A True Time Delay-Steered Conformal Phased Array for Airborne Data Link Applications

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ABSTRACT

Unmanned Air Vehicles (UAVs) and other relatively small airborne platforms are being increasingly pressed into service to perform broadband Intelligence, Surveillance and Reconnaissance (ISR) missions. Typically, these smaller platforms do not have enough space for a dish antenna and gimbal mechanism needed for a high-data-rate telemetry link. This paper presents a unique approach to steering a beam from a broadband conformal aperture that is suitable for space-restricted applications. This approach does not use expensive T/R modules or electronic phase shifters and yields a cost-effective phased array solution with very low size, weight and power (SWAP). A JEM prototype was recently flown by NASA on a sounding rocket mission where a continuous data link was maintained to a TDRSS satellite throughout the entire flight from launch through splashdown and recovery. The paper will present architectures for both 1-D and 2-D beam steering.

INTRODUCTION

Two of the main challenges facing the test and evaluation telemetry community are loss of RF spectrum available for flight test telemetry and providing reliable transmission to a growing number of simultaneous high bit rate users of the telemetry bands. For many current flight vehicle tests, multiple ranges must combine acquisition resources and, in addition, often deploy mobile assets to cover areas outside the fixed coverage range assets. During the past three decades there has been limited success in using space-based tracking and data relay with the NASA Tracking and Data Relay Satellite System (TDRSS). There has also been some success using low rate data relays from mobile tracking systems via commercial satellites like INMARSAT, Globalstar, Iridium and through cellular phones. But many more links at higher data rates from many vehicles at widely separated locations are required to meet Test & Evaluation requirements. Direct relay of very low rate two way or full duplex data to and from system under test to a data center has been demonstrated with Iridium and Globalstar for aircraft, rockets and long duration scientific balloons to eliminate the cost of ground based tracking systems. The limiting factor in many of these cases is the low gain omni-directional antenna. High gain, low cost, phased array tracking antennas are required to fully utilize the higher bit rates available via TDRSS. The subject of this paper is FlexScan beamformer phased array antenna technology, a technology for building low-cost phased array antennas. Specifically, this paper describes the development of a FlexScan beamformer phased array antenna based on this technology, for use in a TDRSS data link array antenna on board an ELV/sounding rocket. This technology could be adapted to other applications needing a low-profile, low-cost phased array, including SAR apertures, missile seeker antennas, and low-power radars.

The performance goals include a gain improvement of 9-12 dB above omni at broadside, a scan rate of +60 degrees to -60 degrees (120 degrees) in less than 0.5 seconds, and beamformer insertion loss less than 1 dB.

FLEXSCAN BEAMFORMER TECHNOLOGY

JEM Engineering has adapted FlexScan phased array technology to NASA's need for S-Band SATCOM Antennas. FlexScan phased array technology can provide high antenna gain with a beam that can be steered up to 60° off broadside from a planar, low profile package.

The FlexScan phased array antenna is based on a patented, variable **true-time-delay** beamformer [1 and 2]. One key to this beamformer is a very-low-loss variable delay transmission line (VDL) whose phase velocity can be controlled by very small-scale electro-mechanical actuation. The low insertion loss of this VDL permits the design of a beamformer that is RF-passive, *i.e.*, requiring no amplifiers or transmit/receive (T/R) modules. It is producible at very low cost, because the array and beamformer can be fabricated monolithically via conventional multi-layer printed circuit board processes. Only minimal assembly is required. Unit costs can thus be very low. The delay control components (VDLs) are embedded in a fractal power divider that forms a single beam in one direction over an ultra-wide band of frequencies. One-dimensional beam scan control is achieved by using only one analog control signal (corresponding to ±x) that is applied to a beamformer control actuator that is integrated with the power divider circuitry. This simplification of control is another key to the low cost of FlexScan phased arrays.

The FlexScan concept is based on sound engineering concepts and currently available materials and manufacturing technologies. The individual variable delay line components have been demonstrated over ultra-wide bandwidths. For the NASA application, an array of 8 ring radiators was combined with a FlexScan beamformer to scan the array over a range of ±60°.

A block diagram of a phased array antenna based on FlexScan beamformer technology is illustrated in Figure 1. The delay control components (VDLs) are embedded in a fractal power divider that forms a single beam in one direction over an ultra-wide band of frequencies. One- or two-dimensional beam scan control is achieved by using only one or two analog control signals (corresponding to ±x and ±y) that are applied to beamformer control actuators that are integrated with the power divider circuitry. Note that FlexScan beam control is analog, so the beam can be pointed to any desired angle, and there is no beam-pointing quantization error.

