

Student Antenna Design for a Nanosatellite

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Abstract—Utah State University is building a nanosatellite that will cooperate with satellites built by the University of Washington and Virginia Tech to perform important ionospheric investigations, as well as test various aspects of formation flying around the earth. These satellites must be able to communicate with each other as well as communicate with the ground stations. This paper describes the nanosatellite program at Utah State University (USU_{sat}). In addition, the communication link budget and antenna designs for this satellite are described in detail. The ground station will have an array of helical antennas, while the antennas on the satellites will be circularly polarized microstrip patches.

- Investigate the global ionospheric structure that affects the performance of space-based radars and other distributed satellite networks.
- Test autonomous formation flying and intersatellite communications within the constellation.
- Baseline new technologies including micro-thrusters, magnetic gimbaled attitude control, and an Internet based operations center.
- Bring a unique, hands-on space experience to students in space systems engineering.

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1. INTRODUCTION

The Ionospheric Observation Nanosat Formation (ION-F) is a constellation of three satellites being built by Utah State University (USUSAT), University of Washington (DawgStar), and Virginia Polytechnic Institute (HokiSat) under the AFSOR/DARPA University Nanosatellite Program (Figure 1). The satellites are to be deployed during an upcoming space station construction mission early in 2002. Student teams with direction from faculty are designing and building these 15-kg satellites. NASA and industry are also funding individual and multi-satellite experiments at each of the universities. The ION-F constellation will provide the first multi-satellite study of density structures and irregularities in the ionosphere.

The satellites will be deployed from the shuttle into a circular low-Earth orbit of approximately 380-km with an inclination of 51.6 degrees. The orbits will decay due to drag over an 8-month period after which the satellites will re-enter the Earth's atmosphere. The objectives of the Ion-F satellites are to

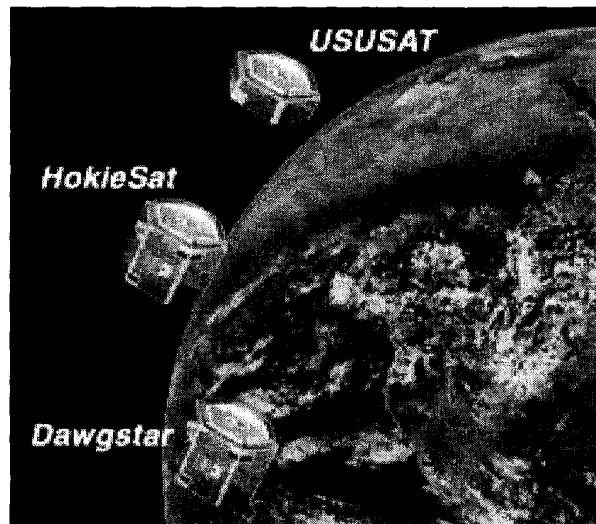


Figure 1. Depiction of the three university satellites in orbit around the earth.

The primary scientific objective is to measure the ionospheric density at each satellite since density irregularities cause large amplitude and phase fluctuations in radio waves passing through them. Single satellites have long studied these variations but they can only provide very limited information on the dimensions and evolutionary time scales of these disturbances. This is because they can only pass through such a disturbed region once. After a full orbit of 90 minutes the ionosphere, which co-rotates with the Earth, has moved. A set of satellites, arranged as a string of beads with varying separations, is what is required to make

detailed measurements of these density structures. The ION-F satellites will provide essential information for the understanding of ionospheric effects on communications, navigation, and GPS systems and for the development and validation of global ionospheric models. These observations are related to the priority measurements set up by the National Space Weather Program.

The ION-F satellites fit together to form a stack 23 inches high with inter satellite separation systems between them. The satellites are hexagonal in shape with an 18-inch diameter. This stack is then integrated onto a Multi Satellite Deployment System (MSDS) being developed by the Air Force Research Labs. Several other satellites being developed by other university teams will also be integrated to the MSDS, Figure 2. The MSDS will be ejected from the shuttle using NASA's SHELS platform and each of the satellite stacks will then be ejected from the MSDS. After being separated from the MSDS the ION-F Satellites will align themselves and then separate relative to each other. The string of beads constellation will be controlled by using Pulsed Plasma Thrusters (PPT's) on HokieSat and DawgStar and by controlling atmospheric drag and lift forces on USUSAT.

