Implementing a Satellite Earth Station – A Student Project

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I. Introduction

Since traditional communications engineering courses are largely theoretical and provide little hands-on experience, they often appear dry and impractical to students. Even in lab sections, students may be asked to design and construct simple modulators and demodulators, but they rarely have the opportunity to participate in the front-end design decisions necessary for a complete communication system. Consequently, they often leave the course with little understanding of how communication theory is applied in practice.

In this paper we describe a group project in which students design and implement an earth station capable of satellite tracking and transmitting and receiving signals via existing communication satellites. Using off-the-shelf amateur radio equipment, the entire project can be implemented for less than $4000. The project requires participating students to develop sub-skills and acquire software and hardware needed for satellite tracking and for amateur radio. Once the earth station is complete (i.e., once the students can transmit and receive signals via the satellites), it becomes:

- a demonstration station useful for recruitment and retention of students; and
- a source for further satellite-oriented student projects.

In the body of the paper we will discuss:

- the decision to use amateur radio satellites and equipment;
- front-end design choices and trade-offs;
- amateur radio satellites;
- equipment selection for the project; and
- other uses for the resulting earth station.

II. The Decision to Use Amateur Radio

Our goals in initiating this project were to (1) provide a high-interest level communication system design experience in the field of satellite communications and (2) develop a system with transmission capability as well as reception. Due to the plethora of satellite communication systems currently under development or in service (Odyssey, Iridium, Teledesic, etc.), and the resulting abundance of job opportunities in the field, almost any satellite project is inherently of interest to students. Thus, goal (1) is easily achieved. However, Federal Communications Commission (FCC) restrictions on signal transmission make goal (2) more difficult to achieve. We note that goal (2) is particularly desirable in spite of this difficulty because transmission capability opens up a whole new arena for future research, particularly in the areas of channel measurement/characterization and propagation studies.

A relatively easy way to obtain transmission capability is to have students obtain (from the FCC) a Technician Class Amateur Radio License. To obtain this license, project participants need only study some very basic material in electronics and communication theory and learn a little about the FCC rules concerning transmission on various frequencies. Knowledge of Morse Code is no longer required. Books, short courses, and software are readily available (e.g., see reference 1) to help students pass the required exam. The Technician's License will enable students to transmit signals via amateur radio satellites and to transmit terrestrial signals over a designated portion of the VHF/UHF band. We hope that the license will also open the door to a future of life-long learning, as recommended by ABET in their *Criteria 2000*,[2] by exposing students to a hobby closely related to their chosen field of study.

A peripheral advantage that results from deciding to use amateur radio satellites is that there is a considerable amount of help available from the amateur radio community. The American Radio Relay League (ARRL) has published numerous articles about the use of amateur radio satellites and the design and construction of the required earth stations. (See references 3, 4 and 5.) The Radio Amateur Satellite Corporation (known as AMSAT) also provides help in the form of a Web page (WWW.AMSAT.org) and monthly publication of *The AMSAT Journal*.

III. Front-End Design Choices and Trade-offs

Once the decision is made to use amateur radio satellites, there are three remaining decisions[4] to be made that will affect the equipment to be purchased, the specific satellites to be tracked, and the skills that participating students will need to acquire. These three decisions and their corresponding engineering trade-offs will be discussed in separate sections below.

III-i. CW/SSB/FM or Packet Radio

Amateur radio satellites typically carry either a linear transponder or a digital transponder. Some of the more recent satellites carry both. A linear transponder takes a band of incoming signals (from the uplink) from one portion of the spectrum, amplifies the entire band, and then shifts the band to another portion of the spectrum to be used for the downlink. The modulation for linear transponders is either Morse Code telegraphy, known as CW (continuous wave) in amateur radio parlance, Single Sideband (SSB), commonly used for voice transmission,[4] or FM. Communication occurs in real time with a linear transponder, requiring that both the sending and receiving earth station be in the satellite's footprint simultaneously.

A digital transponder collects data in digital form, usually in packets, processes it, and retransmits it. This is generally done in "store and forward" mode, meaning that the data may be collected from a particular earth station currently in the footprint of the satellite, and held for retransmission until the addressed receiving earth station is in the footprint of the satellite. Satellites with digital transponders for packet radio communication are called Pacsats. The most commonly used modulation for the newer Pacsats is Phase Shift Keyed (PSK).

