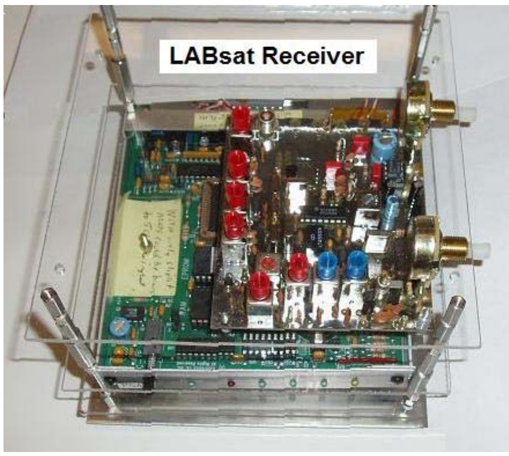
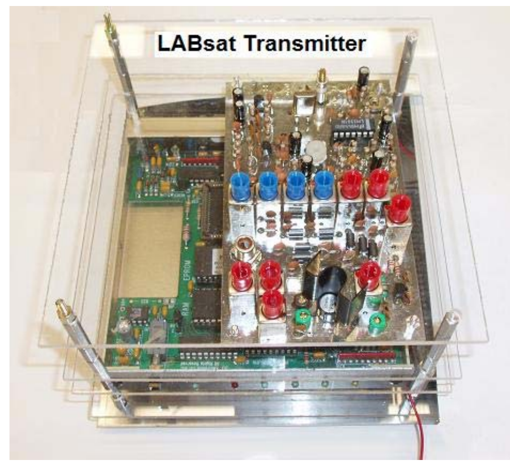
EA467 Comm Lab II: Transmitters and Receivers

(rev 1) Fall 2006

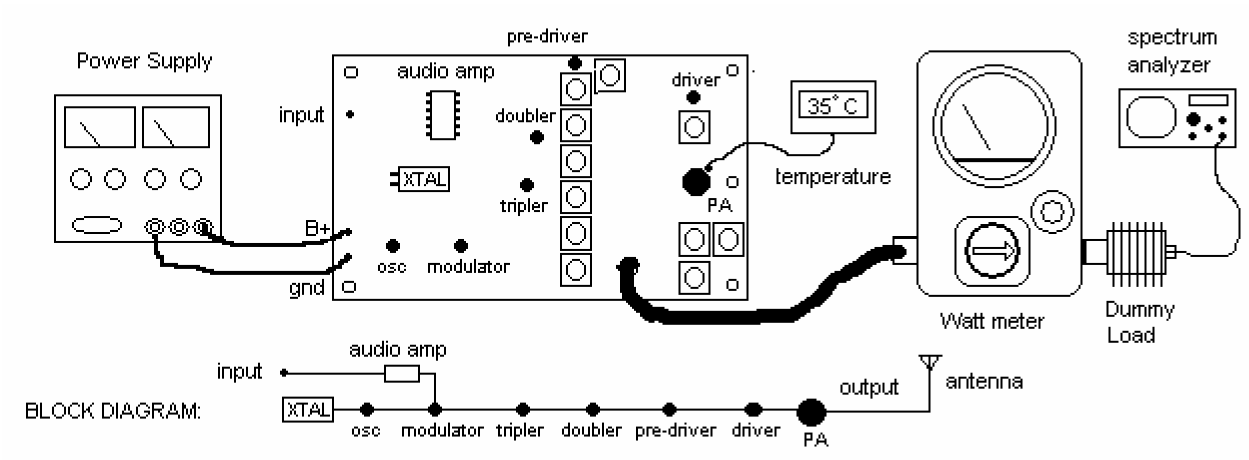
Introduction: Fundamental to all spacecraft is the communications system consisting of antennas, transmitters & receivers and digital communications (telemetry). Transmitters transmit with powers of Watts and consume lots of power but often on a low duty-cycle. The enemy of transmitters is heat and peak currents. Receivers on the other hand must be capable of detecting signals as weak as 10^{-12} Watts while maintaining good signal-to-noise ratio (SNR). Receivers draw little power, but usually are on all the time so they have a 100% duty cycle and sometimes can require more average power than the transmitter's average power. The enemy of receivers is noise. Noise is ever present and gets worse with every stage of the receiving process, every length of cable and every connector.





This lab uses our LABsat comm system to gain experience with transmitters, receivers, coax cables, low noise amplifiers and modulation schemes for achieving the best SNR through the system and then demodulating the data. As you fully integrate your spacecraft, you will do Functional Testing to validate your spacecraft performance against these parameters..