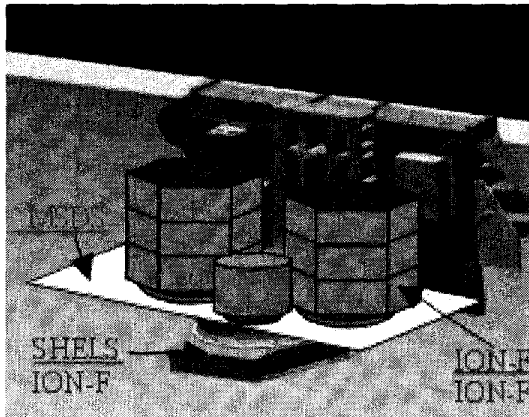


Figure 2. ION-F and other satellites that are part of the University Nanosatellite Program will be deployed from the Space Shuttle using a combination of NASA's SHELS ejection platform and AFRL's MSDS.

A system-level diagram of the ION-F satellite is presented in Figure 3. Each ION-F satellite is three-axis attitude controlled, requiring sun, Earth horizon, and geomagnetic field measurements. Although each of ION-F satellites is being develop by separate student teams at USU, VT and UW, a common command and data handling system is being used. This system provides control of thermal, power, and telemetry subsystems as well as command over various mechanisms on the satellites. Unique to ION-F, among small satellites, is a Crosslink/GPS system being provided by NASA and the Applied Physics Laboratory. This will allow the satellites to directly determine their relative position in the constellation and pass messages to each other. The ionospheric measurement instruments require

significant data handling and storage capabilities when compared to other subsystems. The interior layout of USUSAT is presented in Figure 4.

The access time to ground-stations limits the amount of data that can be collected by the satellites. Each of the three ION-F satellites is required to share a single frequency allocation. This places an additional restriction on both the operation and the telemetry subsystems to avoid interference during communications with ground stations. Primary ground stations will be located at Utah State University and Virginia Polytechnic Institute. The approach taken is to have the satellites share overpasses round-robin style when they are close to each other in the sky.

The rate at which data (scientific and housekeeping) will be collected on-board the spacecraft is 1 kbps. A storage buffer of 16 megabytes will be used to hold data between ground-station accesses. The downlink data rate is 100 kbps and the uplink data rate is 10 kbps.

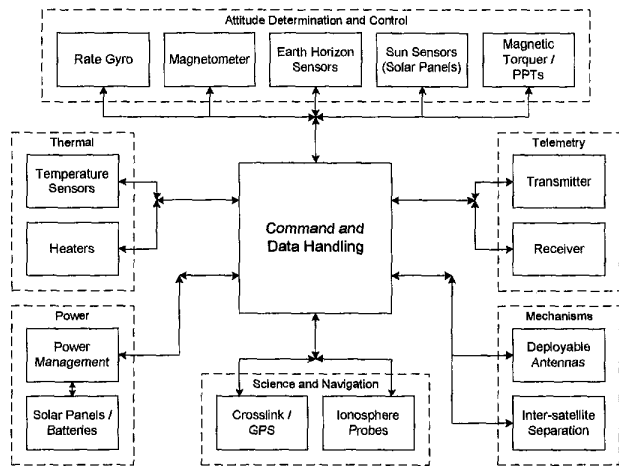


Figure 3. System-level diagram for an ION-F Satellite.

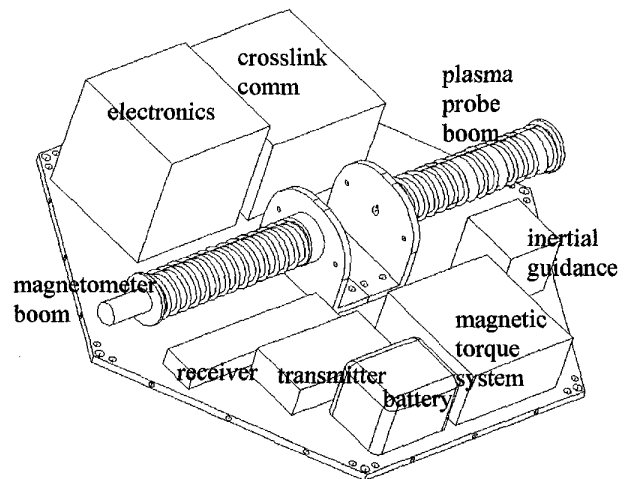


Figure 4. Interior of the satellite.