Choosing between CW/SSB/FM and packet radio is tantamount to choosing whether you want to work satellites with linear transponders or satellites with digital transponders. Choosing packet radio also requires that you purchase a Terminal Node Controller (TNC), which is a specialpurpose modem that breaks down the data to be transmitted into suitably sized packets with address-headers prior to transmission. Of course, the receiving station also must have a TNC to re-assemble the packets into the form of the original data, without the address-headers, after reception. Choosing packet radio requires that participating students develop some additional skills in this area. We chose to work CW/SSB/FM, with the understanding that we could always add packet radio capability at a later time.

III-ii. Low-Earth Orbits or Higher Orbits

Satellites with orbital altitudes of less than approximately 1000 n. mi. are said to be low-earth orbit satellites, or LEO's. Because they are closer to earth, LEO's tend to require lower transmission power both on the uplink and downlink if all other factors are held constant. Equivalently, for a fixed satellite EIRP*, the smaller distance from earth enables us to hear the signals with a less sensitive receiver. The smaller distance from earth also yields a smaller satellite footprint and a correspondingly shorter communication window between two points simultaneously within the footprint. Most Pacsats are in low-earth orbit.

Satellites in higher orbits require more transmission power, or alternatively, more sensitive receivers compared to LEO's if all other factors are held constant The larger distance from earth also yields a larger satellite footprint and a correspondingly larger communication window between two points simultaneously within the footprint. This is particularly true for earth stations in the Northern Hemisphere, per Kepler's third law,[7] since that is where the higher-altitude portions of the orbit tend to occur by design.

Choosing between LEO's and higher orbits largely determines whether or not you need to purchase tracking software to control the direction of your antenna. LEO satellites complete one revolution about the earth in approximately one hundred minutes, so that your earth station will only be within the footprint of the satellite for about fifteen to twenty minutes. This means that your antenna must move from one horizon to the other in fifteen to twenty minutes, which almost necessitates computer control of your antenna. For satellites in higher orbits, it is often possible to manually point your antenna in the direction of the satellite, leave it there for more than an hour, and still be in the footprint of the satellite. We chose to focus on the LEO's, largely due to the educational nature of the required tracking issues.

III-iii. Uplink/Downlink Frequency Pairs (Modes) and Satellites

Each satellite transponder is designed to accommodate certain modes, or pairs of frequency carriers, to be used on the uplink and downlink. By selecting the mode(s) for your earth station, you are essentially limiting the satellites that you can work to those that accommodate your chosen mode(s). Selection of mode also determines the required frequency band of the transceiver to be purchased. Figure 1 shows commonly available pairs of uplink and downlink frequencies, with the corresponding mode designation. The first system of nomenclature for the

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* Effective Isotropically Radiated Power – This is a measure of the power radiated by the transmitting antenna relative to that of an isotropic antenna; thus, EIRP = P_tG_t wher P_t is the transmitted power and G_t is the transmitting antenna gain.

modes called for a single-letter designation for each pair of frequencies. The names of the modes according to this system are shown inside the grid. Mode B, for example, uses an uplink frequency of 435 MHz and a downlink frequency of 145 MHz. A newer system of nomenclature calls for a two-letter designation for each pair of frequencies, where the letters used correspond to commonly used names for the frequency bands. The names for the modes according to this system are shown (in bold) to the right and above the grid lines in Figure 1. The convention is to name the uplink frequency first, so that what was previously called Mode B, for example, would now be Mode UV.

The points in Figure 1 that are not named with a single letter represent proposed modes for the newer Phase 3 satellites, which will be discussed briefly in the next section. In fact, the most recent information available[6] indicates that Phase 3D satellite transponders will accommodate all downlink frequencies in Figure 1 at or above 145 MHz and all uplink frequencies in Figure 1.

Of course each mode has advantages and disadvantages, a few of which we mention below:[4]

- Mode A is usually used on satellites in low-earth orbit. This mode is very easy to use, but is susceptible to disturbances from the sunspot cycle.
- Mode B is suitable for all orbits, and provides a more reliable communications link than mode A. However, it is bandwidth limited and is nearly being used to capacity.
- Mode J is suitable for all orbits, but is available for amateur communications for only a limited amount of time each week.
- Mode K is usually used on satellites in low-earth orbit. It provides a particularly good environment for propagation experiments.
- Mode L generally provides a better quality link than mode B, and also has more available bandwidth.