Part A. Transmitters: This experiment uses a PCSAT / LABsat transmitter to make typical measurements that are important in the design process. You will measure power output versus power input and calculate efficiency. You will also develop a performance curve for your transmitter over the range of voltages of your spacecraft bus and will measure the heat rise in the final amplifier stages that you will have to account for in your thermal design. You will also observe any spurious emissions on a spectrum analyzer.



Lab Procedures:

1) Connect the Dummy Load to the transmitter output (Transmitters must always have a matched load on their output or they could be destroyed by excessive reflected power from a mismatched termination) and set the meter to the times-1 scale using the times-10 SWR slug. This makes the wattmeter read up to 10W full scale.
2) Notice the thermistor attached to the transmitter final amplifier transistor. The transistor is soldered to the circuit board to act as a heatsink. Record the initial temperature. How well will this heat-sink work in space? What will work better?
3) Set the power supply to 8 volts and current limit to about half setting. Temporarily connect the power supply to the transmitter and record power supply Volts, Amps, the RF Power output and temperature. Increase the voltage in half-volt steps up to 14 volts and take readings.

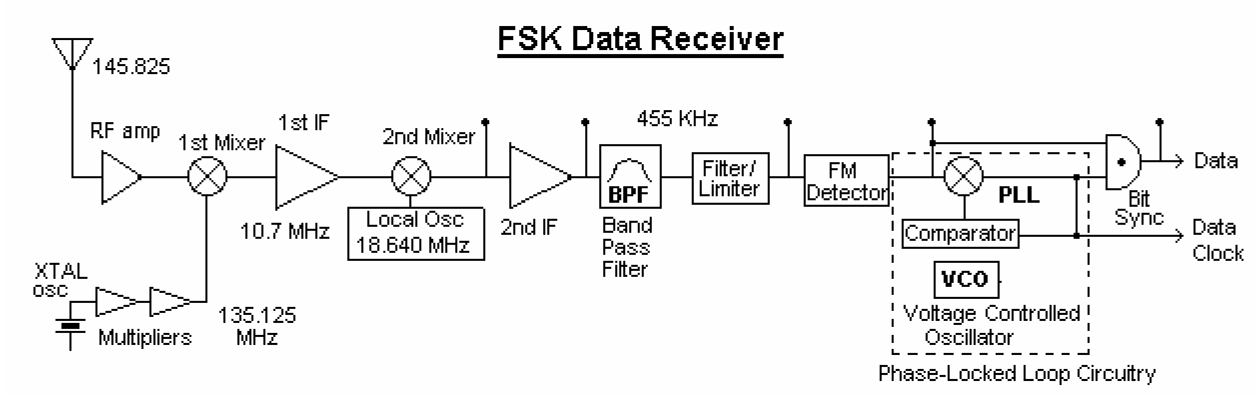
WARNING: DO NOT CONNECT THE LEAD IN STEP 4 FOR MORE THAN 5 SECONDS

4) For two more data points above safe ratings for this transmitter, disconnect the + lead from the power supply, adjust to 15 volts, and then BRIEFLY re-connect it for up to 5 seconds while taking another set of readings, then disconnect again. Repeat for 16 volts.
5) Place your finger on the output transistor and other metallic areas of the transmitter to observe that generally, all the heat is generated in the final stage of the transmitter.
6) Observe on the spectrum analyzer the 2^{nd} and 3^{rd} harmonics and any other spurious emissions. Record their levels relative to the carrier at 145.825. Ignore the spike at 0 frequency. All spectrum analyzers have a spike at 0 Hz.

Post Lab: Plot the power input, power output, and temperature versus voltage. Based on these measurements, and the spectrum analyzer observations, comment on the impact of the transmitter on the design of a spacecraft and other payloads. Compare the levels of the spurious emissions to the typical receiver sensitivity you observed in part B. With a 10% transmit duty cycle, what is the average power required by this transmitter? How much could you degrade system voltage and still have a useful transmitter?

