Nanosatellite Tracking using Passive Radar Retro-reflectors

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ABSTRACT

By integrating a low-cost passive radar retro-reflector, spacecraft in the 1U size range may be more easily detected and tracked in low-earth orbit using terrestrial assets. Retro-reflector prototypes described in this paper utilize a novel antenna design and maintain a consistent radar cross section of a small satellite at all aspect angles. No power is required to operate these retro-reflectors aboard the spacecraft and integration requirements are minimal.

THE NEED FOR TRACKING

Improved satellite detection tracking capability is required as the number of objects in space increases and the respective size of these objects decreases. This will aid with space traffic management, tracking of orbital debris, and generally help spacefaring nations and private companies be good stellar citizens. Improved tracking will also help satellite operators to identify and contact their satellites more quickly after launch.

Traditional non-cooperative tracking systems such as the Space Surveillance Network use radar or electro-optical telescopes to attempt to track all objects in space. Most were designed when few small satellites were launched. Commercial services have augmented government capability, but will continue to have difficulty tracking the large number of small satellites deployed in the next few years. Cooperative tracking systems, where the satellite aids the tracking system, will be required to maintain good space domain awareness.

Multiple small spacecraft cooperative tracking methods have been proposed and demonstrated. The Extremely Low-Resource Optical Identifier (ELROI) uses optical transmissions from the satellite to ground telescopes.[1] CubeSat Identification Tag (CUBIT) uses a radio interrogation and response systems coupled with large ground antennas.[2] The Enhanced Low-Power Transponder (ELT) transmits the satellite's GPS coordinates to the ground by radio, and uses the radio signal characteristics to calculate the orbit.[3]

In this paper we discuss an alternative option: passive radar retro-reflectors that make use of a novel 8 x 8 Van Atta Array design to increase the radar cross section of a small satellite.

NANOSATELLITE TRACKING DEVICES

A flat, passive radar retro-reflector that improves the ability of Space Object Tracking radars to detect and track small satellites was developed under the Naval Information Warfare Center (NIWC) Nanosatellite Tracking Experiment (NTE) effort. Behaving similar to corner reflectors, retro-reflectors are devices that are designed to return electromagnetic energy back to the source with minimal scattering. This may be accomplished by transmitting radio frequency (RF) pulses, such as radar, from a source to a target, which is then reflected back toward the source. Retro-reflectors vastly improve the radar cross section (RCS) of small satellites at all aspect angles other than normal incidence. With strong radar returns at all angles, detection rates and tracking of objects on-orbit is improved.

The Van Atta Array, invented by L. C. Van Atta[4], uses an array of antenna elements connected by transmission lines in pairs symmetrical about center of the array. The incident RF field that is received by each antenna will feed to a corresponding antenna via transmission line, where it is re-radiated. The phase distribution of the re-radiated fields is reversed as a result of the feed structure, causing the wave to be re-radiated in phase towards the incident direction.[5] A simple Van Atta Array is compared to a corner reflector in Figure 1.

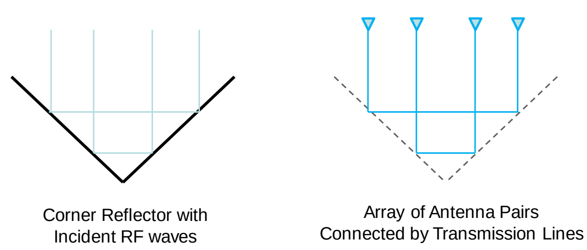

Figure 1: A corner reflector (left) and a Van Atta Array Retro-reflector (right).

For an incident plane wave acting upon the array at angle θ, the receiving phase lag between the adjacent antenna will be $\phi = k_0 d \sin\theta$, where $k_0 = 2\pi/\lambda_0$ is the free-space propagation constant and d is the spacing between the antenna elements. [5] The transmission lines between the paired antenna elements are phase matched to propagate a reflected wave in the same direction from which it was received, as shown in Figure 2. Each paired antenna can transmit and receive simultaneously, producing a propagating wave toward the direction it was originally transmitted. Phase matched transmission line lengths between the paired antennas are essential to producing these redirected waves.

