Title: Universal Beamforming Technology: Application and Tests

Authors: Anand Kelkar, Norm Lamarra Creative Digital Systems Integration (CDSI), Inc.
Brian Krinsley, Naval Air Warfare Center, Weapons Division, Point Mugu
Tom Young, T&E S&T SET Executing Agent, 412 TENG/ENI, Edwards AFB, CA.

1.0 Introduction

This paper describes the technology development and test of a Steerable Multi-band Multi-Beam antenna subsystem suitable for Airborne and Ground-Based applications. We named the approach: Universal Beamforming Technology (UBT).

Beam pointing of microwave phased-array antennas can be effected in various ways. However, until about 20 years ago, it could only be performed by changing the group delay or phase delay of the signal path through the manipulation of some physical property of a medium through which Radio Frequency (RF) signals passed.

Digital Beam Forming (DBF) was first described in the mid-1970s for an array of microphones, where the apparent directivity of the array could be steered with respect to the face of the array through the mathematical manipulation of digitized versions of the waveforms of interest.

It was not until about 2000 that commercially-available devices were able to provide comparable DBF functionality at data rates suitable for use in RF applications such as Telemetry (TM). Since then, developments in consumer markets have rapidly pushed DBF to the forefront for multi-beam antennas. This is primarily because the cost of digital devices continues to fall steadily, while their computational capability has steadily risen. Moreover, the integration of analog functions into hybrid Integrated Circuits (ICs) has also steadily increased, advancing towards the tantalizing goal of low-cost, flexible and light-weight phased-array antennas as a commodity.

2.0 Sponsors of this development

Funding for our UBT development was provided by Test Resource Management Center (TRMC), through their Test and Evaluation (T&E) Science & Technology (S&T) program, and specifically in the Spectrum Efficient Technology (SET) area, in a domain called “Wireless Technologies”. Technical guidance was provided by the SET office at Edwards AFB, CA with assistance from NAVAIR & NAWCWD, in Pt. Mugu, CA.

The goals for UBT were as follows:

- High-Risk/High-Payoff Research & Development (R&D) for Test and Evaluation
- Technology transition (e.g., to major DoD test ranges)
- Risk reduction for test capability developments

3.0 Spring-boarding from previous work

Beginning in 2004, CDSI architected, designed, developed and supported the integration of two airborne DBF TM systems on the USAF E-9A platform at Tyndall AFB. Since the first delivery of these systems in 2008, CDSI has continued to provide sustaining engineering functions in support of TM operations, which are primarily over the Eglin Gulf Range.

As an important and integral part of this development and support, we developed various troubleshooting techniques, tools and applications. These allow us to perform detailed test and measurement functions, often remotely from our west-coast offices. These capabilities as well as valuable experience with real mission operations, along with our Internal R&D efforts, have provided useful background to the UBT work discussed herein.

4.0 Description of a “classic” DBF approach

Although there are effective non-digital approaches to multi-beam systems (e.g., using low-cost phase-shifters), we address only DBF systems here, because they have many advantages for certain applications. A conceptually-convenient DBF approach attaches an array of RF elements to a massively-parallel processor utilizing Field Programmable Gate Arrays (FPGAs). The theory of operation for the DBF functionality is as follows:

- Signals impinging on each antenna element are down-converted to some Intermediate Frequency (IF) and accurately digitized to capture the individual time waveforms. The Analog-to-Digital Conversion (ADC) rate is typically chosen to encompass the desired signal bandwidth, e.g., for a “block” such as S-band, allowing simultaneous processing of multiple TM data streams for each channel within that block.
- Each digitized “element stream” is then separated into one or more streams, and processed digitally. For many airborne applications, the separation is accomplished by

filtering and down-converting each element stream to one or more "channel-element-streams" (CES) at baseband. Each separate CES is then combined with its relevant counterpart across the array to form a beam for each TM channel, typically pointing to a unique spatial position (e.g., a flying source).
- Beam pointing is achieved by phase-shifting each contributing CES appropriately before combining across the array.
- Each resulting aggregated CES can then be used to form a Sum, Difference or other weighted version (low-sidelobe, shaped, etc.) of the beam, and these versions can be used for ancillary functions such as real-time tracking.
- The final output for each beam may be provided in direct digital form, or converted back to a desired IF or RF frequency for downlink or further processing and extraction of data.

