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Electrical Design and Testing of an Uplink Antenna for Nanosatellite Applications

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Abstract. Utah State University, the University of Washington, and Virginia Tech are teamed to form the Ionospheric Observation Nanosatellite Formation (ION-F) to investigate ionospheric turbulence and formation-flying requirements for multiple small satellite missions. A communication subsystem for the mission will be composed of an uplink, a downlink, and satellite-to-satellite crosslink. The uplink will operate at UHF. The downlink and crosslink both will operate in the S-band.

The design and successful implementation of a low profile, compact element with desirable properties at UHF within the physical constraints of a nanosatellite is a challenge. A resonant loop antenna mounted above the bottom surface of the spacecraft was selected for a possible satellite antenna. The linearly polarized resonant loop was chosen to satisfy the physical requirements of the spacecraft while still achieving efficient operation for a UHF signal.

A full-scale prototype was fabricated to measure the frequency dependent characteristics of the antenna. A gamma match and a quarter-wave sleeve balun transformer were integrated to the system to optimize the impedance match between the antenna and the transmission line.

Measured results presented in this paper indicate sufficient performance for the initial design. The antenna operating bandwidth of approximately one percent covers the estimated bandwidth of the uplink channel. However, integration with other components during fabrication could easily de-tune the resonant frequency of the loop antenna out of the required band. Further development of the uplink antenna design should include adjustable mounts and a capacitive tuning element.

Introduction

The Air Force Office of Scientific Research (AFOSR) and the Defense Advanced Research Projects Agency (DARPA) are jointly funding ten universities to individually design and build ten satellites. The University Nanosatellite Program is part of the larger Air Force Techsat 21 initiative to develop the technology of distributed small-satellite systems. The universities are funded to explore creative low-cost space technology experiments in formation-flying, enhanced communications, miniaturized sensors, attitude control and maneuvering. The Air Force Research Laboratory (AFRL) and NASA Goddard Space Flight Center (GSFC) are also contributing to the University Nanosatellite Program.

The university nanosatellites are to be deployed from the shuttlebay using a Shuttle Hitchhiker Experiment Launch System (SHELS). Figure 1 is an illustration of the SHELS ejection system which is designed from payloads up to 182 kg (400 lbs). Three satellites will be deployed from the shuttle as a single module. Once the ION-F stack is deployed, the satellites will detach from the SHELS baseplate using Lightbands™ developed by Planetary Systems Corporation (PSC) and will then maneuver into their initial orbits.

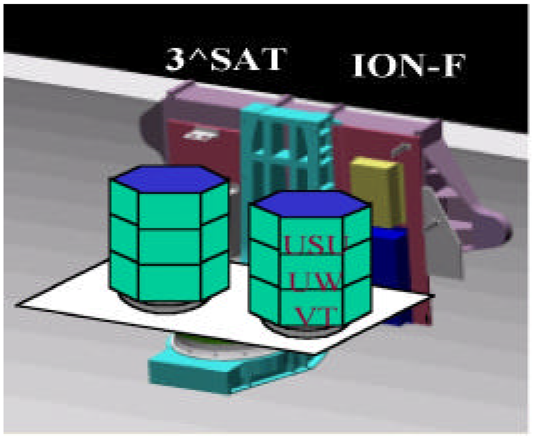


Figure 1. Illustration of the Shuttle Hitchhiker Experiment Launch System (SHELS). SOURCE: ION-F

The overall design of the ION-F satellite is based primarily upon the constraints due to the SHELS platform. Figure 2 is an illustration of the Virginia Tech ION-F satellite. The structure for each satellite is hexagonal with an approximate width of 46 cm (18 in) and height of 30 cm (12 in). Each satellite will weigh approximately 15 kg (33 lbs).

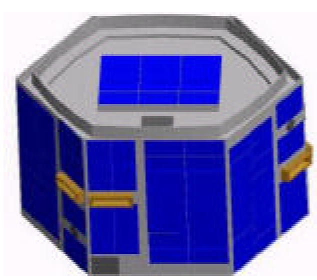


Figure 2. Illustration of the exterior of the Virginia Tech ION-F satellite (AUTOCAD image courtesy of Craig Stevens, VT-AOE)

One of the first tests to be conducted when the satellites detach will be to establish contact on both of the communication links. This paper will detail the electrical design for an uplink receive antenna considered for the ION-F communication subsystem.

