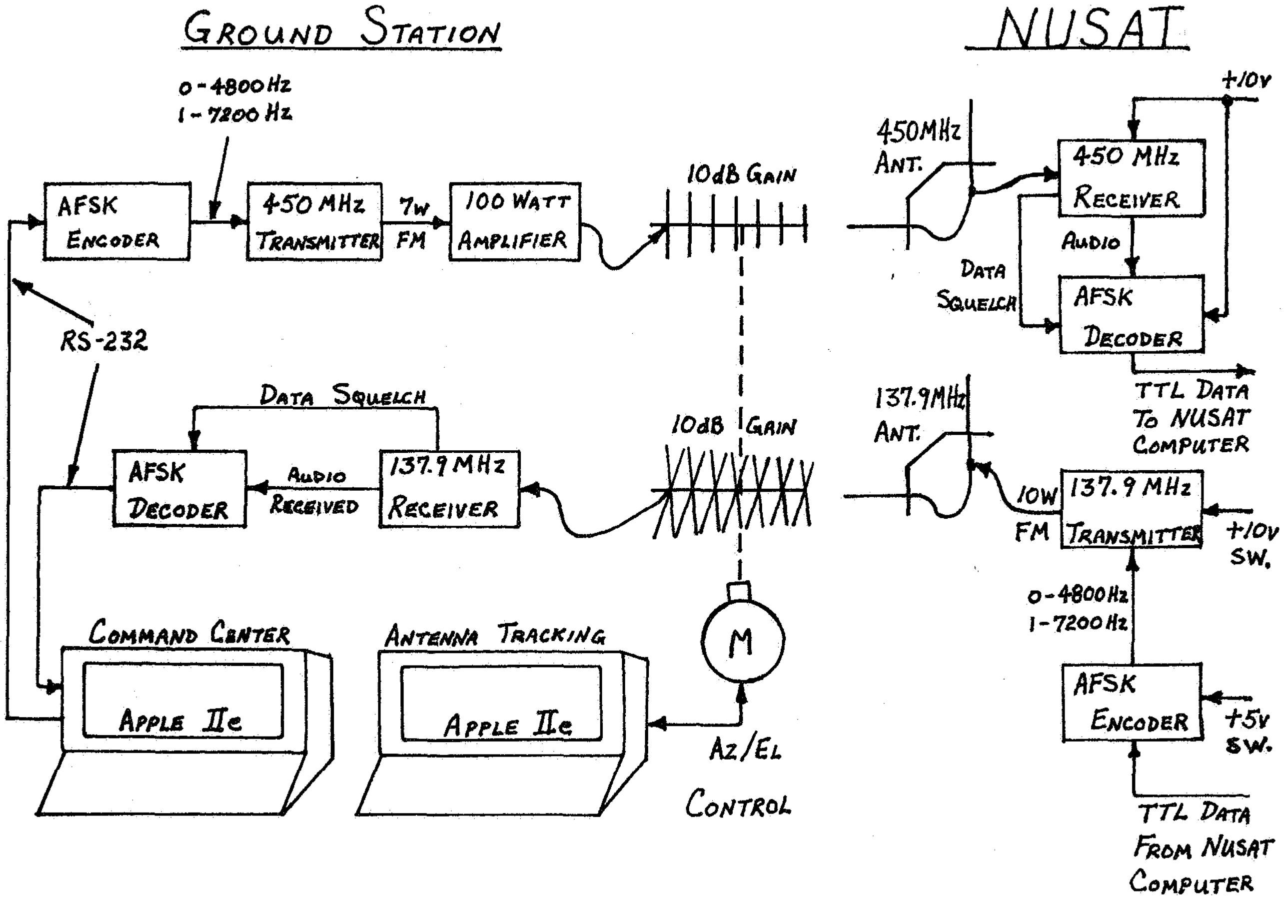

Figure 4. Communications System