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Design and Construction of a VHF Ground Station at San Jose State University*

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A ground station, capable of communicating with Earth-orbiting spacecraft in the VHF band, has been constructed at San Jose State University. Telemetry signals may be received passively from any of the several VHF meteorological satellites, or an SJSU satellite could be controlled from this ground station. Using this facility, many interactive experiments may be designed to illustrate basic principles of RF communications and orbital mechanics. For example, theoretical and actual Doppler can be compared, and the model parameters refined. Or, using NORAD state vectors, a Keplerian description of the orbit can be transformed into local azimuth/elevation angles for antenna pointing. The ground station consists of a 5 ft VHF helix antenna, mounted on the roof of the Engineering Building, a transmitter/receiver, terminal node controller, and software (e.g. for processing the meteorological signals received on the downlink). Described in this paper are the details of the design and fabrication of the ground station, including the structural integrity analysis of the antenna.

INTRODUCTION

AS EDUCATORS, it is our task to create an effective learning environment to meet the increasingly demanding technical challenges of the aerospace industry. To achieve this objective, unique educational methods and innovative curricula must be continuously developed for our undergraduate students. A way of fulfilling this goal is to provide undergraduates with design and research opportunities, as well as experience in creative thinking, communication and teamwork. The purpose of this paper is to make a progress report on such an effort: the development of a spacecraft subsystems hardware laboratory in the Aerospace Engineering Department at San Jose State University (SJSU).

The focus of this paper is the design, construction and operation of a VHF (very high frequency) ground station. The ground station is part of the Space Engineering Laboratory, a hardware lab with experiments which demonstrate each of the major spacecraft subsystems. The purpose of this laboratory is to give astronautics students access to actual spacecraft and ground support hardware. With this experience, they will be able to integrate the theoretical and applied aspects of their technical education much more effectively. Actual hardware is used in the development, with much of the experiment design and fabrication done by students with an interest or expertise appropriate to the project. Currently, two space engineering experiments are under development: a power systems experiment using silicon solar arrays and a nickel-cadmium battery [1], and the ground station described in this paper.

A team of three students is designing and developing the ground station. Two graduate students are fulfilling their two-semester Master's projects in communications link design and ground station hardware/software development. A senior astronautics student is completing a directed individual-study project in antenna design and construction. Upon completion, two communications capabilities will be established: the potential for *active* control of an SJSU satellite and the *passive* reception of telemetered weather data from meteorological satellites. In each case, principles of on-orbit communication and earth satellite orbital mechanics will be applied and demonstrated.

The ground station will support the significant lecture/laboratory curriculum of SJSU's Aerospace Engineering program. Specific cabilities will include: signal processing; analysis of telemetry metrics, such as Doppler shift; and orbit determination and prediction. Educational benefits to the students will be in terms of either open-ended or instructor-directed experiments, as well as demonstrations given to enhance, for example, the Spacecraft Design or Space Systems courses.

Described in this paper are the design and fabrication details of the VHF ground station. Specifically, subsequent sections discuss conceptual design and motivation; communications link design; electronic hardware acquisition and integration; antenna design and fabrication; experiment concepts and curriculum benefits.

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CONCEPTUAL DESIGN

Originally designed to support SJSU's SOESAT (School of Engineering Satellite), the ground station has FCC-approved VHF uplink and downlink frequencies. When launched, SOESAT would downlink data on 136 MHz and receive commands on the 149 MHz uplink. As a stand-alone receiving facility, the ground station has the capability of receiving signals from the many meteorological satellites near 136 MHz. This capability is limited only by the frequency bands of the ground station receiver and terrain obscuring the local horizon.

Figure 1 shows the ground station components which include a:

- steerable antenna (with azimuth/elevation rotator, controller and pre-amplifier) mounted on the roof of the three-story Engineering Building;
- transmitter and receiver;
- frequency spectrum analyzer;
- terminal node controller;
- personal computer with automatic picture transmission (APT) card.