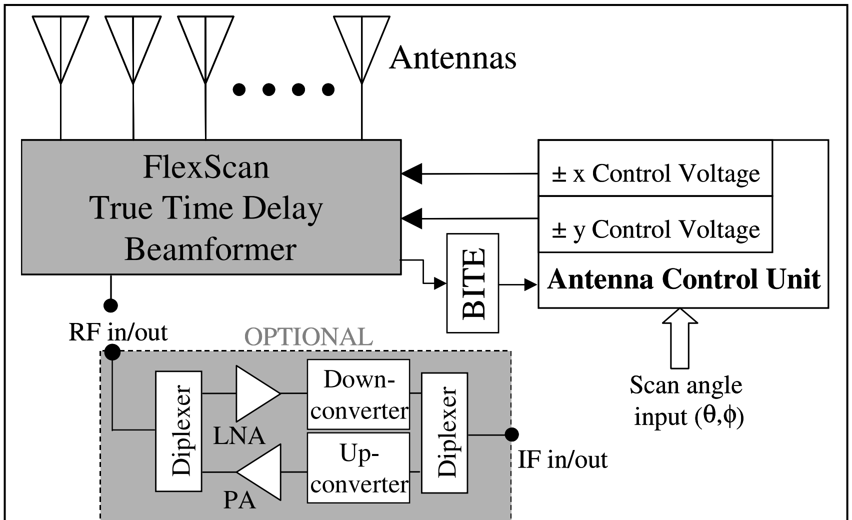

Figure 1. Block diagram of a typical FlexScan Phased Array

FlexScan antennas can be built to achieve any desired directivity, although array gain between 12dBi and 30 dBi will be typical, depending on the frequency and size of the array. Array gain of 25 dBi or more may require sub-arrays to be used, depending on the overall efficiency desired. The beam pointing angle may be steered, up to 60° off broadside, in either one or two dimensions, and the steering angle may be changed between any two available angles in as little as 10 ms, depending on the actuator used.

Shown schematically in Figure 2, the trombone-type VDL is composed of two parallel micro-strip transmission line sections printed on a fixed substrate, and a U-shaped micro-strip section printed on a movable substrate. These parts are arranged such that the movable U-shaped line is held in constant contact with the fixed lines and slides along them, changing the physical length of the line. The portion of the microstrip lines, where sliding contact occurs, typically receives a wear-resistant plating such as "hard" gold.

The return loss, insertion phase, and insertion loss of a single trombone VDL was measured over a 0.5-5 GHz band. The return loss was below –20 dB over the entire band, and below -25 dB from 1.7 to 2.5 GHz. This VDL has excellent phase linearity and very low insertion loss, typically about 0.07 dB for this design, which has a delay range that equates to about 70 electrical degrees of phase change at 2 GHz. Thus, the phase shifter figure-of-merit for this VDL is 1000°/dB, which is far better than any other known phase shifter or variable delay line

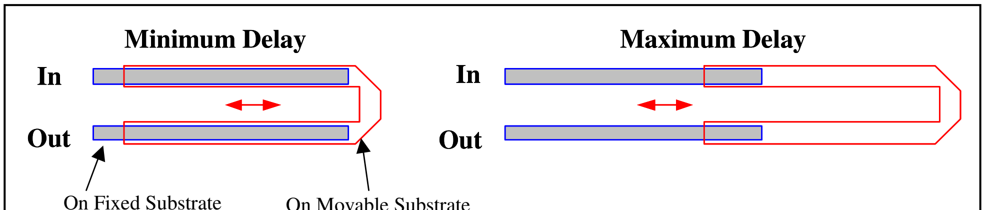

Figure 2 Conceptual Details of a Trombone-type FlexScan VDL

technology. This extremely-low RF loss makes the low-loss FlexScan beamformer practical. The VDL can be controlled by a stepper motor with lead screw, voice coil, or other actuator. The lead screw is preferred in the sounding rocket application, because of its simplicity and resistance to vibration.