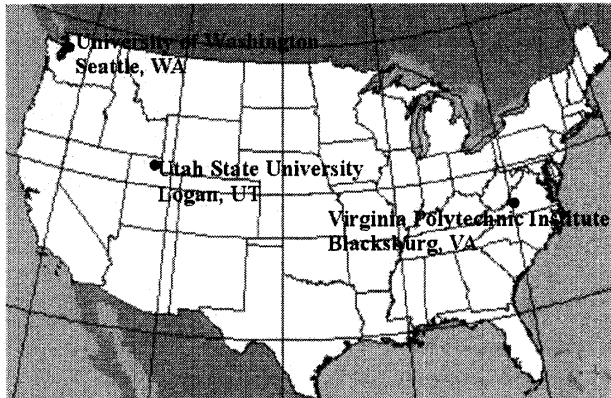


Figure 5. Location of the ground stations for the three university nanosatellites.

2. COMMUNICATIONS LINKS

The communication links for this project are earth/satellite and intersatellite. Ground stations are located at the three universities involved in the project (Figure 5). The Utah State University ground station needs high gain antennas that keep in touch with the low gain antennas on board the satellite. The satellite to satellite communications link has already been designed, so our presentation here focuses on the satellite to ground communications link.

Table 1 shows some of the parameters used to calculate the communications link budget. The antenna gains are the pertinent quantities for the antenna design. We assume all the antennas are circularly polarized. There will be a polarization mismatch at times. The worst case is a 3-dB loss. In addition, the ground station antenna beam may not be pointed directly at the satellite, so an alignment loss is added to each path. Since the antenna on board the satellite cannot be steered, the gain of the antenna facing the ground station may be quite small. If the peak gain of the patch is about five or six dB, then we assume the gain may be as small as 0.5 dB when the antenna does not face the ground station. Figure 6 show the satellite with antenna locations. Ionospheric effects are minimal at these frequencies. The noise levels are optimistic; however, low noise amplifiers that are available today make this noise level reasonable.

3. ANTENNA DESIGN

A microstrip patch was selected for the antennas on board the satellite because no deployment mechanics is necessary and the antennas are conformal to the surface of the satellite. Microstrip antennas are narrow band, but the bandwidth for the up link and for the downlink is less than 1%, so they are quite appropriate for this application. Circular polarization can be achieved a number of ways. We have decided to use a coax fed rectangular patch. Circular polarization is obtained by feeding the patch along the diagonal. Two edges are trimmed from the square patch in order to obtain CP with one feed. This helps in exciting 2 orthogonal

degenerate modes of some resonant frequency of ideally equal amplitudes. By proper trimming of the corners one mode can lead by 45 degrees and the other lag by 45 degrees resulting in the 90 degrees phase shift necessary for circular polarization.

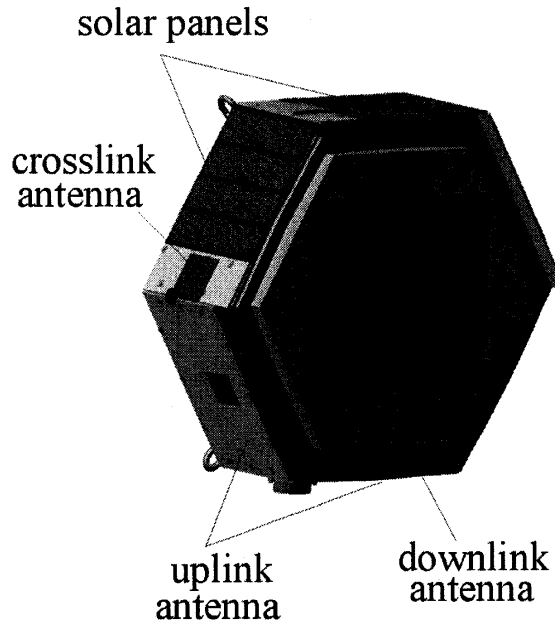


Figure 6. Picture of the USUsat with antennas.