One primary function of the uplink will be to initiate a satellite downlink transmission. The uplink will also be used with downlink attitude data to maintain the desired orbit. The operating frequency has not yet been allocated, but the uplink will most likely be above the amateur UHF band at 450-451 MHz. The 450-470 MHz portion of the spectrum has been designated by the FCC for Auxiliary Broadcasting with 2 way, 20 kHz channels for analog transmission [1].

The anticipated modulation will be narrowband FSK with a peak deviation of 5 kHz. The maximum Doppler frequency based on the initial orbit altitude of 300 km is 11 kHz. The maximum data rate will be 1200 baud with AX.25 as the uplink protocol. The spacecraft uplink receiver hardware will include an antenna, terminal controller, and a MO-96 modem internal to a TEKK 960 L transceiver in receive mode.

The design and implementation of an uplink receive antenna remains the primary task for Virginia Tech's involvement in the uplink subsystem design. The remaining components of the uplink are to be made flight ready by the Space Dynamics Laboratory at Utah State University.

Selection of Uplink Antenna

The primary restrictions in the design for every spacecraft subsystem in this project have been due to the size of the spacecraft and the stack configuration required as part of the mission. The top and bottom surfaces of the structure are both hexagons with a major diameter of 46.4 cm (18.25 in). The limited available surface area of the spacecraft has been a persistent challenge to the layout of the solar panels to satisfy power requirements.

Another physical limitation considered in the selection of the uplink receive antenna is the maximum allowable clearance between the spacecraft while they are in the stack configuration. The satellites will be placed in preliminary orbits by the Space Shuttle. The three satellites will be stowed in the cargo bay during the shuttle flight and will be deployed in the stack configuration.

The satellites will be inter-connected by LightBands. The LightBand will connect the top of one spacecraft to the bottom of the next. A LightBand will limit the maximum clearance between two satellites to be less than 5 cm (2 in). Once the LightBands detach, each of the three satellites will use propulsion to reach their respective orbits. Soon after the satellites detach, both the uplink and downlink will be tested to establish contact with one of the groundstations.

The uplink signal transmitted from the groundstation will be circularly polarized. Circular polarization (CP) can be generated by exciting two linearly polarized equal-amplitude, orthogonal modes in phase quadrature. The quality of polarization in polarized systems is dependent on how the orthogonal modes in the antenna are excited and how well they can be controlled [3].

Circular polarization may be achieved with several different antennas. Two general methods are used to generate CP. Type 1 antennas produce CP due to the unique physical geometry. Examples include helix and spiral antennas. Type 2 CP antennas contain hardware to explicitly generate spatially orthogonal components in phase quadrature [4].

Figures 3 and 4 illustrate two antennas which were initially considered for this project. The microstrip patch and the Quadrifilar Helix (QFH) are both circularly polarized and have been used on previous space missions. The physical requirements for a microstrip patch antenna to operate at the UHF specified by the ION-F project precluded its use on the satellite uplink. The maximum allowable clearance eliminated the possibility of using a QFH.

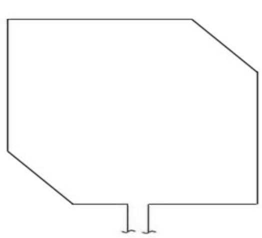


Figure 3. Circularly polarized microstrip patch antenna; degenerate mode single feed