As can be imagined, lock-step synchrony of the array processing, particularly the digitizing and down-conversion, is imperative in order for a DBF system to achieve the promising benefits of reduced cost and weight without loss of performance.

In addition, reliable calibration of the antenna is required, since (just like an analog antenna) balanced group delay is critical amongst the elements, whether originating from RF, IF or digital electronics or cabling (e.g., for TM-signal or clock/data synchronization).

5.0 UBT departures from classic DBF

Many of the practical challenges of dynamic TM scenarios relate to practical aspects of Target Acquisition and Tracking, i.e., "hooking" the beam-steering algorithms to the dynamic position of each source, especially whenever the signal undergoes fading, either due to blockage or multipath. The latter effect is typically caused by the varying relative phase of the RF signal as it arrives via different paths, which can result in destructive cancellation across the antenna face (a multipath "null"). Further, using classic design principles, different mission profiles often require the antenna to be tailored to each mission application.
To address such potential limitations in classic DBF, UBT was conceived to investigate and prototype the following features:

- Intelligent Antenna constructed from a set of identical blocks that can be wired together on an as-needed basis. A useful block size was proposed as a 4x4 dual-polarized subarray, feeding an appropriately-scaled Digital Beamforming Module (DBM). This layout represents a potential "sweet-spot" in the manufacturing and integration space.
- Any desired level of Gain/Temperature (G/T) achieved by incorporating sufficient DBMs in the System utilizing the UBT architecture.
- Antenna elements within each DBM designed to operate through all the frequencies of interest. In our demonstration, this included the L, S & C-band TM frequencies: 1435–1525, 2200–2395, 4400–4940 & 5091–5150 MHz. We chose a prototype tri-band RF panel provided by First RF Corporation in Boulder CO.
- Firmware within the DBM heavily leveraging highly-efficient commercially-available down-conversion and channelization cores, thereby reducing the FPGA resource requirements (per RF element and beam), and hence the cost of the FPGA devices as well as the firmware development.
- Hardware in the DBM designed to utilize components from the global personal-communication industry, thereby reducing hardware costs similarly.
- Interconnection between DBMs achieved via a single digital cable, with the option of redundant data paths to be enabled if needed for increased reliability.
- DBMs to be mounted in a standard lattice grid that conveniently provides infrastructure as needed (e.g., power, clock, etc.).
- Each DBM designed to autonomously locate a likely signal source position for each beam, and fine-tune the beam pointing to provide the best Signal-to-Noise Ratio (SNR) via specifically-developed algorithms.

The benefits of using DBM-level algorithms to maximize the source SNR (rather than classic steering algorithms) can be described in the following manner:

- As the antenna aperture gets larger, the beamwidth necessarily gets smaller, hence conventional spatial search algorithms take more time, since each beam measurement is determined by a time constant commensurate with the source bandwidth, which is independent of the antenna beamwidth.
- Using our UBT acquisition technique, the signal can be maximized across the entire array simultaneously, resulting in extremely rapid acquisition, depending only on the source SNR and bandwidth (not the beamwidth). For example, our simulations indicate that the full aperture gain of the antenna can typically be

achieved within 10 mSec without the need for a spatial search, even at very low SNRs.

- A tracking algorithm is superfluous for this approach, since each DBM continuously maximizes the SNR, thereby keeping each beam on target in an optimal sense.
- Multipath-induced signal fades are also mitigated, since this distributed processing has the effect of pointing each DBM independently, and simultaneously optimizing their combination to reconstruct the maximum final output signal for each beam
- The usual requirement for a contiguous aperture is removed, since during signal acquisition and tracking, pointing commands are derived from the local signal itself and not from the position of the elements in each DBM. DBMs can therefore be installed on conformal surfaces or even in disjoint locations.
- There are no preset angular limits on target acquisition or tracking. As long as there is some signal available, regardless of how it traveled to the antenna, the system will maximize the SNR.

6.0 UBT implementation

Our implementation of a subsystem using UBT architecture was intended as a proof-of-principle demonstration, achieved in the shortest-possible time and cost by using readily-available products (e.g., vendor evaluation boards, off-the-shelf firmware, and open-source software). Developers of the latest hybrid circuits and digital devices are typically eager to introduce a low-cost and versatile operating space to show the capabilities of their devices. Leveraging this phenomenon, we chose Analog Devices FM-COMMS-1 FMC transceiver boards (providing a 250-MHz "block" of bandwidth anywhere between 0.4 and 6GHz), and installed two on each Xilinx ZC-706 board. 16 of these board sets were utilized to process the RF output from the 4x4 dual-polarized tri-band antenna panel.