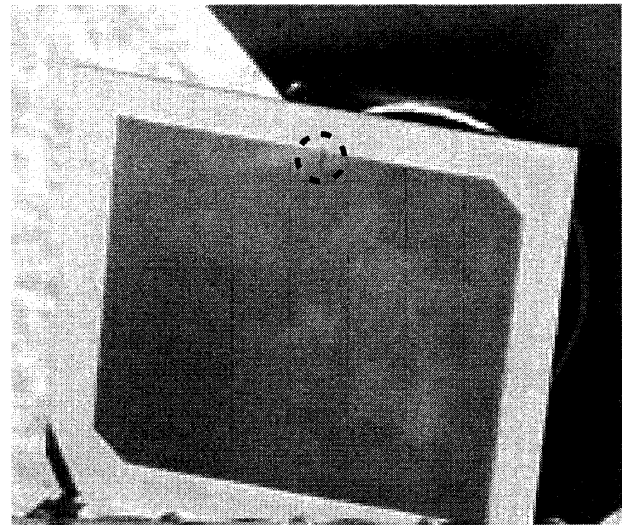


Figure 7. Picture of the circular polarized 450 MHz up link antenna. Note that the patch is fed at the top center edge (inside dashed circle) to create a circularly polarized wave.

A typical square microstrip patch is approximately $\lambda/2$ by $\lambda/2$. At 450 MHz, the up link patch would be approximately

Table 1. Communication link budget for the USUsat

Design Element	Symbol	Units	Source	Down Link	Up Link
Link Frequency	f	GHz	Input	2.2	0.45
Transmitter Power	P	Watts	Input	0.75	25.000
Transmitter Power	P	dBW	Cal	0.000	13.979
-- Transmitter --					
Wavelength	λ_t	cm		13.6	66.7
Antenna Gain	Gt	dB	Input	-3.00	23.83
Antenna Gain	Gt	dimensionless		0.5	676
Approximate effective aperture	A_e	m ²		7.36×10^{-4}	8.55
Antenna Transmitter Losses	Ltx	dB	Input	-0.5	-0.5
Antenna Beamwidth	Theta_t	Deg	Input	180.10	10.96
Antenna Misalignment	Alphabet	Deg	Input	30	1
Alignment Loss	Lt	dB	Cal	-0.333	-0.100
Equivalent Isotropic Radiated Power	EIRP	dBW	Cal	-3.83	37.21
-- Losses --					
Propagation Path Length	S	Km	Input	2274	2274
Space Loss	L_s	dB	Cal	-166.43	-152.65
Atmospheric	L_a	dB	Input	-0.3	-1
Polarization Loss	L_p	dB	Input	-3	-3
Total Losses	L	dB	Cal	-169.73	-156.65
-- Receiver --					
Wavelength	λ_r	cm		13.6	66.7
Antenna Gain	Gr	dB	Input	37.62	-3.00
Effective aperture	A_e	m ²		8.51	
Antenna Receiver Loss	Lrx	dB	Input	-0.5	-0.5
Antenna Beamwidth	Theta_r	Deg	Input	2.2	180.0
Antenna Misalignment	Alpha_r	Deg	Input	1	45
Alignment Loss	Lr	dB	Cal	-2.39	-0.75
Total Receiver	G	dB	Cal	34.73	-4.25
Sky (Antenna) Noise Temperature	Ta	K	Input	17	300
Receiver Temperature	Tr	K	Input	95.2	371.0
System Noise Temperature	T	K	Cal	112.2	671.0
Receiver Merit	G/T	DB(1/K)	Cal	14.23	-32.52
-- Powers --					
Power Flux Density	phi	dB(W/m ²)	Cal	-141.96	-100.92
Carrier Power Received	C	dBW	Cal	-138.83	-123.69
Noise Spectral Density	No	dB(W/Hz)	Cal	-208.10	-200.33
Carrier to Noise Density	C/No	dB(Hz)	Cal	69.27	76.65
-- Rates --					
Data Rate	R	Bps	Input	100.0E+3	10.0E+3
Eb/No	Eb/No	dB	Cal	19.266	36.646
Bit Error Rate	BER		Input	1.00E-05	1.00E-05
Required Eb/No	REb/No	dB	Input	12.4	12.4
Implementation Loss		dB	Input	3	3
Margin		dB	Cal	3.87	21.25