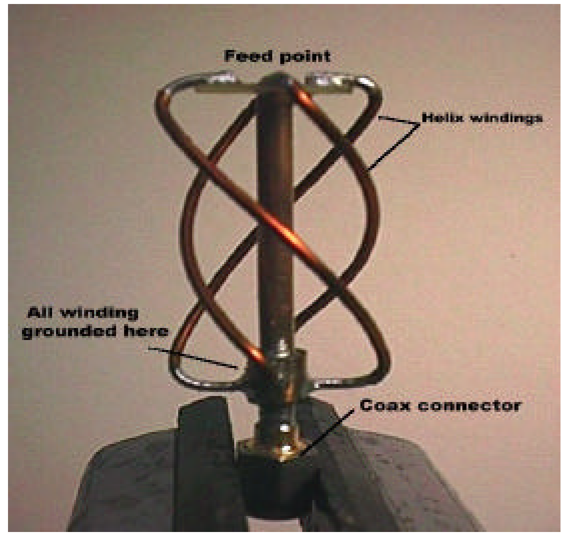


Figure 4. Quadrifilar Helix (Photograph courtesy of R. Michael Barts, VTAG)

A design solution was to investigate linear polarized, limited surface area antennas that are not CP. A linearly polarized antenna receiving a CP transmitted signal will suffer a theoretical loss of 3 dB [3]. However the reduction in received power due to the polarization loss may be offset by the increased gain of the proposed receive antenna. Other parameters in the link budget (e.g. Transmitted Power) can also be varied to compensate for the loss due to the polarization mismatch.

The possible use of the bottom surface of the spacecraft was also considered in the selection process. The nadir surface could act as a ground plane which would improve the total gain patterns of the receive antenna.

A one-wavelength resonant loop antenna mounted above a ground plane was considered for this application. The resonant loop antenna has a low profile, requires limited surface area and can be designed for a moderate gain of approximately 9 dB. A hexagonal shape was considered to facilitate the mechanical connection to the isogrid pattern of the spacecraft.

Resonant Loop Antennas

A resonant loop antenna has a perimeter that is approximately equal to one free space wavelength. The current distribution for a resonant loop antenna is nearly sinusoidal. Figure 5 illustrates how the sinusoidal nature of the current distribution is maintained from the (a) two-wire transmission line to (b) a half-wave dipole, (c) square loop, and (d) a hexagonal loop antenna.

Figure 6 is an illustration of a resonant hexagonal loop with the polarity of the impressed current shown by the direction of the arrows. The far-field radiation patterns may be determined from the magnetic vector potential of an analytical model of the resonant loop. The near sinusoidal current distribution can be approximated by a piece-wise linear current function.

The far-field radiation patterns calculated from the analytical model will not illustrate the asymmetry due to the presence of the antenna feed, however a comparison of the analytical model to the more accurate numeric electromagnetic code (NEC) model using the integral-equation based Method of Moments can be made [4]. Further radiation pattern comparisons show good agreement between the analytical and NEC models of the hexagonal loop in free space to published results for both the circular and square resonant loops.