The antenna is under construction on campus using purchased materials. Once the track of a desired satellite has been determined, the antenna can be steered in azimuth (0–360°) and in elevation (0–90°) by the antenna controller.

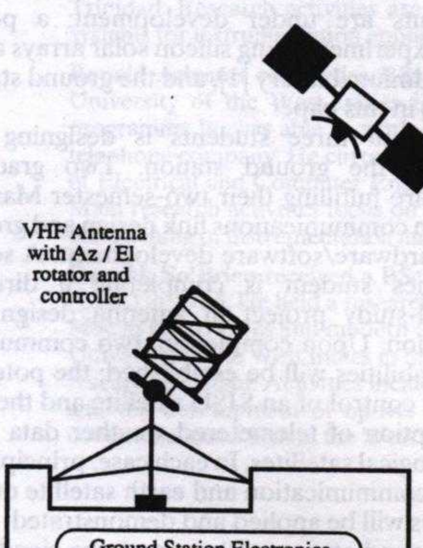

Fig. 1. SJSU telemetry ground station.

The transmitter, receiver, terminal node controller and APT demodulator are either being purchased or donated. Functions of the electronics hardware include: monitoring signal strength, compensating for downlink Doppler effects and modulating/demodulating AFSK (audio frequency shift keying) signals. The personal computer, a department resource, is an IBM PS-2 with 2 MByte RAM and an internal clock speed of 16 MHz. It has multiple responsibilities, including:

- calculation of satellite ephemeris from state vectors;
- computation of antenna steering commands (local azimuth and elevation) to align the antenna with the desired satellite;
- transmission of commands to SOESAT (upon launch);
- process and display of received telemetry data, either from SOESAT or a meteorololgical satellite.

Experimental concepts include those which supplement the theoretical astronautics curriculum in traditional ways (e.g. orbital mechanics) as well as those which are more innovative (e.g. applications of RF (radio frequency) communications theory).

Satellite ephemeris prediction, used to calculate visibility times and local azimuth/elevation angles for antenna pointing, will teach students ephemeris propagation theory and technique. Using NORAD orbital element sets, students may predict satellite position and velocity using classical orbital mechanics *theory*. Observing the *actual* satellite orbit gives the students an indication of the accuracy of their theoretical predictions as well as the opportunity to evaluate potential error sources.

Whether actively or passively tracking a satellite target, both the signal metrics and the encoded information are of interest. Passively tracked satellite signals can be examined for their signal strength variations. If demodulation is possible, the encoded data can also be observed. Many of the on-orbit spacecraft in the ground station's frequency range are US, Russian and Chinese meteorological satellites (Table 1) [2]. Downlink signals involve the APT (automatic picture transmission) of weather photographs which can be demodulated and displayed on the computer. In addition, voice transmissions from the Russian Mir space station and the US Space Shuttle can be received [3].

COMMUNICATIONS LINK DESIGN

The purpose of the communications link design process is to ensure that (1) the ground receiver's characteristics are consistent with those of the transmitting satellite and (2) the signal-to-noise ratio is sufficiently large that the received signal may be demodulated with an acceptably low level of error. Using the relatively weak SOESAT transmitter as the communications link design point ensured that the ground station would be able to receive signals from any of the desired satellites. As designed, SOESAT has a maximum transmission power of 10 W with a 5 dB gain on its omnidirectional quadrafilar helix antenna. The NOAA satellites which will provide the pictorial weather updates, have more powerful transmitters, so their signals will be received easily using a ground station designed for the 'worst case' SOESAT transmitter.

The link characteristics which define the antenna's physical design are frequency, polarization and gain. A large helix was chosen for the ground station antenna, due to simplicity of design and construction. The helix diameter was determined by the design frequency (a downlink frequency of 136 MHz implies a diameter of 27.62 in.). Polarization was specified by the direction the helix was wrapped: right-hand circular polarization has been chosen for SOESAT and the ground station.