13 inches by 13 inches (Figure 7). These dimensions exceed the width of the sides of the satellite. Thus, we used a high dielectric substrate ($\epsilon_r = 10.2$) to get the dimensions of the patch down to 4.2x4.2 inches. Using such a high dielectric constant with a relatively thin substrate creates a very narrow band antenna. The calculated bandwidth and the measured bandwidth is 7 MHz. Thus, the design is within specifications.

The down link antenna is also a microstrip patch. The same high dielectric substrate was used for this antenna too in order to keep the patch small. Small antennas free real estate on the satellite for solar cells. This patch is also fed along the diagonal. It is 0.8x0.8 inches square. The corners are trimmed to get circular polarization.

The microstrip patches were designed using formulas from Balanis [1]. Next these approximate design parameters were entered into HP EEs of Advanced System Design (ADS) software package. This input file was modified until the center frequency for the patch was correct and the axial ratio was one (circular polarization).

Figures 8 and 9 show the calculated frequency response of a rectangular patch designed to have a center frequency at 2.34 GHz. The bandwidth is defined as the difference in frequencies between the two points where the standing wave ratio (swr) is two divided by the center frequency. Figure 8 is a patch fed at the center of one edge and two opposite corners of the patch trimmed (similar to the patch in Figure 7). The bandwidth of this patch is 0.98%. Figure 9 is the swr vs. frequency for a rectangular patch with the feed point along the diagonal of the patch. The bandwidth of this patch is 0.43%. Both feed methods create a patch with circular polarization. The actual design frequency for the patch is 2.2 GHz. We have found that the software tends to create a design that has a slightly higher resonant frequency in the model than the corresponding patch that is experimentally tested.

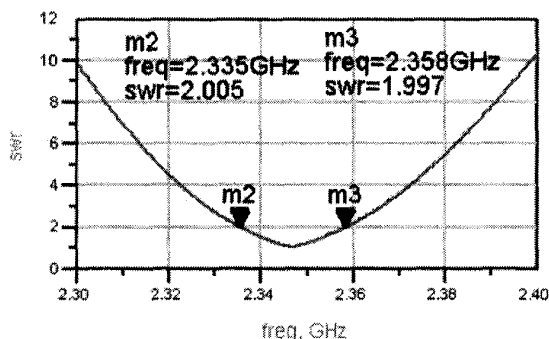


Figure 8. Plot of the swr vs. frequency for the rectangular patch with trimmed edges.

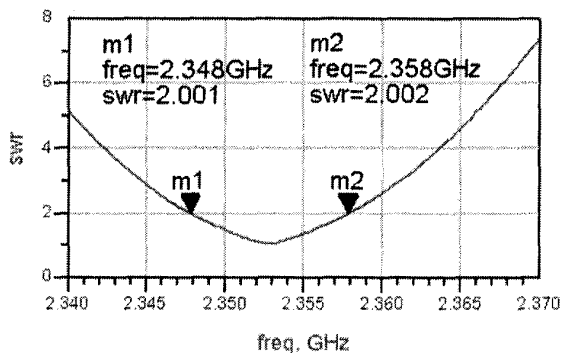


Figure 9. Plot of the swr vs. frequency for the rectangular patch with a feed point along the diagonal of the patch.

One diagonally fed patch designed at 2.2 GHz has the following measured specifications:

- Length = 790 mils
- Width = 790 mils
- Probe feed at (340 mils, 340 mils) from corner
- Resonant at 2.26GHz (33.187 Ω , -0.7227 Ω)
- VSWR: 1.4353
- Bandwidth: 0.75%
- Gain: 4.9 dB

The measured frequency is less than that predicted by the computer simulation, and the bandwidth is less than the bandwidth predicted by the computer simulation. The resulting experimentally measured resonant frequency is very close to the design specification of 2.2 GHz.