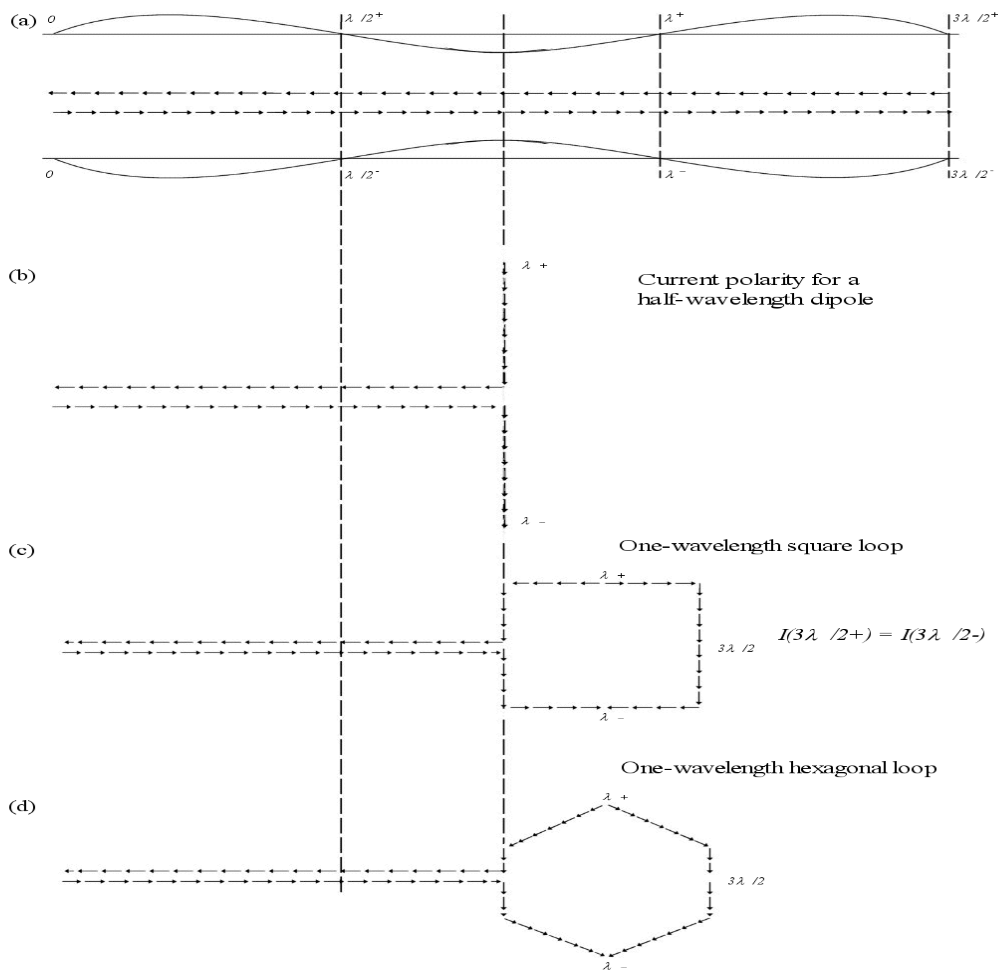


Figure 5. Sinusoidal current distribution for (a) two-wire transmission line, (b) half-wave dipole, (c) one-wave square loop antenna, (d) one-wavelength hexagonal loop antenna

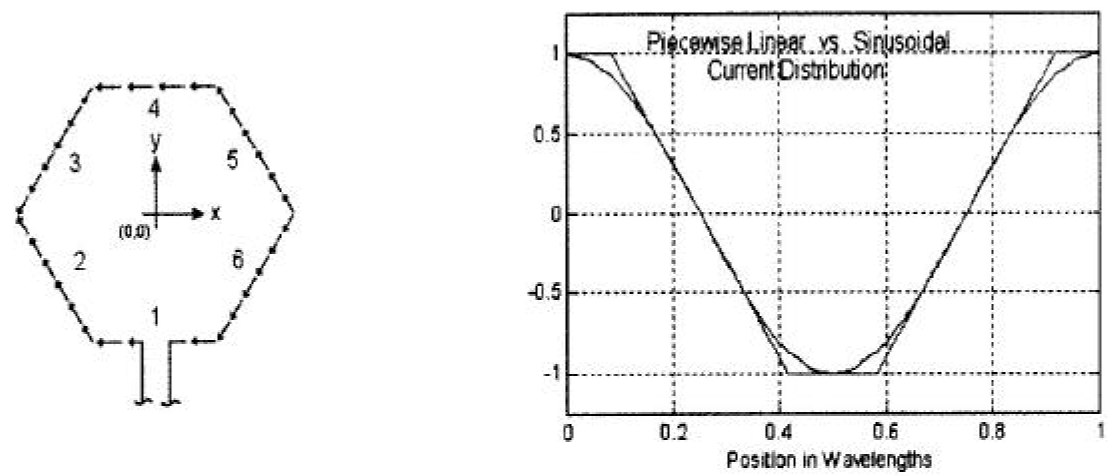


Figure 6. Piece-wise linear approximation of the current distribution for a one-wavelength hexagonal loop antenna

Groundplane Effects

The radiation characteristics of a one-wavelength circular loop antenna mounted above a planar reflector have been investigated and the results are available [5]. The ground plane can be used to form the pattern of the resonant loop such that it is omnidirectional in the azimuth plane with peak directivity in the direction normal to the loop. Two important considerations are the distance the loop is placed above the reflector (d/λ) and the size of the ground plane relative to the loop.