Antenna gain is determined by the number of turns in the helix. Gain is the link design parameter which assures an acceptable signal-to-noise ratio (i.e. bit error rate) in the received signal. Transmitted waves encounter several sources of attenuation along their path. The antenna gain must be designed such that the signal may be received and accurately demodulated in the presence of these attenuating factors. Signal attenuation parameters for the SJSU ground station have been estimated as follows:

- free space spreading loss, 168.2 dB;
- atmospheric absorption, 0.03 dB;
- antenna misalignment, $\leqslant 1$ dB;
- rainfall attenuation, $\leqslant 0.2$ dB.

Table 1. Meteorological satellites in ground station frequency range

Frequency (MHz)	Name	Inclination (deg)
137.3 APT	METEOR 2-18 (USSR)	82.5
137 33 APT	COSMOS 1602 (USSR)	82.5
137.5 APT	NOAA-6 (US)	98.5
137.5 APT	NOAA-10 (US)	98.6
137.62 APT	NOAA-9 (US)	99.1
137.62 APT	NOAA-11 (US)	98.9
137.795	FENGYUN-1 (China)	99.2

Considering these losses, the desired bit error rate was obtained using a six turn helix with a gain of 13 dB. [Resulting signal to noise ratios are: 18.5 dB (for receiving signals from SOESAT); 43.7 dB (from NOAA satellites); bit error rate, $<10^{-7}$ (from either SOESAT or the NOAA satellites).] This bit error rate implies only one erroneous bit during the transmission of 10^7 information bits. For the purposes of the planned experiments, this error rate is excellent and will provide more than the necessary accuracy.

GROUND STATION ELECTRONIC COMPONENTS

A strong emphasis has been placed on student involvement in the design of the ground station; this has required imagination in the process of hardware acquisition, and experiment design. Seeking financial support is always a challenge, while the university and industry have enthusiastic technical interest in this development, their financial resources are very limited. These funding constraints have made the desirable, but expensive, electronic components unavailable in this development. In the absence of adequate financial support, our students have learned the value of creativity in designing the electronic component interfaces as well as the experiments.

Figure 2 shows the electronic components of the ground station. These components are identified in Fig. 3, where dashed lines represent future hardware acquisitions. When used as a passive receiving station, the capability for transmitting is unnecessary, so purchase of the expensive VHF transmitter has been delayed until SOESAT is launched. The other electronic components were either donated or acquired inexpensively, and the necessary interfaces were developed.

Some of these unusual equipment interfaces were created to facilitate specific data acquisition

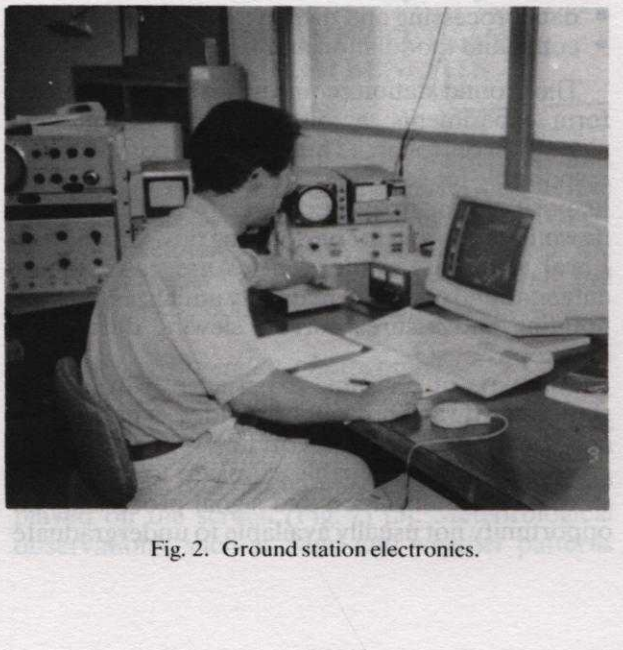

Fig. 2. Ground station electronics.