While low-loss variable delay lines are essential components, another major key to FlexScan is the beamformer architecture, which arranges the VDLs to achieve a true-time-delay beamformer that requires only one to four controls. To illustrate the FlexScan fractal beamformer concept, consider the 4x4 element beamformer shown in Figure 3. The 36 rectangles in the legs of the feed network represent identical VDLs. Four

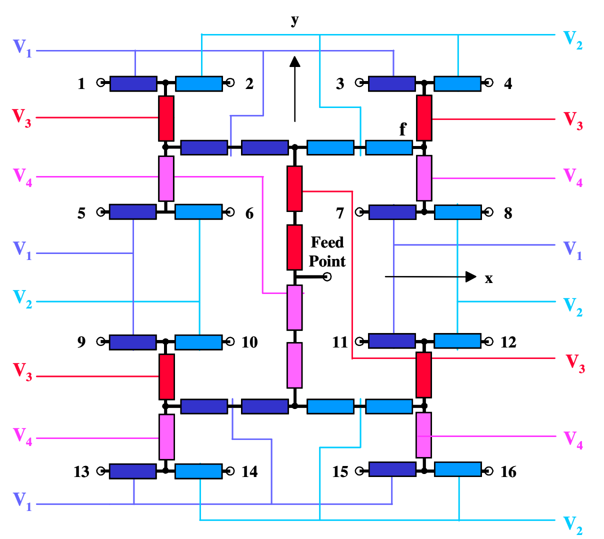

Figure 3. Sixteen-port FlexScan beamformer network.

analog control signals, V_1 through V_4, are used to control the delays through these sections. Thus, V_1 through V_4 represent the positions of trombone VDLs. Through the unique distribution of VDLs, the application of only four analog control signals yields analog two-dimensional scanning (both θ and ϕ). If only one-dimensional scanning is required, then only two control signals are needed. This greatly simplifies the antenna control electronics, as compared to a conventional phased array.

It is easy to see that the delay required from the group of VDLs controlled by V_1 is complementary to the delay required from the group controlled by V_2. If the VDLs have a linear delay-vs.-control response, this fact can be used to reduce the number of controls by half, to two control signals for 2D scan, and one control signal for 1D scan. This is precisely the case for the trombone VDL, where delay is a linear function of the slide position. Thus, a 1D scanned FlexScan phased array using trombone VDLs can be controlled with only one actuator. Figure 4 shows the beamformer layout schematic for an 8-port, 1D scanned beamformer. This beamformer contains 24 VDLs, all mounted on one fixed and one movable substrate, and controlled with a single actuator. A prototype of this beamformer has been developed for use in a TDRSS data link array.

CONFORMAL APERTURE

Of course, to build a useful phased array, the FlexScan beamformer must be coupled with an array of appropriate antenna elements. Omni-directional wraparound antennas for small ELV's and sounding rockets typically have gains on the order of about -4 dbi with approximately 3-4 dB of roll plane variation in the gain. These low gain numbers result in TDRSS data rates that are unacceptably low for science data links and marginal for housekeeping data links.

The antenna array design used in the sounding-rocket application is an 8-element high by 32 feed roll version of the 2-element high by 32 feed roll prototype array shown in Figure 5 below. The basic wraparound element has been proven on sounding rockets, where it has been used to provide a broadside beam that is omnidirectional

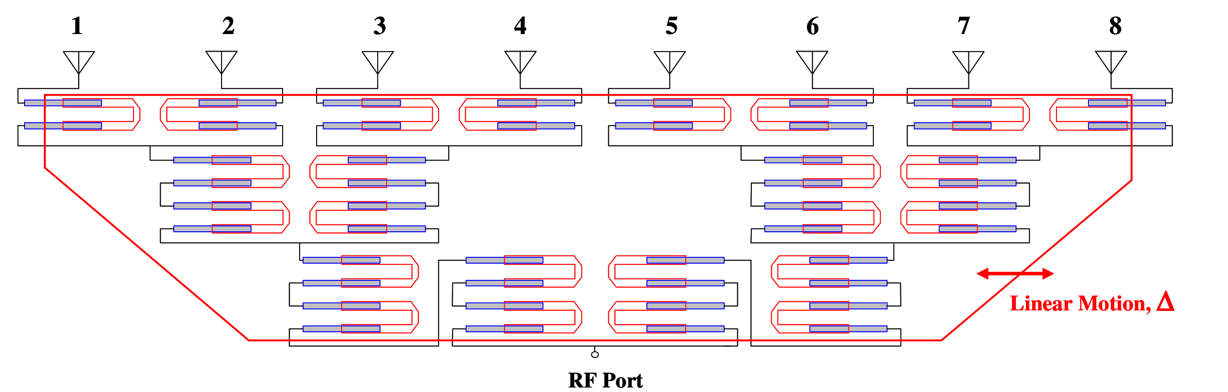

Figure 4. 8-port FlexScan beamformer schematic using trombone VDLs for 1D scanning

about the roll axis. The eight full-wrap elements will have an element to element spacing of 0.54 wavelengths to allow +/- 60 degree scan angles from broadside without grating lobes.