Figure 7 is a plot of the directivity of a resonant circular loop versus the distance from the reflector. The maximum offset for the ION-F uplink antenna is one inch. At a nominal operating frequency of 450 MHz, $(d/\lambda)_{max}=0.04$. Referring to Figure 7, the maximum allowable offset approaches a region of maximum directivity. An approximate value of directivity for the hexagonal loop antenna should be $D\approx 9.5$dB.

The second consideration is the size of the ground plane relative to the loop (S/λ). For the proposed ION-F design, the radius ratio for the two hexagons is 2. The hexagonal loop may suffer additional edge diffraction effects when compared to published results. However, the presence of the LightBand along the edge of the hexagonal groundplane will minimize the "spillover" of radiated power.

Far-field power gain patterns for a one wavelength hexagonal loop with and without a groundplane were computed with NEC models. Figure 8 is an illustration of the input geometry for the NEC model. Figure 9 contains plots of the far-field radiation patterns and the input impedance response. Figure 9 illustrates that placing the loop over a planar surface will increase gain, but the input impedance will become highly dependent upon the distance between the antenna and the reflector.

Maximum transfer of power from the uplink antenna and the 50 ohm coaxial transmission line will occur with a conjugate impedance match between two components. The 50 ohm characteristic impedance of the transmission line is nearly independent of frequency. In comparison, a resonant loop antenna is a narrow bandwidth device. The following section will describe a matching technique used to optimize the impedance match to the range of frequencies encountered in the uplink design.

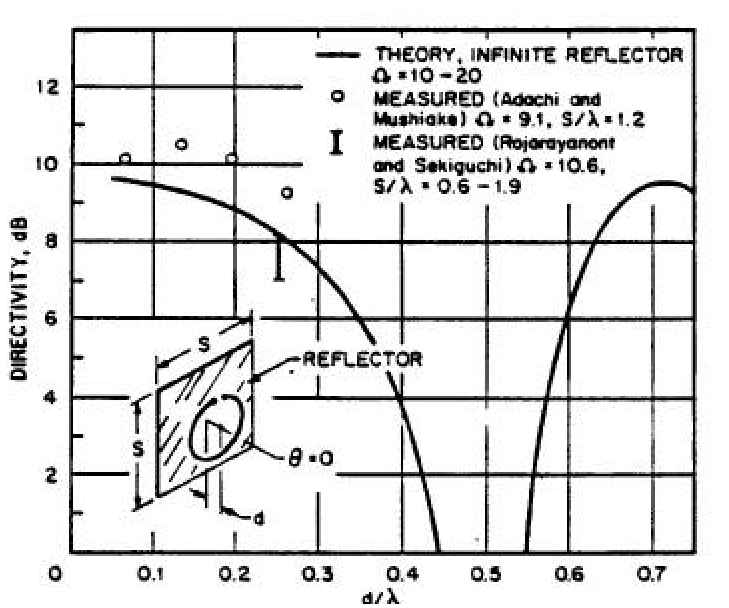


Figure 7. Directivity of a resonant circular loop antenna for $\theta = 0$ versus distance from the reflector d/λ. The theoretical curve is for the infinite planar reflector; The measured points are for the square reflector. SOURCE: R.C. Johnson, Ed., *Antenna Engineering Handbook*, 3rd ed.