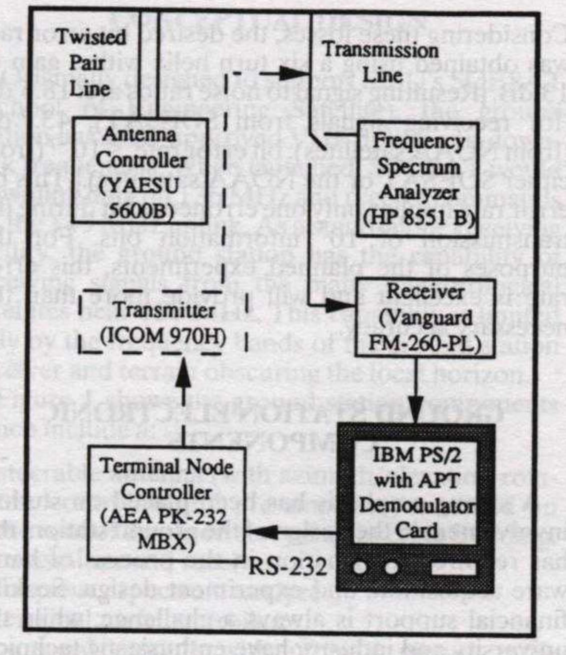

Fig. 3. Schematic of ground station electronics.

for the students' lab experiments. For example, a standard method of measuring received frequency (effectively Doppler shift) is to track the signal using a scanning receiver. Due to limited resources, an inexpensive receiver (lacking this capability) will be used. The signal will then be tracked using an existing frequency spectrum analyzer (discussed in the last section of this paper).

The ground station has been designed as a department resource to be operated, maintained and enhanced by the students. When complete, its signal receiving capabilities will support analytical coursework as well as projects and theses at both the undergraduate and graduate levels.

Operationally, students will have the opportunity to learn the principles involved in [3]:

- antenna pointing;
- telemetry reception and demodulation;
- data processing and display;
- command modulation and transmission.

The ground station requires two students to perform experiments: a mission controller and an antenna controller. The mission controller is responsible for selecting a satellite and determining its position; for monitoring receipt and storage of downlink data; and for performing post-processing. Local azimuth/elevation angles are given to the antenna controller who manually initializes antenna pointing and assures correct slewing during the intercept.

This type of real-time experience with ground station hardware not only provides experimental confirmation of their theoretical education, but gives the students valuable exposure to real-world satellite communication and signal processing, an opportunity not usually available to undergraduate engineering students, perhaps even graduate students.

VHF ANTENNA DESIGN AND CONSTRUCTION

The physical design of the antenna was dictated by RF performance and satellite tracking requirements as well as specifications for structural integrity. In the Communication Link Design section, a ground station capable of receiving the very low power SOESAT signals was discussed. However, structural considerations made the redesign of the antenna assembly necessary. This section describes the structural analysis and final antenna design (Fig. 4).

The helix assembly is constructed of heliac cable and supported by four cedar spars, connected to the aluminum base plate and steel reflector mesh (Fig. 5). Both the helix/reflector plate structure and counterweight are connected to the azimuth/elevation rotator and supported by a steel mast.

Since the antenna structure is large and will be permanently mounted on the Engineering Building roof, its structural integrity is critical. Windloading

Fig. 4. Roof-mounted VHF antenna.