We chose to work modes B and J, since they are both particularly well suited to CW/SSB/FM, and a large number of currently active satellites support these modes.

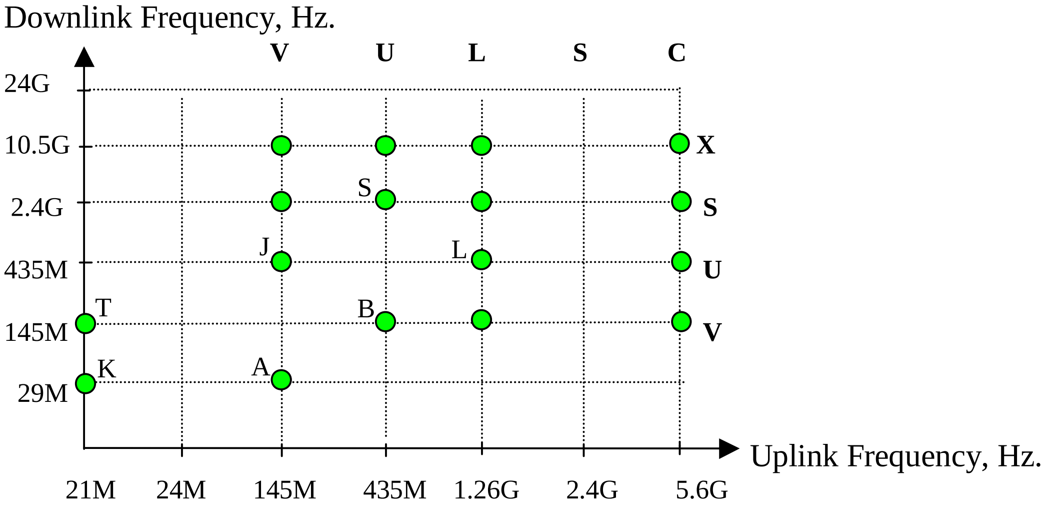

Figure 1. Modes and Corresponding Frequency Pairs[4, 5, 6]

IV. Description of Amateur Radio Satellites

The amateur radio satellite program dates back to December 12, 1961 when OSCAR I was launched. (OSCAR is an acronym for Orbiting Satellite Carrying Amateur Radio). The OSCAR I satellite transmitted a beacon signal at 144.983 MHz for three weeks. It was the first of over fifty satellites to operate beacons and/or transponders in the amateur radio frequency spectrum. Tables 1 and 2 list the amateur radio satellites that have been launched to date. The currently active satellites are in Table 2.[6]

Table 1. Inactive Amateur Radio Satellites

Satellite	Date Launched	Date of Last Use	Transponder or Beacon	Uplink Frequency	Downlink Frequency	Mode
OSCAR I	12/12/61	1/1/62	Beacon		145 MHz	
OSCAR II	6/2/62	6/20/62	Beacon		145 MHz	
OSCAR III	3/9/65	3/27/65	Transponder	145 MHz	145 MHz	
OSCAR IV	12/21/65	3/16/66	Transponder	145 MHz	435 MHz	J
Australis-OSCAR 5	1/23/70	3/10/70	Beacon		145 MHz	
			Beacon		29 MHz	
AMSAT-OSCAR 6	10/15/72	6/21/77	Transponder	145 MHz	29 MHz	A
AMSAT-OSCAR 7	11/15/74	1981	Transponder	145 MHz	29 MHz	A
			Transponder	435 MHz	145 MHz	B
			Beacon		145 MHz	
			Beacon		29 MHz	
AMSAT-OSCAR 8	3/5/78	6/24/83	Transponder	145 MHz	29 MHz	A
			Transponder	145 MHz	435 MHz	J
			Beacon		435 MHz	
			Beacon		29 MHz	
RS-1/RS-2	10/26/78	1979	Transponder	145 MHz	29 MHz	A
			Beacon		29 MHz	
UoSAT-OSCAR 9	10/6/81	10/13/89	Beacon		29 MHz	
			Beacon		145 MHz	
			Beacon		435 MHz	
			Beacon		2.4 GHz	
RS-3/RS-4	12/17/81		Beacon		29 MHz	
RS-5/RS-6/RS-7/RS-8	12/17/81		Transponder	145 MHz	29 MHz	A
ISKRA-2	5/17/82	7/9/82	Beacon			
ISKRA-3	11/18/82	12/16/82	Beacon			
RS-10/RS-11	6/23/87	5/1/97	Transponder	145 MHz	29 MHz	A
			Beacon		29 MHz	
AMSAT-OSCAR 13	6/15/88	12/5/96	Transponder	435 MHz	145 MHz	B
			Transponder	435 MHz	2.4 GHz	S
			Beacon		145 MHz	
			Beacon		2.4 GHz	
DOVE-OSCAR 17	1/22/90	7/1/98	Beacon		145 MHz	
			Beacon		2.4 GHz	
RS-14/AMSAT-OSCAR-21	1/29/91	9/16/94	Transponder	435 MHz	145 MHz	B
Arsene-OSCAR 24	5/13/93	1993	Transponder	435 MHz	2.4 GHz	S
Mexico-OSCAR 30	9/5/96	9/6/96	Transponder	145 MHz	435 MHz	J