Using the new JEM FlexScan beamformer to feed the 8-element high array configuration yields a total gain of approximately +7 dBi. This is about 11 dBi above the gain of the omni-directional design at broadside. Beamformer losses will reduce this by about 1-1.5 dB, but the resulting steerable array meets meet the gain performance goal for a TDRSS data link.

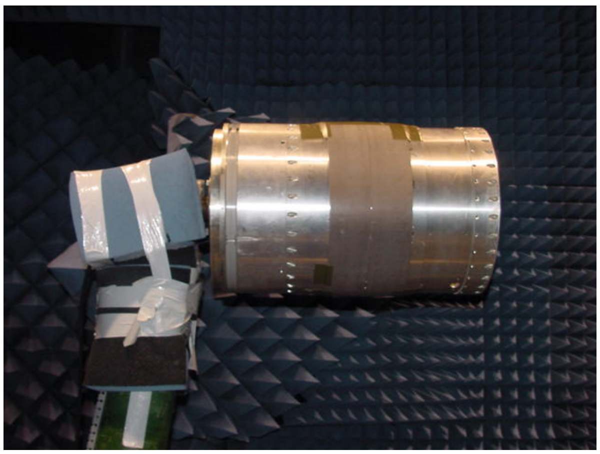

Figure 5: 2 element high x 32 element roll prototype array

The pointing control system uses ELV/Sounding rocket position and attitude data retrieved from internal IMU and GPS systems along with updated TDRSS ephemeris information. A single board antenna control unit (ACU) computer computes real-time antenna pointing vector information. This pointing vector is translated by the ACU into an appropriate control signal for the beamformer actuator to properly steer the beam. The beamformer is actuated via a small stepper motor with an appropriate indexer. The actuator position is verified by the ACU control loop with absolute and incremental shaft encoders.

CONCLUSIONS

As shown in Figure 6, the FlexScan beamformer and wraparound array were flown aboard a sounding rocket launched from NASA's Wallops Flight Facility in May of 2009. The steerable array performed flawlessly, maintaining a continuous data link to a TDRSS satellite from pre-launch to the beginning of the re-entry phase. Excellent performance was achieved even though one of one of the rocket's stabilization fins fell off during launch, resulting in a pronounced wobble that the array had to compensate for. After splashdown, the array re-acquired the satellite and continued to provide a data link until the rocket was recovered from the ocean.

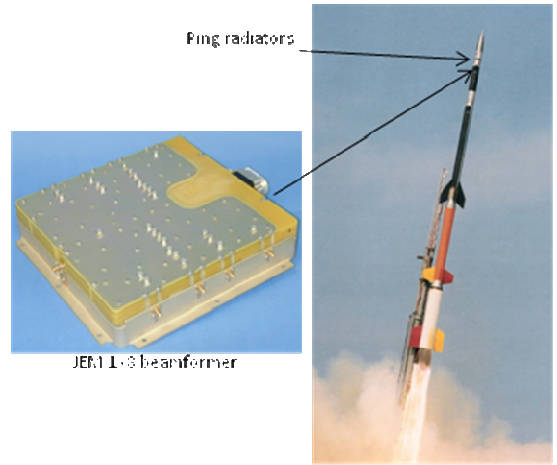

Figure 6: Picture of flight hardware and sounding rocket launch.

A novel and innovative concept for constructing a phased array antenna system was introduced, along with its application to a telemetry data link between a sounding rocket/ELV and TDRSS satellite. The design, construction, and integration of a phased array antenna system for a sounding rocket is described. The antenna system is composed of an array of wraparound radiators, a 1-D scanning FlexScan beamformer, and a pointing control system. The basic wraparound element has been proven on sounding rockets, where it has been used to provide a broadside beam that is omnidirectional about the roll axis. In this new application, eight wraparound elements are arrayed and phased to steer a conical beam between 60º forward and 60º aft. A low-cost, electromagnetically-actuated FlexScan beamformer drives the antennas, providing true-time-delay beam steering for extremely broad bandwidth, along with very low insertion loss. Antenna pointing control comes from a single board computer, and will leverage and build upon technology that was previously proven in control systems for gimbaled antennas.

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REFERENCES

[1] US Patent No. 6,590,531 Planar, Fractal, Time-Delay Beamformer, W. Mckinzie and J. Lilly

[2] US Patent No. 6,831,602 Low Cost Trombone Line Beamformer, W. McKinzie, et. al.