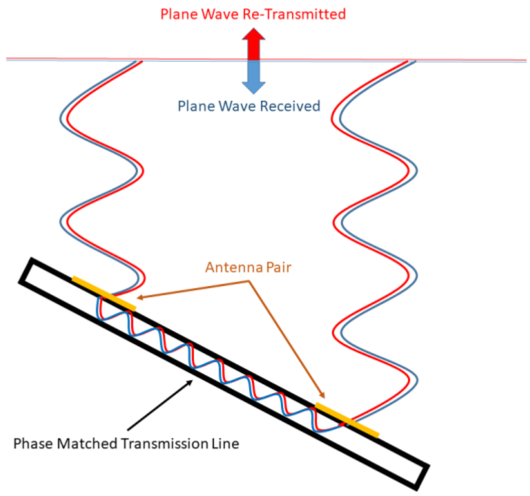

Figure 2: Phase matched transmission lines between paired antenna elements are used to propagate a reflected wave in the same direction from which it was received.

A 64-element Van Atta Array that operates in the Ku-band was developed to fit a standard 1U cube satellite panel (10 cm x 10 cm). Pairs of slot-fed dipole antennas, arranged in an 8 x 8 formation, were connected via phase matched transmission lines symmetrical about the center of the array. The array was designed and simulated using Ansys HFSS, then fabricated and verified experimentally.

The NTE retro-reflector devices were designed to operate in the Ku-band for detection and tracking with the Massachusetts Institute of Technology Lincoln Laboratory (MIT LL) Haystack Auxiliary (HAX) radar. The operating frequency range is 15.7 GHz to 17.7 GHz, with Right Hand Circular Polarization (RHCP). Following simulation, design and performance optimization, the NTE devices were fabricated using Rogers 3003 substrate material. The simulated finite element method (FEM) design model and fabricated NTE devices are shown in Figures 3 and 4, respectively.

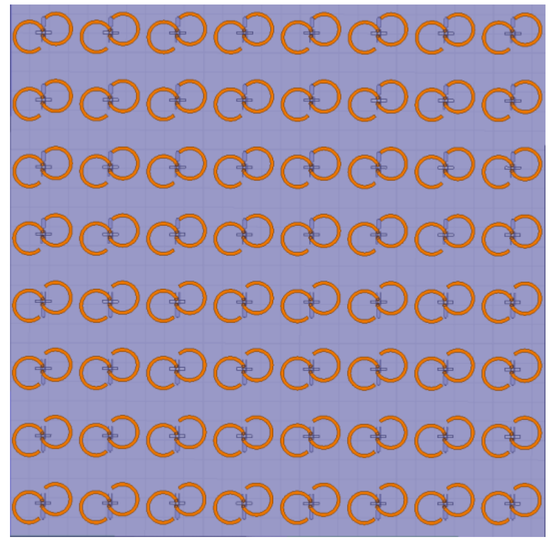

Figure 3: FEM model of a 64-element Van Atta Array used in the Nanosat Tracking Experiment (NTE) devices.

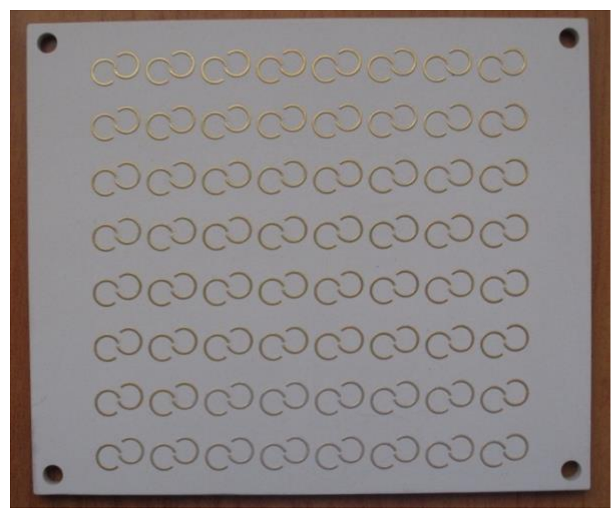

Figure 4: A fabricated 8 x 8 NTE Van Atta Array in 1U form-factor operating in Ku-band.