For a modest cost, we were thus able to implement a small tri-band UBT TM subsystem (representing a single brassboard DBM) in under 12 months, and to demonstrate its functionality via a TM flight test at Edwards AFB.

Figure 1 shows the configuration for this demonstration. The black square object on the left is the prototype tri-band antenna panel provided by First RF Corporation of Boulder CO. It is 8"x8" in size, and contains 4x4 dual-polarized elements with a fixed inter-element spacing of approximately 0.25λ at the low end of its operating bandwidth (1.435 GHz) and 0.88λ at the high end (5.2 GHz). It contained limiters for protection, and one stage of

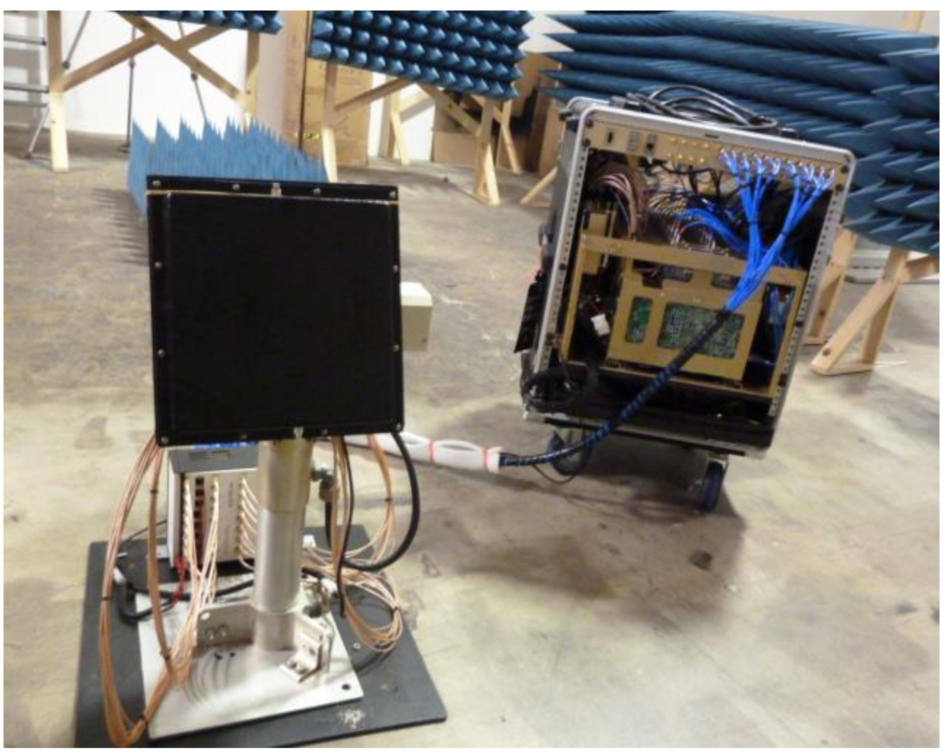

Figure 1 - UBT Demonstrator DBM leveraging Commercial products

 412TW-PA-15616 Approved for public release; distribution is unlimited low-noise amplification, but no filtering (which would be needed for typical applications to reject EMI). Directly behind the antenna is a small enclosure that contains 32 buffer amplifiers (one per element, per polarization). These amplifiers could be incorporated directly in the antenna element circuit card assembly in a future production article, along with EMI filtering as required.

On the right side of Figure 1 is a small roll-away enclosure that has been attached to the buffer amplifiers and then to the antenna through an umbilical cable set carrying amplifier power and RF signals. This enclosure represents the complete functionality of a 4x4 brassboard DBM, but constructed from available off-the-shelf evaluation boards.

For demonstration purposes, we also included an IF output capability within our brassboard DBM, which can produce an IF signal for each beam via another commercially-available FPGA core (a multi-channel digital up-converter) feeding DACs existing on the FM-COMMS-1 boards. We typically tuned at least one upconverter to provide standard 70 MHz IF output signal to feed a Bit-Error-Rate Tester (BERT).