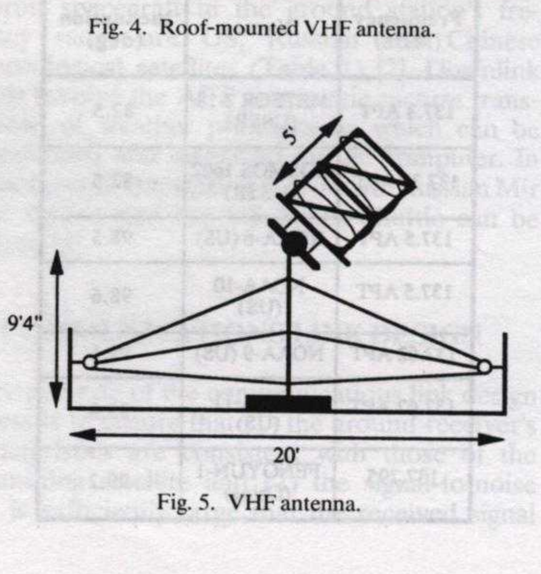

Fig. 5. VHF antenna.

was of primary concern, and the design wind pressure was estimated as 28.3 psf [4]. The vertical mast is supported by steel cables (in tension) connected to large eye screws in the wall of the antenna well (Fig. 6A). Using the materials specified in the figure, the strength of this part of the antenna structure was designed to be far greater than that required by the anticipated worst case wind loading.

The structural challenges in the antenna design were the helix/cedar spar assembly and its attachment to the vertical mast. In order to support the shape of the helix, four cedar spars were mounted perpendicular to the aluminum reflecting plate; the helix is wrapped around these spars. Diagonal cedar bracings and plywood supports were glued to the spars (forming a box structure) to give the spars both strength and rigidity. This spar-bracing combination was adequate to support the helix; however, the weight and wind resistance of the assembly became a concern, requiring the redesign of this part of the antenna structure.

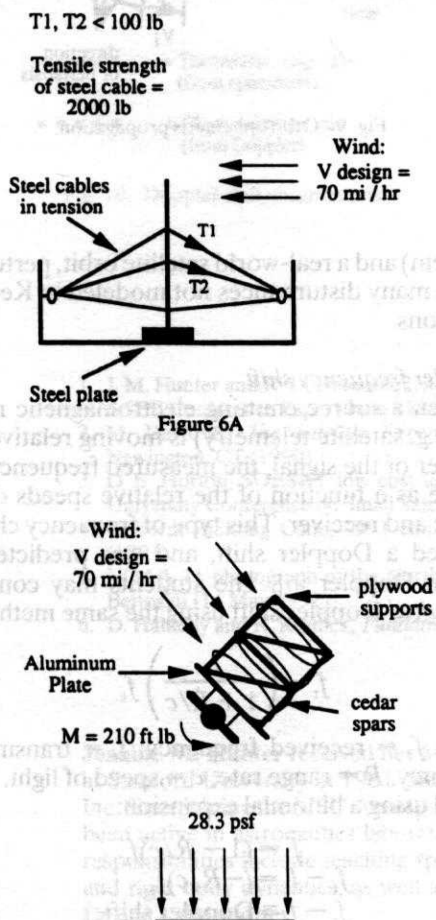

Fig. 6. Antenna structural analysis.

As discussed in the Communication Link Design section, the antenna was originally designed for communication with the very low power SOESAT transmitter. This design objective resulted in a ground station antenna gain of 13 dB, and required a six-turn helix with dimensions of 10 by 2 ft. For a design wind pressure of 28.3 psf, the tension and compression of the wood members was high, but considered acceptably within their critical limits. However, the bending moment experienced at the attachment point of the azimuth/elevation rotator was too large to maintain a reasonable safety factor. Since an inexpensive, non-conductive helix support was required, the redesign options were limited.

The redesign goal of reducing the weight and wind resistance of the wood helix supports could only be accomplished by reducing the length of the helix, with the effect of also reducing the antenna gain. Since the two applications of the ground station are so different in terms of their received signal strength (i.e. receiving either NOAA or SOESAT signals), two helix assemblies are planned. The first helix is a reduced weight, lower gain structure with the following characteristics:

- three-turn helix configuration (5 by 2 ft.);
- angular limits of 0–90° in elevation and 0–360° in azimuth;
- tuned to 136 MHz, bandwidth 108.8–176.8 MHz;
- right-hand circular polarization;
- gain, 10 dB.