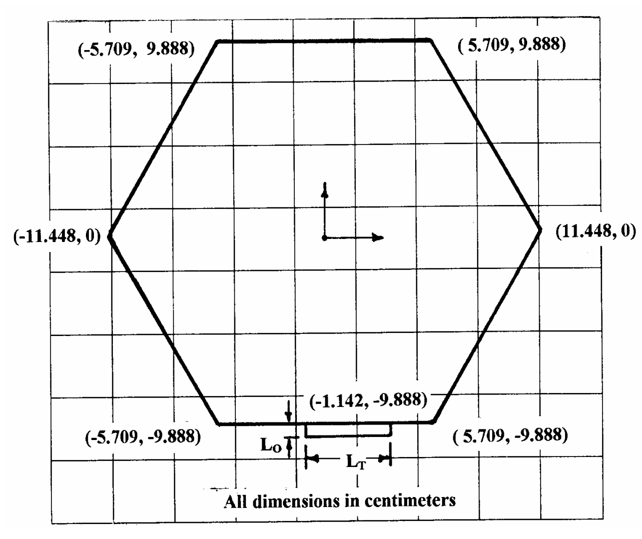
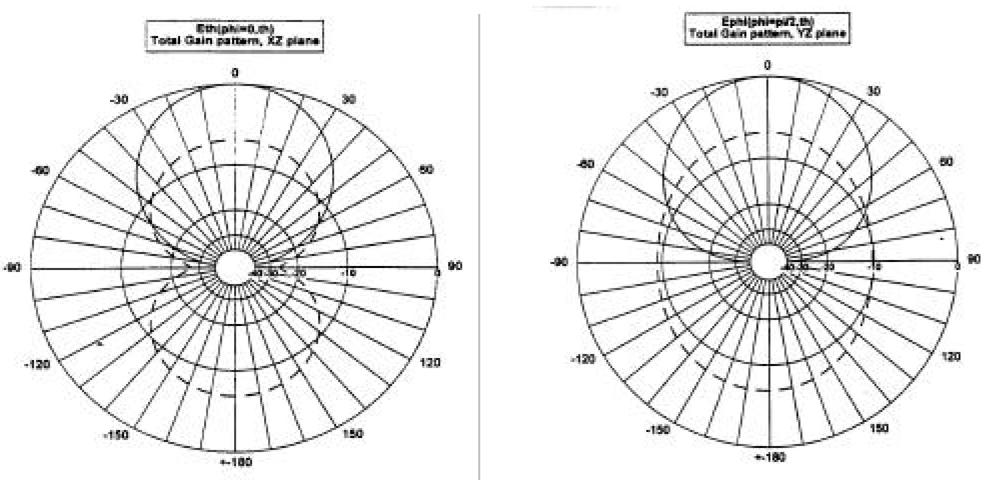


Figure 8. **Input geometry for a one-wavelength hexagonal loop antenna at the maximum ION-F offset above a ground plane.**



Far-field principal plane power patterns for a one-wavelength hexagonal loop antenna. The solid lines represent the gain patterns with the antenna mounted at the maximum ION-F offset above an infinite ground plane. The dashed lines represent the gain patterns for the antenna in free space. Numerical methods were used to calculate the total gain patterns.

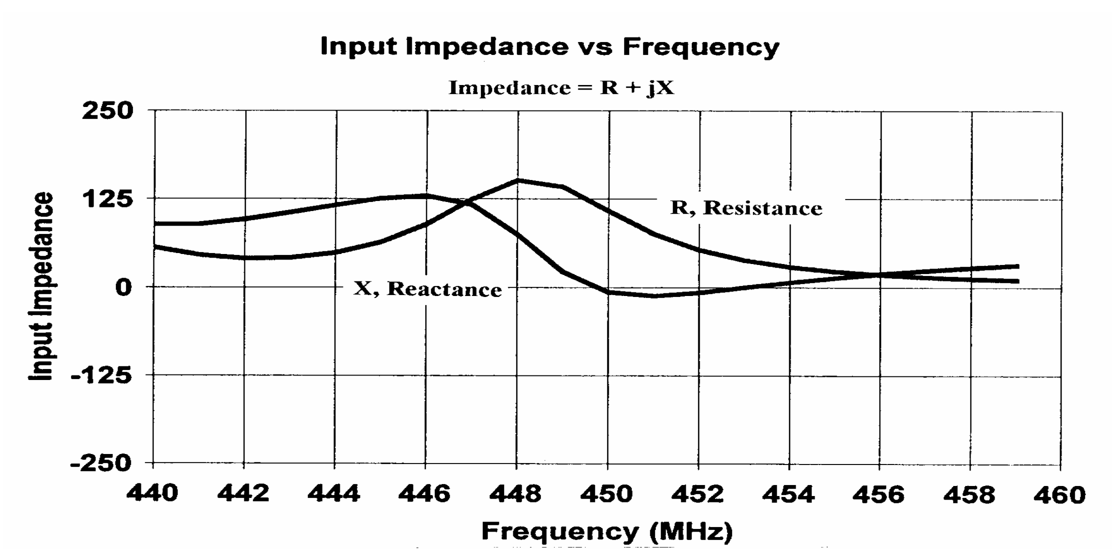


Figure 9. Far-field principal plane patterns and input impedance response for a one wavelength hexagonal loop antenna mounted at the maximum ION-F offset above an infinite ground plane.