EXPERIMENTAL RESULTS

Far field RCS measurements were taken for NTE retro-reflectors mounted on a 1U cube satellite model in an anechoic chamber at NIWC Pacific. For all RCS measurements, a flat metal plate (10 x 10 cm) oriented normal to the test emitter was used for reference. Ku-band conical horn antennas, circular waveguide mode transistors and Ku-band linear to circular polarizers were used in monostatic configuration to transmit the Ku-band RHCP signal. For the two test cases shown in Figures 5 and 6, the cube satellite model was rotated 360 degrees about the vertical axis. In Figure 5, the cube satellite model was oriented so it would rotate from face to face. In Figure 6, the model is oriented so that it would rotate from face to edge to face. Measurement of the 8x8 NTE array show a radar cross section improvement in the range of 20 to 30 dB when the aspect angle of the cubesat model surface is any angle other than normal to the incident radar pulses. At normal incidence, there is no improvement, as expected.

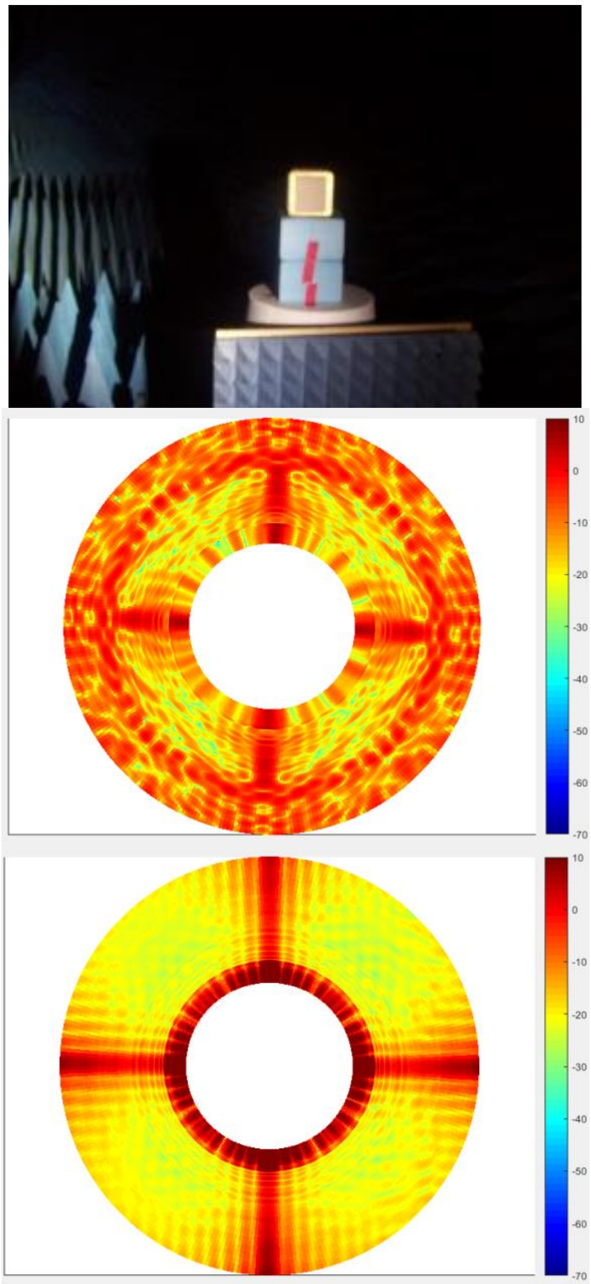

Figure 5: Radar cross section measurements of a 1U cube oriented so it rotates from face to face in the vertical axis (top). RCS measurement vs. frequency (in radial axis) and angle with NTE retro-reflectors (middle) and without (bottom).