This revised design is more than adequate to receive the transmissions of the meteorological satellites. Figure 6B shows the resulting load and moment. The second helix is the original antenna (10 by 2 ft, with a gain of 13 dB) which will be built and placed in limited use to communicate with SOESAT upon its launch.

EXPERIMENT CONCEPTS AND CURRICULUM BENEFITS

When the ground station is used as a passive receiving facility, several very instructive and motivating experiments can be performed by the undergraduate astronautics students. The NOAA satellite telemetry may be demodulated or the satellite may be tracked and its position and velocity may be both estimated and observed.

Meteorological satellite photographs

Using the APT card (readily available commercially) in the computer, NOAA satellite signals may be demodulated, and the resulting weather photographs may be captured in a file and displayed on the screen (Fig. 7) [5]. Meteorological observations, such as wind and weather patterns

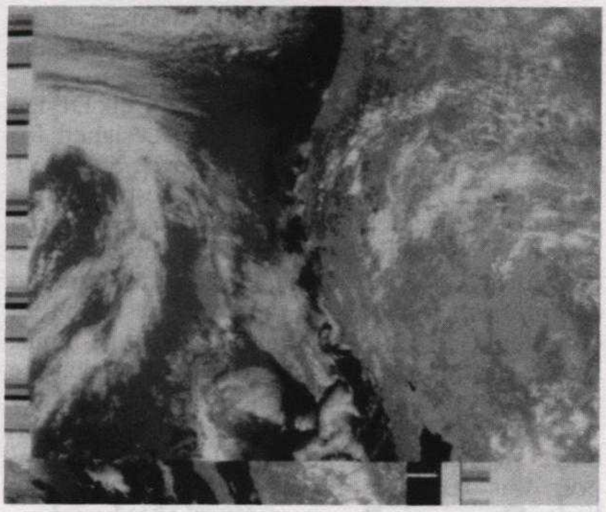

Fig. 7. Demodulated APT transmission.

can be predicted or studied for short term and seasonal variations. Eventually, this capability will be able to support the SJSU Meteorology Department in their experimental observations.

Orbital mechanics experiments

Using NOAA satellite state vectors obtained from NORAD, antenna pointing angles (azimuth and elevation) relative to the SJSU ground station may be calculated. The students may develop an algorithm for these angles using orbit and Earth geometry, and then check their results using commercially available software (Fig. 8).

After obtaining the satellite's position at a given time, the students may propagate the ephemeris to another time point, comparing the results with a NORAD state vector at the new time point (Fig. 9). This may be done using Kepler's time equation or Lambert's theorem, depending on the particular experiment being performed. Accuracy of the chosen propagation method can be assessed, and sources of error determined.

Tracking the Keplerian elements over time will allow the students to assess the differences between a theoretical orbit (predicted by the two-body problem) and a real-world satellite orbit, perturbed by the many disturbances not modeled in Kepler's equations.

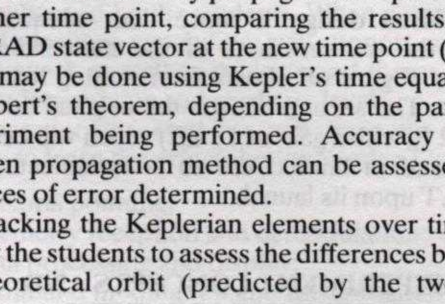

Fig. 8. Calculation of local azimuth/elevation angles.