Design Considerations for Narrowband Operation

The uplink antenna will operate within a small fraction of its design impedance bandwidth. Design considerations for a narrowband device are somewhat simpler than for broadband performance. The primary objective for narrowband antenna design is to satisfy the conjugate impedance match at the interface between the antenna and the coaxial transmission line.

The input resistance of a symmetric antenna can be changed by displacing the feed off center. Figure 10 is an illustration of a gamma match. Figure 11 is an illustration of a gamma match feed to one $\lambda/6$ element of a one-wavelength hexagonal loop antenna.

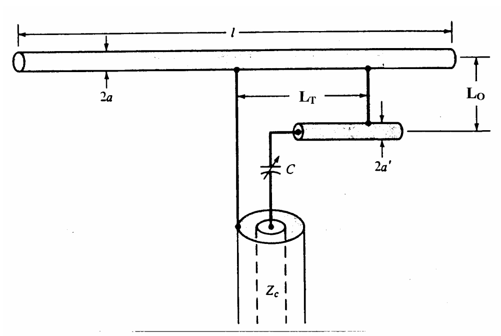


Figure 10. Gamma match. SOURCE: *Antenna Theory and Design*, Balanis

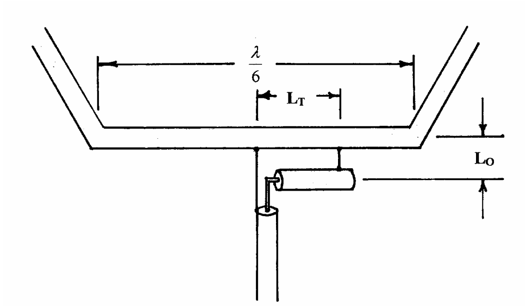


Figure 11. Gamma match feed to one λ/6 element of a one-wavelength loop antenna

A gamma match is effective for coupling a balanced antenna to an unbalanced coaxial transmission line. The RF voltage at the unmatched feed point is at a minimum, or null. The RF current at the unmatched feed point is a maximum. The outer conductor or shield is connected at the voltage null. The input current at the feed point decreases. The net result is an increase in the antenna input impedance [4].

Fabrication and Testing of Prototypes

Initially, one full-scale prototype was constructed for impedance measurements and tuning. A one-third scale model was also created to measure far-field radiation patterns in the Virginia Tech anechoic chamber. Once the electrical characteristics were verified, a more accurate full-scale model was fabricated to work through some of the mechanical considerations for flight-ready hardware.

The first full-scale and 1/3 scale models were fabricated from brass C-sections. Each resonant hexagonal loop had a perimeter length of 1.09λ which was divided into six sections or elements of equal length. The sections were interconnected and soldered together with wire segments which acted as tenons. Flanges were then soldered on each element such that the locations of the standoffs matched the isogrid hole pattern. The standoffs were ¼" diameter nylon rods with threaded metal pedestals. The full-scale prototype used for impedance measurements included a copper replica of the LightBand, which will be in place on the flight model. Figure 12 is a photograph of the full-scale prototype uplink antenna used for initial testing.

Subsequent full-scale models have been fabricated in a similar manner. The only exception has been the use of copper tubing rather than the original brass sections. Quarter-wave sleeve balanced to unbalanced transformers (baluns) were constructed to isolate the antenna from the coaxial feed. Measurements were made on a network analyzer to tune the balun transformer to the nominal operating frequency of 450 MHz.

The dimensions from the full-scale prototype were scaled by 1/3 to create a model for far-field measurements in the Virginia Tech anechoic chamber. Figure 13 contains both of the far-field principal plane radiation patterns for the 1/3 scale prototype. The symmetry of the measured patterns in Figure 13 suggests the balun transformer is operating properly and the losses due to stray currents are minimized. A maximum gain of 9.25 dB is also consistent with published results for one-wavelength circular loops.