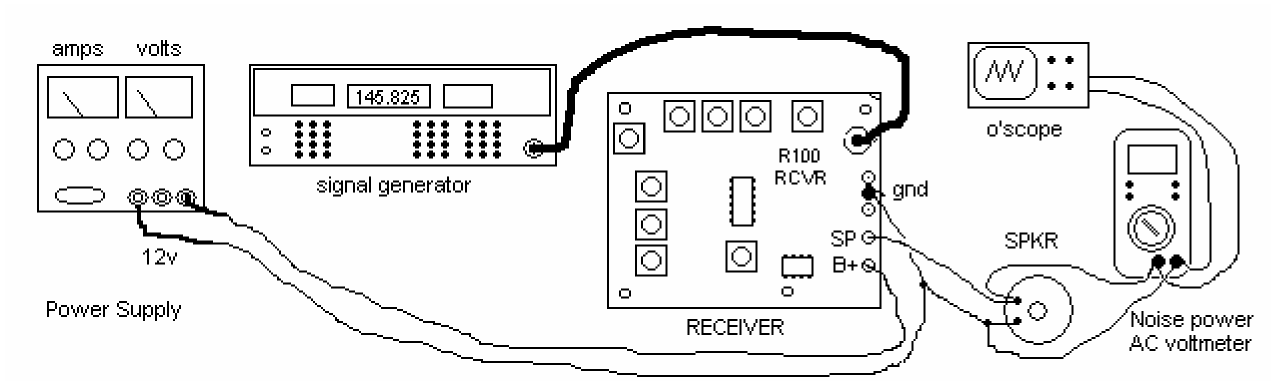
Part B. Receivers: The most important aspects of a receiver are its sensitivity and selectivity and less important, its power requirements. *Selectivity* means it has filters to block out unwanted signals that are not in its frequency band, while *sensitivity* indicates how well it can receive weak signals. This experiment will measure the sensitivity and selectivity of a typical receiver that we have used in PCsats.

The typical block diagram of a receiver consists of a low noise RF amplifier to get the signal above the noise floor, then a mixer to heterodyne it down to a first Intermediate Frequency (IF) where it is amplified and filtered with very efficient amplifiers. It is then often, mixed again to an even lower and higher quality second IF amplifier and filters before being passed to the detector. The detector demodulates the signal to recover the original signal from the carrier. In this lab, you will use an FM receiver where the detector is called a discriminator.



Lab Period:

1) *Signal Generator Setup:* Connect the sig-gen to the receiver as shown and set the amplitude to -127 dBm by pressing the amplitude button, then keying in the value, and then pressing the dBm button. Turn off modulation from the modulation section of the generator, and toggle the RF ON/OFF button to off. Press the Freq button and key in 145.825 and press MHz.

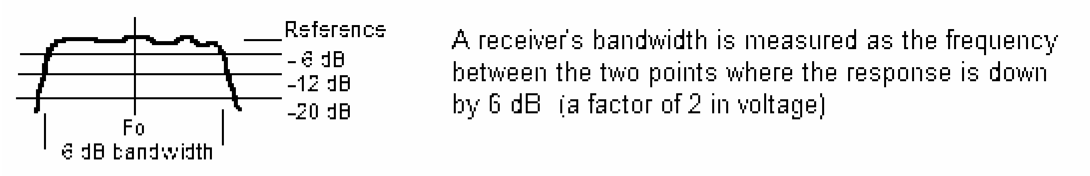


2) *Receiver Setup:* Set the power supply to 12 volts and connect to the receiver. Turn the squelch control fully CCW. Set the digital voltmeter to AC to measure the speaker output and adjust the volume control CCW for zero output. Read the receiver current. Now rotate the volume control for nominal output and a reading that averages about 1V. Record the current drawn by the receiver now while producing full noise power.

3) *Measure Receive Sensitivity* by toggling ON the RF ON/OFF button and notice a weak signal beginning to be heard. Now slowly step up the signal level, 1 dB at a time until the noise in the receiver quiets by 10 dB (as measured on the AC voltmeter). If you get above -60 dBm, STOP, because something is wrong. Remember that a change in noise voltage of SQR(10) is the same as a 10 dB change in noise power. Record the signal generator output at this point which represents the receiver's sensitivity measurement and is called the "10 dB signal-to-noise" sensitivity. Temporarily turn on the FM modulation (press FM) and adjust the deviation and notice the quality of the tone signal relative to the noise. What is the best deviation without adding distortion? Do this for both 400 Hz and 1 Khz modulation tones. Turn the modulation back off. This 10 dB SNR sensitivity is usually considered enough for minimum voice communications.