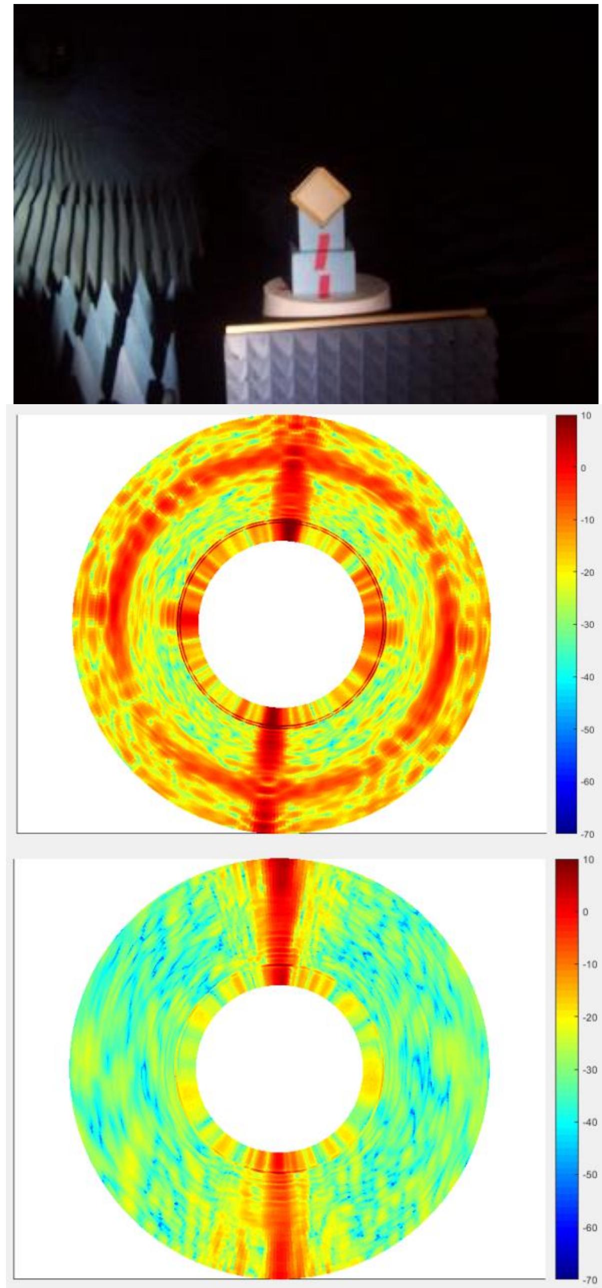

Figure 6: Radar cross section measurements of 1U cube oriented so it rotates face to edge to face in the vertical axis (top). RCS vs. frequency (in radial axis) and angle measurements with NTE retro-reflectors (middle) and without (bottom).

Following radar cross section measurements, the NTE retro-reflector devices completed full space flight qualification and acceptance testing including thermal vacuum, shock and vibration testing. The NTE devices have since flown on multiple Department of Defense and Commercial space missions.

The STAR-3 Mission, which consists of three passive 1U satellites to be used as calibration and characterization targets, was launched aboard the SSO-A SmallSat Express in December 2018. One of the STAR-3 satellites contains six NTE devices, mounted on each external panel of a 1U chassis. Another spacecraft has NTE devices on three surfaces and optical retro-reflectors on the other three surfaces. The third 1U has optical retro-reflectors on all six surfaces. Data from the STAR-3 mission was used for on-orbit characterization of the passive optical and radar retro-reflector devices. The assembled STAR-3 satellites are shown in Figures 7 and 8.