Table 2. Active Amateur Radio Satellites

Satellite	Date Launched	Transponder or Beacon	Uplink Frequency	Downlink Frequency	Mode	Modulation
AMSAT-OSCAR 10	6/16/83	Transponder Beacon	435 MHz	145 MHz 145 MHz	B	CW/SSB CW
UoSAT-OSCAR 11	3/1/84	Beacon		145 MHz		1200 bps
AMSAT-OSCAR 16	1/22/90	Transponder Beacon	145 MHz	435 MHz 2.4 GHz	J	1200 bps FSK/PSK 1200 bps PSK
WEBERSAT-OSCAR 18	1/22/90	Beacon		435 MHz		1200 bps PSK
LUSAT-OSCAR 19	1/22/90	Transponder Beacon	145 MHz	435 MHz 435 MHz	J	1200 bps FSK/PSK CW
Fuji-OSCAR 20	2/7/90	Transponder Beacon	145 MHz	435 MHz 435 MHz	J	CW/SSB CW
RS-12/RS-13	2/5/91	Transponder Transponder Transponder Beacon	145 MHz 21 MHz 21 MHz	29 MHz 29 MHz 145 MHz 29 MHz	A K T	CW/SSB CW/SSB CW/SSB CW
UoSAT-OSCAR 22	7/17/91	Transponder	145 MHz	435 MHz	J	9600 bps FM
KITSAT-OSCAR 23	8/10/92	Transponder	145 MHz	435 MHz	J	9600 bps FM
KITSAT-OSCAR 25	9/26/93	Transponder	145 MHz	435 MHz	J	9600 bps FM
Italy-OSCAR 26	9/26/93	Transponder	145 MHz	435 MHz	J	1200 bps FSK/PSK
AMRAD-OSCAR 27	9/26/93	Transponder	145 MHz	435 MHz	J	FM Voice
RS-15	12/16/94	Transponder Beacon	145 MHz	29 MHz 29 MHz	A	CW/SSB CW
POSAT-28	6/16/96	Transponder	145 MHz	435 MHz	J	9600 bps FM
Fuji-OSCAR 29	8/17/96	Transponder Transponder Transponder Beacon	145 MHz 145 MHz 145 MHz	435 MHz 435 MHz 435 MHz 435 MHz	J J J	CW/SSB 1200 bps FSK/PSK 9600 bps FM CW
RS-16	3/4/97	Beacon		435 MHz		
TMSAT-OSCAR 31	7/10/98	Beacon		435 MHz		
TechSAT-OSCAR 32	7/10/98	Beacon		435 MHz		9600 bps FM

These satellites are roughly classified in three phases. Phase I refers to the early, short-lived spacecraft, OSCAR I through OSCAR 5, placed in low-earth orbit. The Phase 2 satellites were also placed in low-earth orbit, but were designed for much longer lifetimes than the earlier Phase I satellites. Phase 2 began with the launch of OSCAR 6. The Phase 3 satellites are designed to be launched into a highly elliptical Molniya-type orbit in order to provide intercontinental coverage for large periods of time each day.[5]

The Radio Amateur Satellite Corporation (AMSAT) has been responsible for constructing many of the amateur radio satellites in use today. AMSAT is a predominately volunteer group consisting of amateur radio operators. They are involved in several educational activities. One of these activities places them in partnerships with universities that are interested in satellite construction and launch. Additional information (e.g., orbit descriptions, major purpose, country-of-origin) about the satellites in Tables 1 and 2 can be found on the AMSAT Web page. (See reference 6.)