4) Notice there is still quite a bit of noise on the signal. Continue to raise the signal generator level until you see the noise power drop by 20 dB (a voltage ratio of 10) from its initial value and record this "20 dB SNR sensitivity" level. Turn on the modulation of the carrier as before and notice the modulation tone is quite pure now. Record the signal generator setting at this point as the 20 dB SNR sensitivity. Further increase the signal and note the levels for 30 and 40 dB of

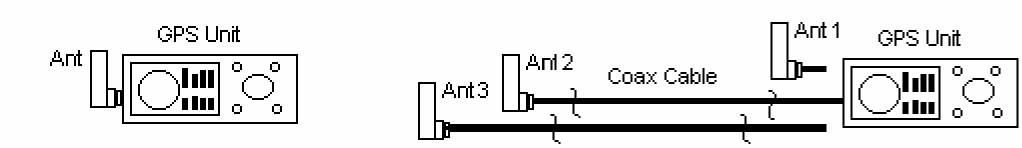
noise reduction. Continue to increase signal level to -90 dBm. Notice how quiet the receiver is, and how pure the modulation is (if you turn it on).



5) *Measure the Selectivity or Bandwidth* of the receiver by going back to the signal power setting for 20 dB noise quieting. Then swing the signal generator frequency up and then down in 1 KHz steps to where you see the noise power increase by 6 dB(2), 12 dB (4), and 20 dB (back to the original full noise). Plotting this response against frequency will show the useable bandwidth of this receiver like the sketch above.

Post Lab: Report the signal level you measured to get 10, 20, 30 and 40 dB of noise quieting. Was it linear? This is called the FM threashold effect. Plot the selectivity data to determine the useable bandwidth of your receiver.

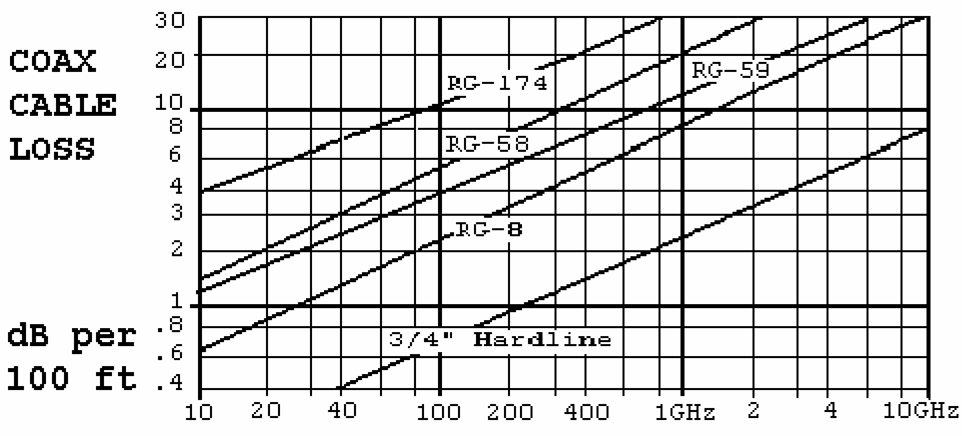
<u>Part C. Cable Loss (GPS):</u> To get higher in frequency where cable loss is more apparent, we will use a GPS receiver for this experiment out on the Plaza. Long cables waste power in transmit systems and weaken signals in receive systems. This experiment demonstrates the loss of signal and SNR using two lengths of coaxial cable at the GPS operating frequency of 1575 MHz. At this high frequency, even short cables have measurable loss.



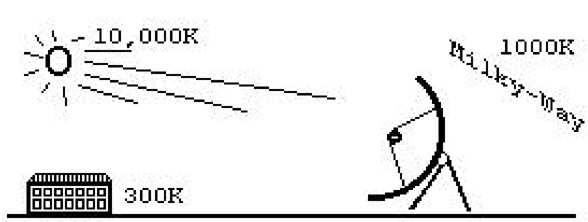
Lab Period: (Plaza)

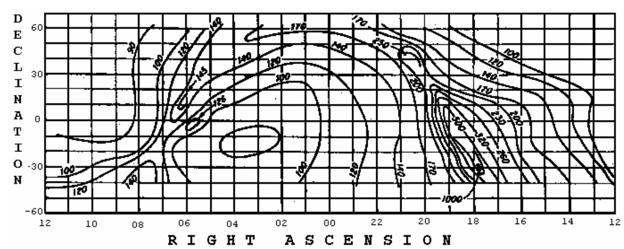
1. Connect the GPS unit directly to the external antenna and hold it clear of all objects. Allow a minute for the receiver to obtain a fix. Record the relative signal strength and position of the satellites. Assume the top line is the 0 dB reference and each line is -3 dB from the line above.
2. Connect the other antenna with the 20' length of RG-58 cable. Allow a minute for the receiver to resume lock. Record the satellite relative signal strengths and positions.
3. Connect the 3rd antenna with the 20' length of low-loss RG-8 cable. Allow a minute for the receiver to obtain lock. Record the satellite relative signal strengths and positions.