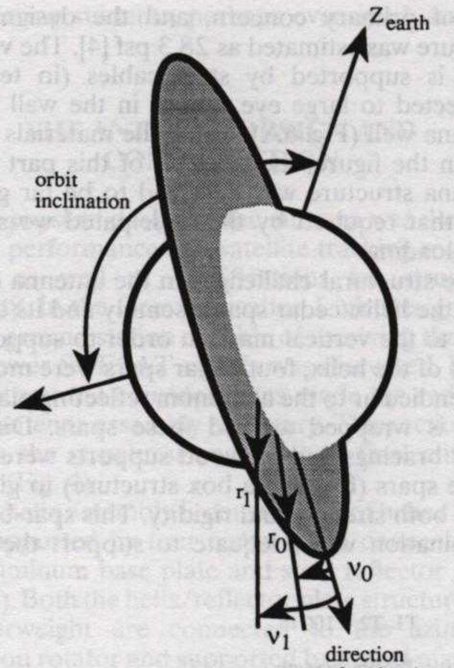

Fig. 9. Orbit ephemeris propagation.

Doppler frequency shift

When a source emitting electromagnetic radiation (e.g. satellite telemetry) is moving relative to a receiver of the signal, the measured frequency will change as a function of the relative speeds of the source and receiver. This type of frequency change is called a Doppler shift, and was predicted by Johann Doppler [6]. The students may compute *theoretical* Doppler shift using the same method:

$$f_r = \left(\frac{1}{1 + \dot{R}/c} \right) f_t$$

where: f_r = received frequency; f_t = transmitted frequency; $\dot{R}$ = range rate; c = speed of light.

And using a binomial expansion:

$$f_r = (1 - \dot{R}/c) f_t$$
$$f_r - f_t = (-\dot{R}/c) f_t$$

where: $f_r - f_t \equiv$ Doppler shift.

Assuming a stable (constant) satellite transmission frequency, the *actual* Doppler shift can then be observed by tracking the signal using the spectrum analyzer.

After propagating the satellite's state vector to obtain an ephemeris, range rate as a function of time may be predicted. This may be compared to the observed Doppler shift time history (Fig. 10) and the propagation algorithm refined to eliminate as much error as possible.

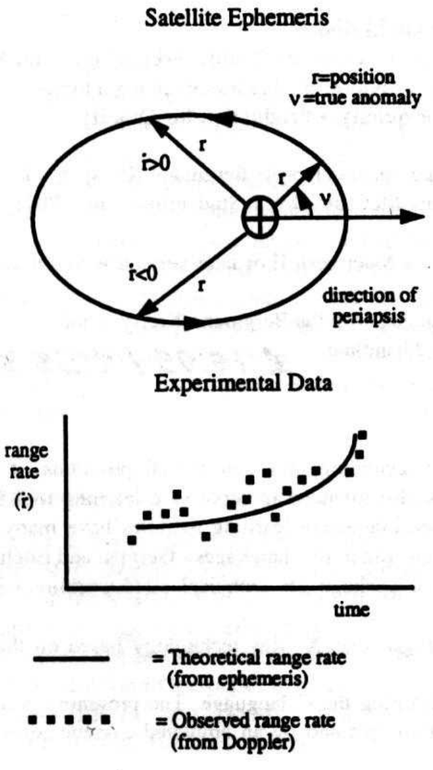

Fig. 10. Doppler shift observations.

CONCLUSIONS

The Aerospace Engineering curriculum at SJSU has been designed to provide astronautics students with the experience of hands-on engineering applications and experiment design. To facilitate this goal, student-designed and built experiments are integrated into the courses as laboratory assignments or demonstrations. Currently, one development of the Space Engineering Laboratory is a VHF ground station, designed and built by three students under faculty supervision. Upon completion, broad benefits to students and faculty, in terms of course enhancement and research opportunities, will be realized.

The faculty remains committed to this type of innovative, multi-disciplinary development, with a focus on student involvement. In particular, the authors would like to thank their colleagues whose collaboration made this project a reality: Franklin Liu, for his ground station software development efforts; Mark Bettosini, for his creativity and innovation during the antenna construction; Professor Steve Arnold for his consultation and redesign suggestions regarding the antenna construction; and Dr Henry T. Yang for his excellent professional advice in assuring the structural integrity of the antenna assembly as well as his thoughtful critique of the text of this paper.

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