V. Selection and Installation of Equipment

In this section we first discuss the equipment selected for the project, based on the front-end decisions detailed in Section III. The block diagram for the earth station is shown in Figure 2.

V-i. Personal Computer with Tracking Software and Hardware

To save money, we had the personal computer specially built, with the following specifications: a 2.1 GB hard drive, 16 MB RAM, a CD-ROM drive, a 15-inch color monitor, a 3D sound card, and an Ethernet 10-Base-T network card to provide internet access. To provide communication between the PC and the rotor controller, we chose Kansas City Tracker, which is essentially a PC board that enables the PC to track any object in orbit about the earth, commanding the rotor controller so that the antenna points in the right direction.

We also purchased LogSat (by LogSat Software Corporation), which is a software package that works with Kansas City Tracker to provide ground maps displaying the track of the sub-satellite point as the satellite orbits the earth. LogSat allows us to view a list of currently available satellites, i.e. those for which our earth station would be in the footprint at any given point in time. From the list of available satellites, we choose one to be tracked, using LogSat to display its footprint and sub-satellite point. LogSat also provides us information about the altitude, range, and Doppler shift for the satellite, and allows us to command the rotor-controller to track the satellite automatically. In order to provide accurate tracking information, LogSat needs to have current orbital descriptions for each of the thousands of satellites in its data base. A satellite's elliptical orbit is typically described using a set of six numbers called a Keplerian element set,[7] which can be updated periodically from the internet, say from the AMSAT Web page. (See reference 6.)

V-ii. The Transceiver

To operate on modes B and J, we needed a transceiver that would cover the frequency range from 145 MHz to 435 MHz and that could handle both CW and SSB modulation. We selected a model from Yaesu, with the following specifications:

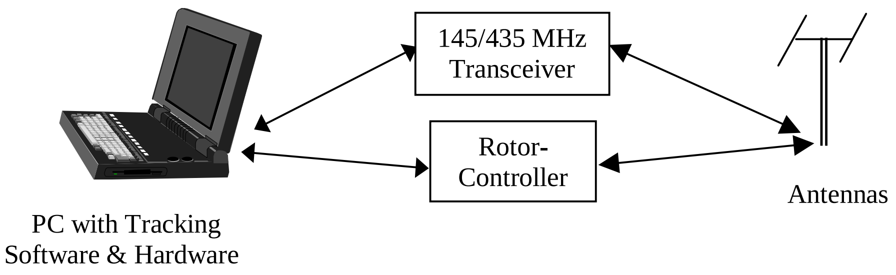

Figure 2. Block Diagram for the Earth Station

Model	Frequency Range	Modulation	Output Power
Yaesu FT-736R	21 MHz – 1.2 GHz	CW/SSB	25 W

V-iii. Antennas and Rotor Controller

Operation on both modes B and J require antennas for 145 MHz and 435 MHz. As suggested in *A Beginner's Guide to Oscar-13*,[3] we chose to use circularly polarized antennas to avoid attenuation resulting from polarization rotation. The two antennas that we selected were both from KLM Antennas, Inc., and had the following specifications:

Model	Frequency Range	Gain	Beamwidth
KLM 2M-22C	144 – 150 MHz	12.5 dBd	34°
KLM 435-40CX	420 – 440 MHz	15.2 dBd	25°

The circular polarization for these antennas results from a crossed Yagi configuration, and can be switched (remotely) from right-handed to left-handed circular polarization. The rotor controller that we selected is Yaesu Model G-5400B. This model allows us to remotely vary the elevation angle of the antenna by as much as 180° and the azimuth angle by a full 360°. Complete angular sweeps on either axis take from fifty to sixty seconds.

V-iv. Installing the Equipment

The initial design of the earth station also required students to do a site study including a link budget analysis. The antenna had to be placed in a way to minimize cable loss while simultaneously providing an unobstructed view of the horizon. The link budget analysis was necessary to insure that we would still have adequate received power after accounting for the losses due to cable length, coupling, etc.