Post-Lab: Compare the measured signal losses to the expected losses and to each other. Discuss the importance of cable selection. See the chart of coax cable loss per 100 feet below. How does your data compare?



Part D. Sun, Galactic and Terrestrial Noise: The limit to how much we can amplify weak signals from space depends on how much stronger they are than all other contributing noise sources. Significant contributors external to the receiver system are the Sun, ground and our own Galaxy.





Lab Period: (Plaza/Lobby) Use the 5' black dish (now configured with an S-Band 2.4 down converter) and tune the general coverage receiver to the down converter output at about 122 MHz USB (or AM?) which represents the RF frequency of 2.400 GHz (AO-40's downlink frequency).. The AGC must be off, IF bandwidth at 15 KHz (or 6 KHz?) . Connect an audio voltmeter to the ACC1 or Phones jack to measure receiver audio noise power. Tune to find pure noise without any man made interference (wireless LAN's or wireless phones). This experiment is getting harder every year due to spectrum pollution by more an more un-licensed wireless devices.

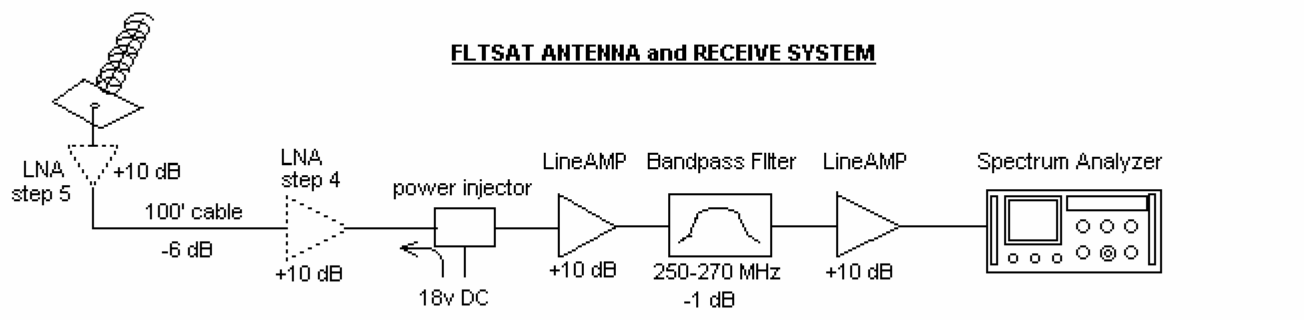
BE CAREFUL! AS YOU MOVE THE ANTENNA, DO NOT WRAP THE CABLES AROUND THE MOUNT.

1. Point the dish off to an area of cold sky (not at the sun) and record the minimum signal level. This is the noise floor of the receiver. If the receiver electronics were cooled to near absolute zero, then the receiver noise would be less and the only noise we would hear would be the background cosmic radiation near 4K.
2. Point the dish down at the horizon (Maury oe Rickover building) and take a new reading. You should be able to see a slight noise increase due to the 300K noise temperature of the building. Remember that power ratio's in volts use the equation 20 Log V, not 10 log P.
3. Next point the dish at the sun and peak for the maximum increase in the noise heard and as recorded on the noise voltmeter. You might find this increase is not as much as you anticipated. Even though the Sun is very hot and noisy, remember that its cross sectional area is only about 0.5 degree. Compare this to the total beamwidth of the antenna and you will see that the sun is only a small portion of the sky seen by the dish, thus its contribution to the noise power received at the antenna is not as great as the 10,000K you might expect.

4. Another noise source is the stars. In the fall, our galactic center (Milky Way) rises about 2 PM in the East. Then you can point the dish at Sagittarius (a strong radio noise source) and detect its noise peak at the galactic center.

Post-Lab: Compare the Sun and ground noise powers to the cold sky measurement in dB. Discuss your observations on sky noise sources and how this impacts the signal-to-noise ratio and Link Budget.

Part E. Low Noise Amplifiers (LNAs): In this section you will use FLTSATCOM as a signal source to study the effects of noise on the signal-to-noise ratio and cable losses that determine receive side performance. You will make several signal and noise measurements with and without the LNA at each end of the cable. For consistency, we will use the 6th transponder from the left.