The ground stations must have large apertures. If the gain of the transmit antenna is 23.8 dB, then the aperture is at least

$$A_e \square 8.55m^2 \quad (1)$$

and the receive antenna must be at least

$$A_e \square 8.51m^2 \quad (2)$$

A satellite dish would be quite large at these frequencies: it would have to be at least 3.5m in diameter. In order to reduce the size of the antenna, an array of helical antennas is being built. A single 450 MHz element in the transmit array is shown in Figure 10. The element has 8 turns, each having a diameter of 8.36 inches, and a spacing between turns of 6.56 inches. The design gain is 13.8 dB. The receive array helical element has 30 turns, each having a diameter of 2 inches, and a spacing between turns of 1.315 inches. The design gain is 20 dB.

The 450 MHz array will have 4 elements (2 rows 2 columns) spaced 23.625 inches apart in a square lattice.

The array gain is 16 dB, resulting in a total antenna gain of 29.8 dB. The 2.2 GHz array will have 9 elements (3 rows 3 columns) spaced 4.734 inches apart in a square lattice. The array gain is 19 dB resulting in a total gain of 39 dB.

We are currently in the process of measuring the antenna patterns of the patch antennas and assembling the antenna arrays.

4. CONCLUSIONS

This paper described the student led satellite project at Utah State University. The communication link budget specified that a high gain circularly polarized ground station and small, circularly polarized, conformal satellite antennas are needed. The satellite antennas are microstrip patches. The ground antennas will be arrays of helical antennas. Figure 11 shows the relative sizes of the antennas next to a full scale model of the satellite.

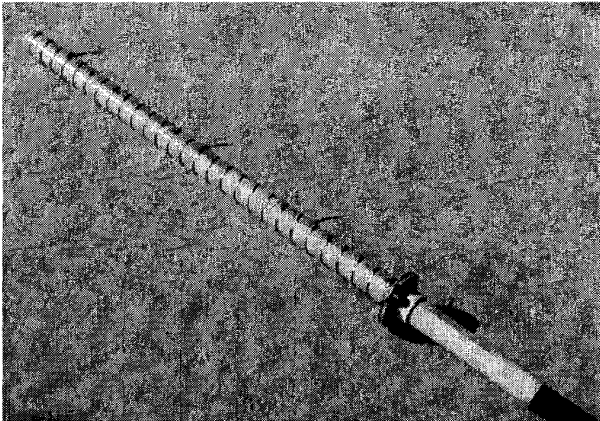


Figure 10. Picture of the helical antenna element.

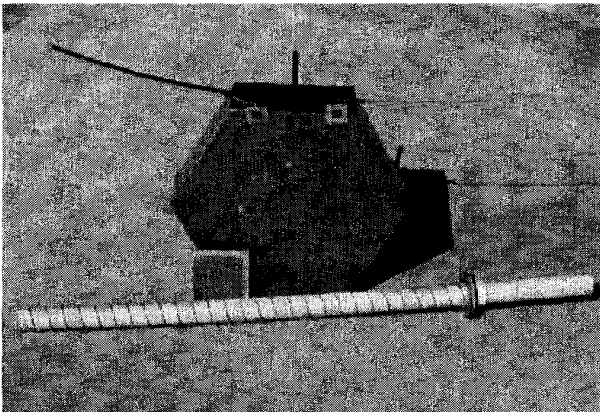


Figure 11. This picture shows the aluminum satellite model for antenna testing and the different antenna designs in this project.

REFERENCE

- [1] C. A. Balanis, *Antenna Theory Analysis and Design*, New York: Wiley, 1997.

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Charles Swenson is an Associate Professor of Electrical and Computer Engineering at Utah State University. He is the principal investigator for the ionospheric science measurements on ION-F and a co-investigator on USUSAT. Dr. Swenson is currently on sabbatical at The Aerospace Corporation in El Segundo, CA where he is working on small satellite and nanosatellite systems engineering. He has a PhD from the Cornell University, MS and BS from Utah State University.