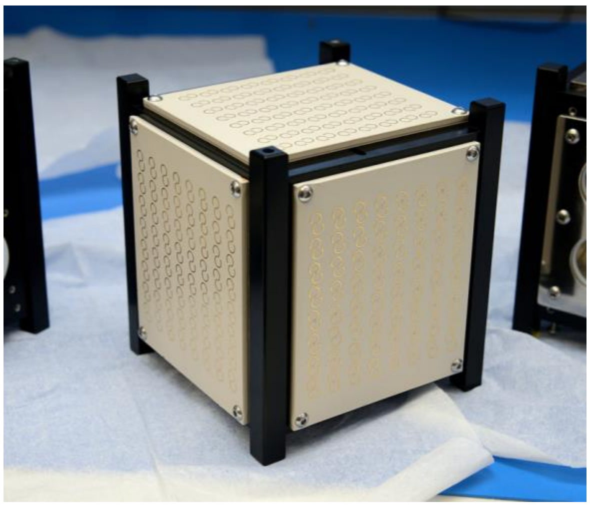

Figure 7: 1U STAR-3 cubesat with NTE retro-reflector panels.

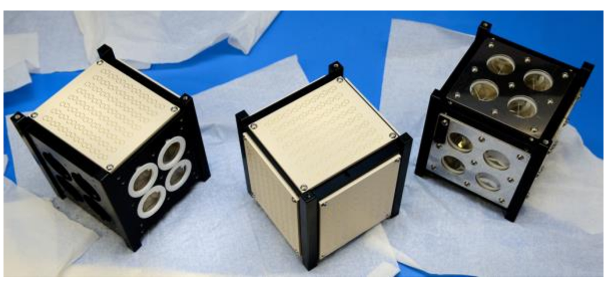

Figure 8: Final fabricated STAR-3 satellites with radar and optical retro-reflectors.

COMPARISON TO ALTERNATIVES

Each of the previously described cooperative tracking systems have advantages and disadvantages compared to the NTE devices. Having multiple options will allow spacecraft builders to make appropriate system trades. A summary of the NTE comparison to alternative technologies is given in Table 1.

Function

The current NTE devices do not provide a unique identifier for the spacecraft, they only enable improved detection and tracking. A unique identification capability is presently under development, with on-orbit testing anticipated in 2021. The ELROI, CUBIT and ELT presently provide unique identification.

Size, Weight and Power

Power from a battery, integrated solar panel, or the host satellite is required for operation of ELROI, CUBIT and ELT. The NTE device requires no power and will function as long as the object is in orbit.

Integration Requirements

In most cases NTE devices are mechanically attached by four bolts. No power, data or antenna cables are required. In addition, the passive operation of NTE device minimizes potential interference with sensitive electronics such as magnetometers and receivers.

One integration factor that must be accounted for is that the material composition of NTE devices makes them an insulator. The primary substrate material used is Rogers 3003, which is Teflon impregnated with ceramic. The devices must also be mounted on a surface that is expected to be visible to ground radars. In some cases this could make the placement of NTE devices more difficult than other options.

Supporting Ground Equipment

NTE requires support from large ground-based radar systems to illuminate it and process the return response. Returns are automatically processed and contribute to the space surveillance network. This means results are available via the space-track.org website, requiring no additional ground hardware or processing capability for satellite owners.

Cost

The first fabrication of NTE devices resulted in 80 devices at approximately $200 each. If produced in larger quantities the cost would significantly decrease.

Table 1: NTE Device Comparison to Alternatives

Feature	CUBIT	ELROI	ELT	NTE
Improved tracking	Yes	Yes	Yes	Yes
Unique identification	Yes	Yes	Yes	No
Power required	Yes	Yes	Yes	No
Passive operation	No	No	No	Yes
Frequency filing required	Yes	No	Yes	No
GPS dependency	No	No	Yes	No

Ground RF aperture (m)	45.7	N/A	-	12.2
Ground optical aperture (m)	N/A	0.36	N/A	N/A
Inhibit(s) required	Yes	-	Yes	No
Estimated Cost (US Dollars)	-	1000	-	<200

CONCLUSIONS AND FUTURE WORK

In this paper we present the design and RCS measurement responses for a passive 1U form-factor Nanosatellite Tracking Experiment device. Although the notional operating frequency for the passive NTE devices was Ku-band, other frequency bands may be utilized by modifying the antenna design elements and feed network.

Development is presently underway to design a low size, weight and power modulated retro-reflector payload that provides a unique identification capability for small satellites, in addition to improved detection and tracking capabilities.

References

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