Lab Period: (Plaza/Lobby)

1. With nothing connected to the Spectrum Analyzer, tune to 254 MHz with a bandwidth of 100 kHz and scanwidth of 5 MHz per division. Set the Log Reference Level to –50 dBm and Linear Sensitivity to 0 dBm. Determine the noise strength in dBm (the RMS average) of the Analyzer noise floor.
2. With the LNA connected out at the antenna, point to FLTSAT 7 (220° AZ and 45° EL) Notice how the 10 signal channels are well above the noise floor (at least 10 dB or more). Observe the signal power level compared to the noise power level and thus, the Signal-to-Noise ration SNR.
3. Now move the LNA from the antenna into the lobby operating position. Connect it in front of the power injector and two line amps where the cable connectors are marked with yellow tape. Observe the noise level, signal, and SNR.
4. Now remove the LNA completely (re-connect the coax straight through). Observe the noise level, signal level and SNR.
5. Now disconnect the two additional line amps by disconnecting the antenna cable at the BNC connector and connecting it directly to the input of the spectrum analyzer. Now observe the noise level, the signal (if any) and the SNR. Probably you cannot see the signal at all because you have lost over 30 dB of amplifier gain that was being used to get the signal above the noise floor of the spectrum analyzer.
6. Restore the system to normal, re-connect the two 20 dB line amps and move the LNA back out to the antenna for the next group.

Post-Lab: Compare the expected and measured signal losses. Discuss the signal-to-noise ratio and sketch the arrangements for each step. Explain the purpose of and need for each piece of equipment between the antenna and receiver (spectrum analyzer). Discuss the best position for the LNA and why.

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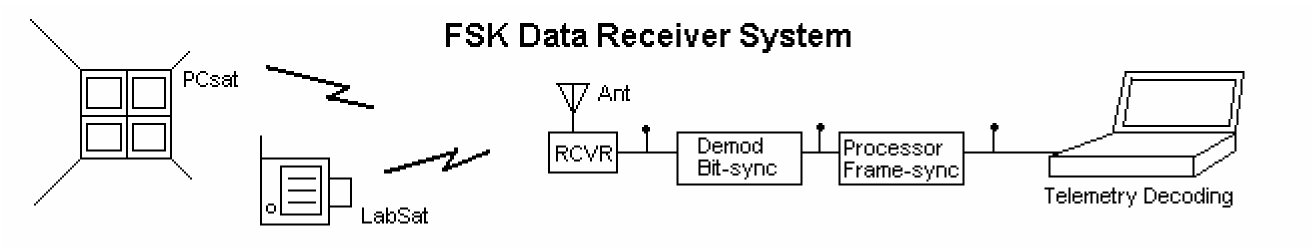
Part F. FM Demodulation. FSK Data Receiver on a TDMA Channel (Rickover 122):



Lab Period: (Ground Station) Set up your LABsat connected to your workstation as shown above. Four of our USNA spacecraft use this system for digital communications.

Many spacecraft communication systems use FSK; some of the user channels on UFO and many amateur satellites are good examples. The USNA LabSats, RAFT, ANDE and the PCSATs all transmit telemetry packets periodically using the AX.25 packet radio protocol. Packet digital communications is the name for "bursty" types of data exchange where many stations can share a channel or transponder in the Time domain. This is called TDMA for Time Division Multiple Access. In the lab we will set the LABSAT telemetry to every 10 seconds and a beacon text packet to every 60 seconds. The ground station receiver receives the VHF telemetry FSK signals as a pair of shifting audio tones. The terminal node controller (TNC) then amplifies and demodulates and decodes the packet data for display on a PC.

1. Connect the ch-1 PC oscilloscope probe to the VHF receiver's audio output (the audio input near the back of the telemetry decoder). Set oscilloscope vertical scale to 0.5 V and time base to 1 ms. Capture and save the data bursts' analog waveform consisting of two alternating sinusoidal tones. This is frequency-shift keying (FSK) where one tone represents a digital 1 and the other tone represents a digital 0. Estimate the frequency of the two tones by observing the period of the waveforms.