VI. Other Uses for the Earth Station

Once the earth station was operational, it became available as a demonstration tool to aid in the recruitment and retention of students. The station can now be operated during an open house or lab tour, allowing visiting students to select any satellite for which a communication window is available, display the moving footprint for the selected satellite, and listen to conversations on the appropriate frequencies. Students can also select a weather satellite, and display the image of the earth as seen from the satellite. By locating the earth station in the communications lab, we hope to also expose our undergraduate students to the high-interest level field of satellite communications.

The earth station is also available for more advanced satellite-oriented research projects concerning issues such as clock-acquisition, modulation, coding, and pulse shaping. Other potential project areas include packet radio, antenna design, amplifier design, channel measurement/characterization, propagation studies, multipath, and signal processing.

VII. Conclusion/Lessons Learned

In summary, we have presented a group project that exposes students to the exciting world of satellite communications. Participating students were involved in front-end design decisions based on engineering tradeoffs as presented in Section III. Students also learned practical satellite engineering vocabulary and concepts (such as Keplerian elements, ephemeris data, transponders, and frequency bands) that are rarely covered in class.

If lack of time is a problem, the project can be simplified by dropping the transmission capability and opting to track and receive only. This would eliminate the need for the participating students to obtain a Technician Class Amateur Radio License. However, we would emphasize that engineering students should have no trouble obtaining the license, and the students will learn considerably more if the requirement is enforced.

Bibliography

1. Wolfgang, Larry D., et. al, editor, *Now You're Talking – All You Need to Get Your First Ham Radio License,* 2nd ed., The American Radio Relay League, Newington, CT, 1993.
2. Accreditation Board for Engineering and Technology, *1997 Manual of Evaluation Process For Engineering Criteria 2000,* Baltimore, MD, 1997.
3. Berglund, Keith, *A Beginner's Guide to OSCAR-13,* The Radio Amateur Satellite Corporation (AMSAT), Washington, D.C., 1989.
4. Davidoff, Martin, *The Satellite Experimenter's Handbook,* The American Radio Relay League, Newington, CT, 1990.
5. *The ARRL Satellite Anthology*, The American Radio Relay League, Newington, CT, 1994.
6. The AMSAT Web Page, url:www.amsat.org (last revised 8/98).
7. Pratt, Timothy, and Bostian, Charles W., *Satellite Communications*, John Wiley & Sons, New York, NY, 1986.

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Sharlene Katz is the Associate Dean of the College of Engineering and Computer Science and a Professor of Electrical Engineering at California State University, Northridge. She earned a Ph.D., an Engineer's Degree, an M.S. and a B.S. all in Electrical Engineering and all from the University of California, Los Angeles. Her areas of expertise are communication systems and electronics.

Earth station antennas are at the earth end of satellite links. High gain is needed to receive the weak signals from the satellite, or to transmit strong signals to the satellite. The antennas can be divided into three typesÂ Earth stations are required to detect small signals so the control of the noise parameters is important. The noise appearing at the output terminals of an earth station used as a receiver has three components; the noise received by the main beam of the reflector; the spillover noise due to the spillover from the feed; the receiver noise. The first component may be due to natural sources or to man made interference. Can a satellite be left stationary deep in outer space? Can an individual launch a satellite? James Nevik. , contractor at NASA (1992-present).Â Launching a satellite is entirely within reach for a reasonably well off hobbyist, a university project, or a small company. Sahil Chaudhari. , Space science enthusiast.Â What is the farthest a satellite can go into space and still send a reachable signal to earth? Is it theoretically possible that a satellite has its own satellites? What happens to the remains of a rocket once the satellite is launched into space? Earth observation satellites These are used to photograph and image the Earth. Low Earth orbits are mainly used so that a more detailed image can be produced. Astronomical satellites These are used to monitor and image space. A satellite such as the Hubble Space Telescope orbits at an altitude of 600 km and provides very sharp images of stars and distant galaxies. Other space telescopes include Spitzer and Chandra.Â International Space Station (ISS) This is a habitable space laboratory. At an altitude of 400 km, the ISS travels at a speed of 28,000 km/h and orbits the Earth once every 92 minutes. Scientists inside the ISS are able to perform many valuable experiments in a microgravity environment. Satellite design.