From the firmware viewpoint, we utilized off-the-shelf cores where possible to reduce the development effort and cost. From the software viewpoint, since each FPGA can support Linux and each ZC706 development board includes many interfaces such as Ethernet, we chose to implement a Linux server on each FPGA that receives and processes commands via Ethernet from a single Linux laptop host controller, which also provided a Graphical User interface GUI) for configuration, monitoring, and display. This represents the entirety of our demonstration UBT subsystem, providing the desired functionality in the simplest possible way, in order to minimize the total development cost and time.

A production version of this DBM electronic package is being designed to fit directly behind each 4x4 antenna panel. Its overall dimensions are expected to be about 8”x8”x5”. Interconnection between each DBM (and eventually to the User site) can be achieved with a one or more high-speed serial data cables, which can be either fiber optic or copper as notionally seen in Figure 2.

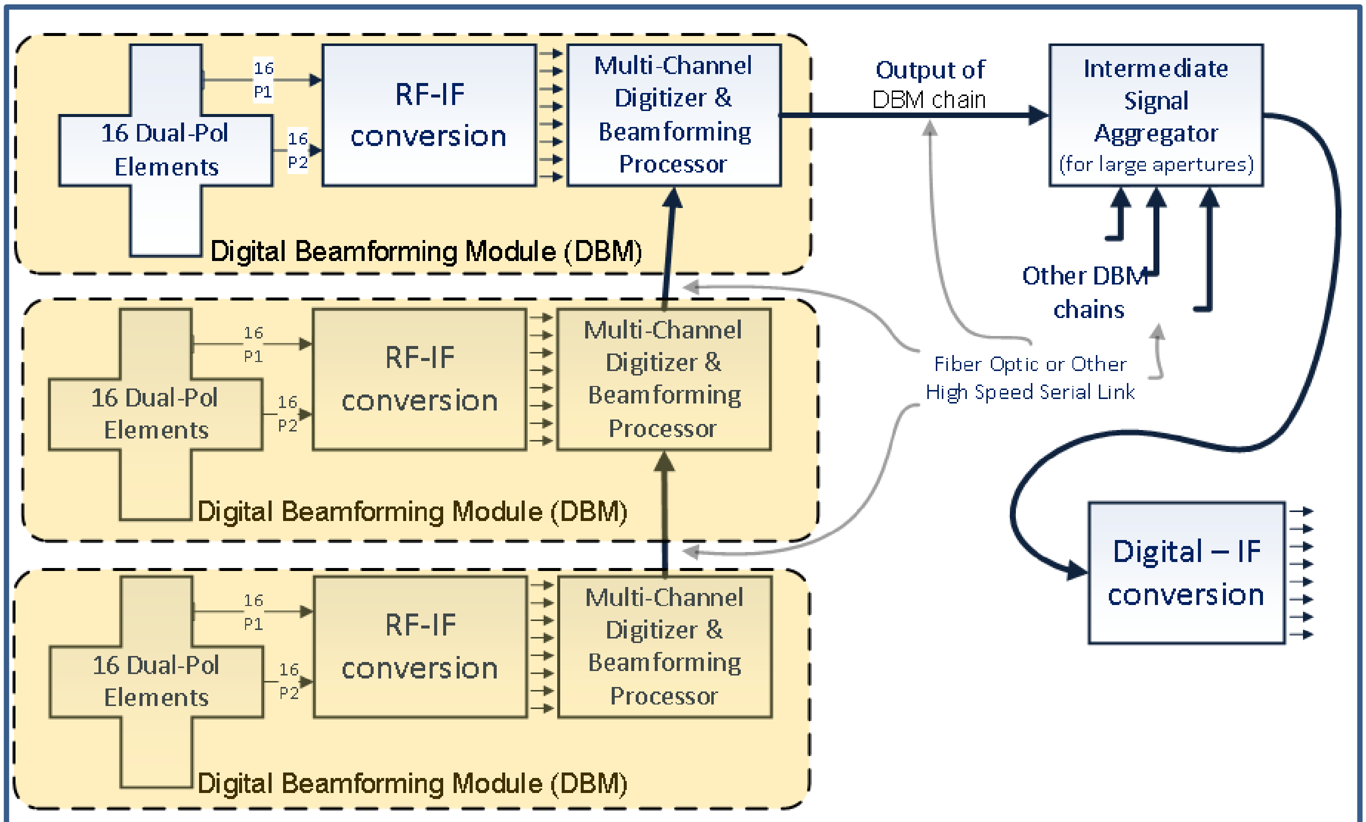

Figure 2 - Block Diagram of interconnection of an arbitrary size/shape antenna

It is interesting to observe that while UBT can support a discontinuous active aperture, and an element spacing of >0.5λ, both of which could produce grating lobes, this problem can also be mitigated within the architecture. We have investigated this in detail, but can heuristically explain this additional benefit by recalling that grating lobes are traditionally most problematic during the search/acquisition process, and also in the rare situation when a grating lobe is pointing to a "hot" source in the same frequency band, thereby raising the effective noise temperature (and impairing the sensitivity) of the antenna for that beam. Our investigations have shown that these problems can be significantly mitigated through judicious placement and orientation of elements to avoid a uniformly-spaced recti-linear grid.

7.0 Testing of the UBT

At CDSI – The UBT brassboard DBM was tested at CDSI using 6 individual antenna sources, each transmitting at a different frequency, mounted around the edge of a wheel suspended from the ceiling. This allowed us to demonstrate 6 simultaneous tracking beams (our firmware provides 16 such beams). The wheel was approximately 5ft in diameter and was suspended 5 ft. above the face of the antenna panel (which was pointed upward to the center of the wheel). The wheel could be spun up to about 20 RPM, producing angular rates of >120 deg./sec. in both Azimuth and Elevaiton for each source. One of the antennas transmitted from a wheel-mounted TM source producing a 30 Mbps SOQPSK signal using a Pseudo Noise (PN)-23 data sequence. The IF output (70MHz) from that beam was connected to a Quasonix receiver/BERT for validation.