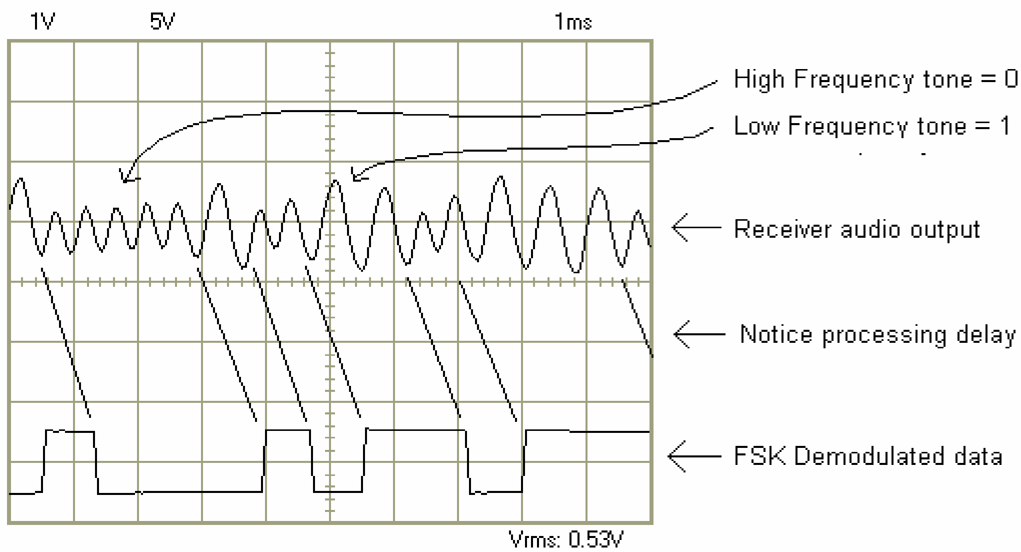
SEE FIGURE ON THE NEXT PAGE FOR DETAILS.

2. Connect the ch-2 probe to the FSK demodulator output. Observe the bits are in bursts. Estimate the approximate data rate (bits/sec) from the observed bit width. Estimate (by ear) the data packet length (audible signal length). Estimate the number of 8-bit words (from the estimated data rate and data packet length). Or you can slow the sweep rate to 2 seconds and try to capture one.
3. Observe the ASCII equivalent of the FSK data words on the PC serial port using the HYPERTERM software that is built into every PC. Record one of these telemetry frames. Notice the number of bytes (characters) in each packet. Later in the Telemetry Lab, we will decode these bytes into meaningful telemetry.

Post-Lab:

Discuss the advantages and limitations of this FSK digital transmission type used by LabSat and our satellites. Think bandwidth and speed. Also, how many stations transmitting like these 3 labsats could share the TDMA channel, and at what overall throughput would each get? How can they avoid collisions? Since the bandwidth is approximately the same as the bit rate in Hz, comment on its relevance to the link budget for PCSat. Explain what is happening (and why) at each stage of the process (use the waveforms as support).

FSK Modulation, TDMA Channel Sharing, and Baud Rate



- Notice that receiver noise is very strong and always present in an FM receiver but that it quiets down when there is a signal. Each of our satellites also seems to have different audio settings (deviation). The proper setting of modulation levels (deviation) is essential to get the best SNR on receipt.

- Click on the RUN button to try to capture your own set of data.

- Notice that there is NOT a 1-to-1 correlation between the period of the tones and the length of a data bit. It is only the presence of one tone or another for a given length of time that determines the start and end of a bit or stream of bits.

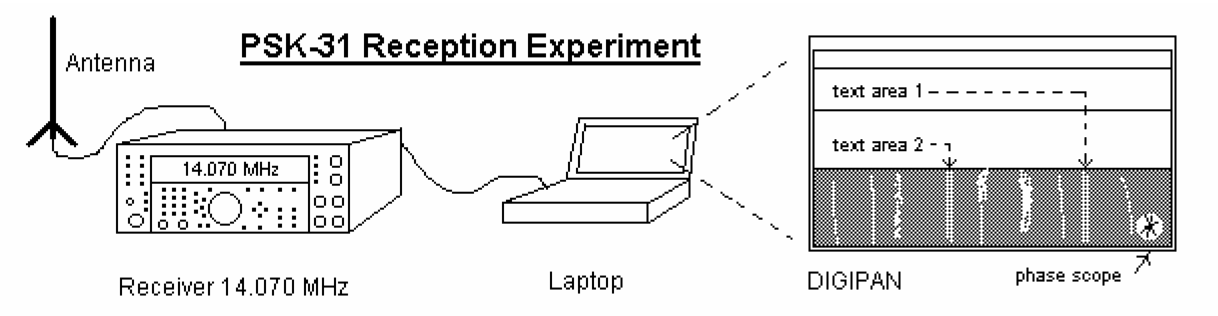
- Your challenge is to determine the period (and therefore the frequency) of the two tones being used for the FSK modulation. And then separately to determine the bit period in the recovered bit stream. Remember that multiple 1's and 0's can run together, so you need to find what you think is the occurence of a single 1 or a single 0 to determine this bit length. Then use that to figure the BAUD rate.