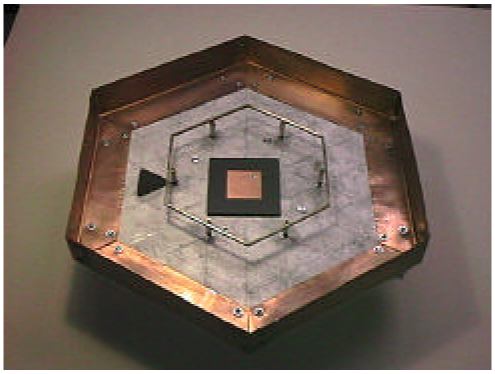


Figure 12. Full-scale prototype of VT-ION-F One-wavelength Uplink Antenna. The coaxial feed is attached at the midpoint of one of the λ/6 elements. The gamma matching section is in the plane of the loop.

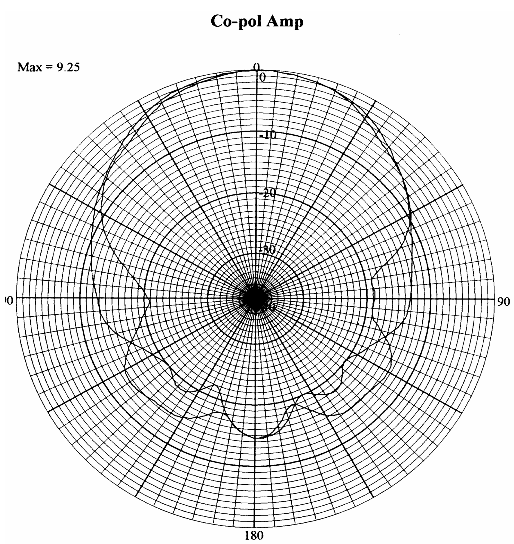


Figure 13. Far-field Radiation Patterns for the 1/3 scale prototype. The symmetry of the measured patterns suggests the quarter-wave sleeve balun transformer is operating properly and the losses due to stray currents are minimized.

Conclusions

The hexagonal one-wavelength loop antenna mounted over the plane of the spacecraft was chosen for its moderate gain, low profile, and minimal surface area requirement. A total gain of more than 9.25 dB is made possible with the use of the bottom surface of the satellite as a ground plane. The presence of the ground plane will make the pattern unidirectional pointing in the direction normal to the bottom surface of the spacecraft. A unidirectional beam is desired for a three-axis stabilized satellite.

The primary tradeoff of the loop antenna for this application will be the loss in received power due to the polarization mismatch. The transmitted signal will be circularly polarized, but the proposed satellite antenna will be linearly polarized. The polarization loss may be offset by an increase in transmitted power or a reduction of the uplink data rate.

One major concern for future prototypes will be the necessity to tune the antenna continuously during the fabrication stage of the project. The operating bandwidth of the first prototype was a very narrow 0.75%. It was noted that impedance measurements were particularly sensitive to any changes made on the ground plane.

Revisions in the design and layout of the bottom exterior surface of the spacecraft will affect the operating frequency and input impedance of the uplink antenna system. Adjustments in the antenna system will be necessary to keep the final allocated frequency with the operating bandwidth of the antenna.

Two foreseeable changes that will require additional tuning will be the addition of flight-model standoffs for the antenna as well as the solar panels to the bottom surface of the spacecraft. Future prototypes may need to integrate a capacitive tuning element and adjustable standoffs for in-situ antenna adjustments.

Acknowledgements

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Biography:

Christian W. Hearn, P.E., was born on February 25, 1966 in Norfolk, Virginia. He received a B.S. in Mechanical Engineering from Virginia Tech in 1989. From 1989 to 1997 he worked for the Underwater Explosions Research Division of the Naval Surface Warfare Center. During his employment, he completed a second B.S. in Electrical Engineering Technology at Old Dominion University. He is currently pursuing a Ph.D. in Electrical Engineering at Virginia Tech. His research interests include antenna design, testing, and measurements.