The UBT subsystem was able to demonstrate error-free reception regardless of how its pointing angle on the small pedestal (seen in Figure 1) was changed. This was sufficient proof that the UBT tracking was indeed working well for all beams even at angular rates of >120 deg/sec, and also that there was almost instantaneous acquisition of all sources simultaneously.
Subsequent testing was performed with an SOQPSK source on a small quadcopter to demonstrate error-free data link at 30 Mbps in a "real-world" environment outside the lab.

Tests at Edwards AFB, Mojave, CA – The 8" square antenna was set up next to an 8 ft. dish for comparison with our UBT subsystem, which was acting like a miniature TM ground station. A Beechcraft C-12 USAF asset was flown, carrying a TM source in arcs of increasing range as measured from the antenna site. The GPS record of this flight path is shown in blue superimposed on the map in Figure 3. The static pointing direction of the UBT antenna face is indicated by the red arrow, and the flight path was chosen to traverse the desired azimuth range (+/-50 deg.).
The aircraft carried a source that transmitted a known Pseudo-Noise (PN) sequence modulated as Shaped-Offset Quadrature Phase-Shift Keying (SOQPSK) at 5 Mbps. This data rate was chosen because it represents the lowest practical use of SOQPSK, and could expose issues such as oscillator or clock instability that might be lurking in the closely-synchronized timing on which the UBT relies. Error-free decoding of the DBM output was sufficient to indicate that a solid link was present, and that the aggregation of all such potential errors was insignificant in a real-world context, as had already been demonstrated in our lab (with much higher angular dynamics and bit-rates).

7.1 Issues encountered

As might be expected by normal field-testing experience, we encountered several issues that required us to adapt in real time to the real-world conditions encountered on the test day.

Multipath

- We encountered significant multipath when the aircraft was on the flight-line and on the runway preparing for takeoff. The transmission frequency was C-band.
- There was plenty of signal available: the aggregate signal was approximately 35 dB above the quiescent noise level as seen in the UBT instrumentation.
- The 8 ft. TM dish was not able to produce any intelligible data whatsoever in this scenario. The spectrum appeared extremely distorted as seen at the operator console for the 8 ft. dish.

UBT Multipath mitigation

- In contrast, the UBT system was able to produce error-free data for some of the time in this scenario. It natively corrects for the root cause of short-delay multipath because of the autonomy within each DBM. When the aircraft was stationary the UBT output spectrum appeared adequately repaired through this process, but when the aircraft was taxiing, the UBT output spectrum continually changed, so that the data became unintelligible again. We did not have time to find optimal UBT settings to

Figure 3 - Test location (Left) and view from antenna location (Right)

minimize the deleterious effect of this dynamic multipath.