Part G: PSK Reception on an FDMA Channel

Satellites with low power and long distances often use Phase Shift Keying (PSK) instead of the simpler FSK because it has about a 4.5 dB better signal-to-noise link than FSK. For live signals, we will tune to the ham radio spectrum at 14.070 MHz. There, weak transmitters as low as 5 watts are frequently heard around the world using PSK at 31 baud. Deep space probes also operate at very low data rates as low as 10 baud because the lower the baud rate the less the bandwidth, the less the noise and the better the signal to noise ratio for a given spacecraft power (but the longer it takes to download appreciable data).

This lab will also demonstrate the concept of FDMA or Frequency Division Multiple Access. FDMA is a means for multiple users of a single transponder or channel by separating the signals in the frequency domain. This is in contrast to TDMA observed in section E of this Lab.

The free downloadable DIGIPAN software uses the PC sound card for PSK demodulation and it also displays the receiver spectrum, a phase vector scope, and the recovered data. The small phase vector scope in the lower right corner displays the instantaneous phase of the signal. Since PSK-31 operates on phase shift, you can see the quality of the decoding on this 0-360 degree phase scope. Noise will cause errors in amplitude and phase that are visible in the recovered text and vector scope.



Lab Procedure: There are two DIGIPAN stations so two groups can operate in parallel.

1. The receiver is the Kenwood TS-2000 transceiver on the right side of the R122 ground station console. It is connected to a dipole antenna on the roof through over 100 feet of coax. Tune to 14.070 MHz Upper Sideband (USB).
2. Set the audio level for a good modulation on the spectrum waterfall display (seeing some quiet blue and some yellow noise levels). The spectrum displayed is from 0 to about 5000 Hz and represents what you can hear by ear but the actual IF bandwidth is less as you can see from the waterfall. PSK-31 signals will have two clear peaks or "tracks" representing the width of the modulated waveform in the frequency domain. You can decode two different signals at the same time by right clicking on one and left clicking on the other… As you first click on a strong signal, watch the vector scope as the phase-lock-loop acquires the signal and gets into phase lock…
3. Receiver RF tuning must be very precise because of the very narrow bandwidth of each signal. But by eye you can easily find and click on a signal. To show how difficult it is to do this manually, adjust the radio receiver's main tuning dial to try to change operating frequency for another station. You must tune to about 1 Hz tolerance! Also, note for your write up, the overall bandwidth of this broadband multi-user channel. Pick a signal and tune the RX up and down to see where the signal disappears.
4. You can see where these signals are originating, by watching for 4-to-6 character call signs in upper case that have a single numeral for the 2nd or 3rd character. Then use the USA map and World map provided on the cart to identify the location or country of origin. Try to find at least 3 decodable call signs.. Usually they are preceded by "de" which in teletype means "from".

Post Lab: Write up what you learned… Based on the bandwidth you observed, comment on the number of signals possible on this FDMA channel, the number you saw, the quality of the signals, the phase shift used, the relationship between the vector scope observations and quality of data recovery. How much bandwidth is used by each signal. How much "guardband" should be allowed between signals. What kind of impact did noise make on the signal? What happened to everyone on the channel when a strong signal drove up the AGC level (Automatic Gain Control) on the receiver ?

Laboratory Report: For this report we will use what I call a summary format. It is somewhere between the formal write-up and the memo format. You will complete the classical steps of describing set-up, discussing data and results and writing conclusions, but on a summary basis for each part (Part A-G). You must do the following:

- Describe the lab's purpose and provide a theoretical discussion of transmitter parameters as they affect spacecraft design and receiver functions and other parameters that affect the overall link budget, citing relevant laboratory portions demonstrating functionality. Include block diagrams, as appropriate.
- Briefly describe the laboratory setup for each section of the laboratory procedure above, including block diagrams where appropriate.
- Allowing for a 10 dB link margin, an Omni antenna on the spacecraft and a 10 dBi gain antenna on the roof of Rickover and 100 feet of RG8 coax to the roof, what is the maximum range we could achieve with the transmitter and receiver you measured in the lab.
- Complete all tasks in the "Post-Lab" sections. Complete the analysis and discuss the results by making comparisons between measurements and theory. Use computer generated figures and plots to support your conclusions.
- Summarize your conclusions regarding the different receivers and discuss:
  - How well the theory supports the observations.
  - The functions of the various components.
  - The significance of line loss and noise for the frequencies examined.
  - Make specific comments concerning knowledge gained, the knowledge's suitability for naval officers, and the laboratory's value as a learning tool.