- We had enabled an additional conventionally-pointed beam for comparison purposes with the tracking beam. When the aircraft was stationary on the tarmac, the conventionally-steered beam output showed a distorted spectrum as well (like the 8 ft. dish).

RF Interference

- We also encountered strong RF pulsed interference that we eventually identified as coming from an Air Search Radar in close vicinity (21 miles away in Boron, CA). Every 11–12 sec., (as the Radar scanned past our position), we noticed large amplitude dips in the IF signal output of our UBT subsystem. Quick research indicated that this Radar (AN/FPS-67) operates between 1250 & 1350 MHz, transmitting at 2.5 MW. The prototype antenna was provided by First RF Corp. as a wide-band technology demonstrator. Consequently, appropriate band-specific filters were not installed, and the unfiltered antenna was thus receiving signals at problematic levels even though they were located spectrally outside the three desired TM bands.
  Effects of this interference were most evident for channels tuned to the L-band TM frequencies. Because of this dominating interference, we could not maintain a link at L-band beyond the 1st flight arc, (approximately 7 miles from the antenna). Clearly, a high-pass front-end filter would be required in the antenna to attenuate this out-of-band Radar signal sufficiently to achieve full performance in the desired TM L-band region.
- The interference was somewhat less problematic at S-band and C-band, so we were able to show periods of error-free reception even when the aircraft flew out to a range of 45 miles, despite the extremely small size of our antenna.

Mitigation of Interference effects

- To minimize the effect of the interference on our measurements, we reduced the integration time on the BERT to 2 sec., and this allowed any bit errors to be flushed from the running tally within 2 sec. after the radar scan passed our position (thus leaving 9-10 seconds of error-free results).
- Figure 4 shows this behavior clearly. Approximately every 11-12 sec., a pulse burst produces a group of bit errors (shown by the red trace). We also discovered other pulsed-interference sources interspersed between the bursts from the Air Surveillance Radar. The black trace indicates the range of the source, as calculated from the GPS record. The blue trace indicates the Eb/N0 as reported by the BERT, and the green trace shows the SNR as recorded by the UBT native logging functions.
- Both the SNR and Eb/N0 indicate sufficient signal to provide error-free reception at all ranges flown. From Figure 4, we can logically conclude that (between the pulsed interference bursts) there are sustained periods of zero error reception at ranges up to 45 mi. It further stands to reason that with the appropriate filtering installed in the antenna, such interference would be rendered harmless to our UBT subsystem.

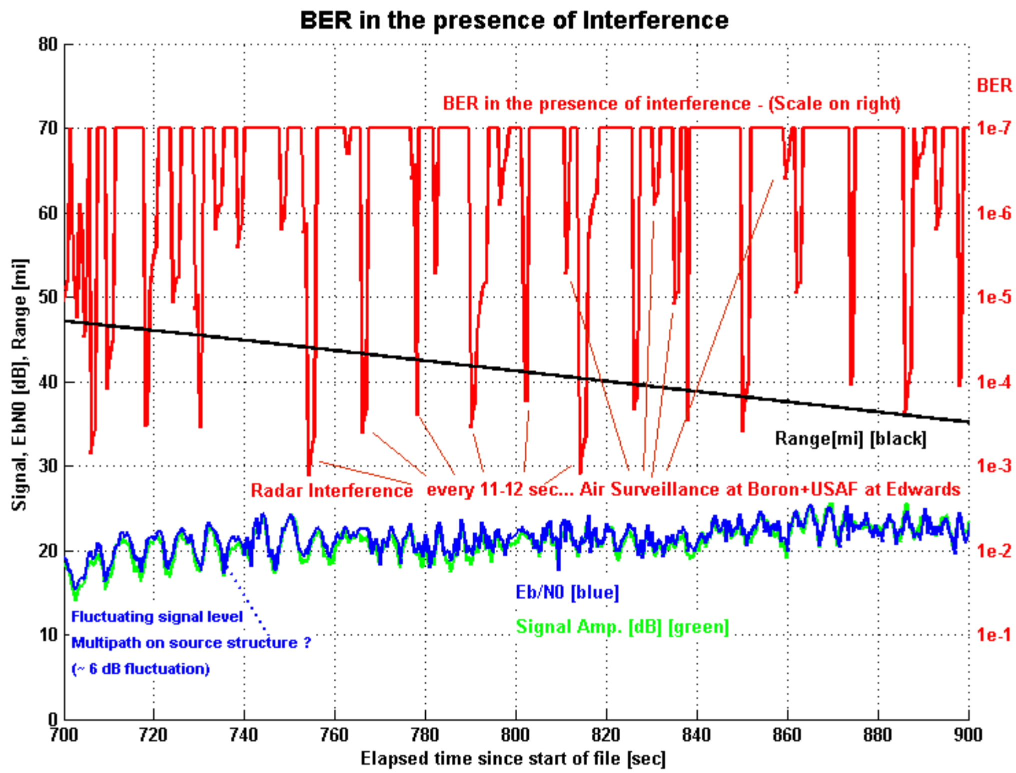

Figure 4- Error bursts at 11 - 12 Sec intervals. Source between 48 & 35 miles

8.0 Performance analysis

We utilized a simple model to analyze the sensitivity of our system:
The Signal power received at the antenna is provided by the Friis' Free Space Link Equation

$$P_R = \frac{\lambda^2 G_T G_R P_T}{(4\pi d)^2} \qquad (1)$$

Where:

P_T	=	10W	Transmit (TX) pwr. (40 dBm)
G_T	=	-3 dBi	TX antenna gain (signal split and cable losses considered below)
G_R	=	14.4 dBi	RX gain at S-band
λ	=	-8.9 dBmtr	Wavelength at 2.3 GHz
d	=	45 mi	Range (48.6 dBmtr)

… and the Noise power is

$$P_N = k\, T_0\, W \qquad (2)$$

Where:

k = -228.6 dBW/(Hzdeg.K) : Boltzmann's constant

T_0 = 280°K (24.5dB deg.K) Including 0.5 dB loss prior to 1.5 dB LNA & Sky + Earth-Sidelobe Temp = 100°K

W = 3 MHz (64.7dBHz): Effective Bandwidth (used for 5 MSPS SOQPSK capture)

After considering losses of 5 dB for miscellaneous items such as splitter and cable losses on the Tx side, the calculated Signal-to-Noise Ratio SNR is:

$$SNR = P_R/P_N = 18.9 \text{ dB}$$

This compares very favorably with the 17 – 22 dB SNR measured when the aircraft was at 45 miles. Looking again at Figure 4, we see a 5-6 dB signal fluctuation, which resembles the interference that would be seen between 2 antennas that are simultaneously fed and both visible to an observer, while the aspect angle of the aircraft changes slowly with respect to the observer.

9.0 UBT as a potential replacement for reflector antenna systems

The UBT architecture has been designed with a great deal of flexibility in mind. Though originally targeted for an airborne application, for ground-based applications, we could easily separate the digital processing from the RF elements and connect more than 16 RF elements to each DBM in situations where fewer beams were simultaneously required.
Our prototype design for a production DBM has the capacity to handle 256 beam-elements – which can be utilized as 16 dual-pol elements processed to provide 8 independent beams, or 256 single-pol elements combined to make a single beam… or any combination in between. This flexibility is contained in the firmware, and can be achieved with re-cabling of each DBM to the appropriate RF elements.
When considered in this way, we suggest that UBT-based antenna systems can provide cost-effective alternatives even for large ground-based single-beam reflectors.

To investigate this assertion, we compared the estimated production cost for a ground-based model UBT system on a low-dynamics pedestal (to point the DBF system in the general area of interest) with that for a single reflector system providing the same aperture performance. We were able to model a decision space as seen in the graphic in Figure 5.

In this model, a cost-based decision favors a UBT system if the requirements lie on the GREEN side of the black line (which represents 20 dB G/T in our model). If the performance requirements lie on the RED side of the black line, there may still be compelling reasons not to use a reflector solution, stemming from requirements for an airborne application or for high-performance target tracking, or something mundane like limited space.
We also considered complex scenarios where multiple simultaneous beams were required at various G/T performance levels and frequencies. When we graphed a complex set of requirements on Figure 5, we found that the UBT still provided a lower cost solution as long as "most" of the Frequency/Performance beams fell on the GREEN side of the black line, even if there were a few points on the RED side.

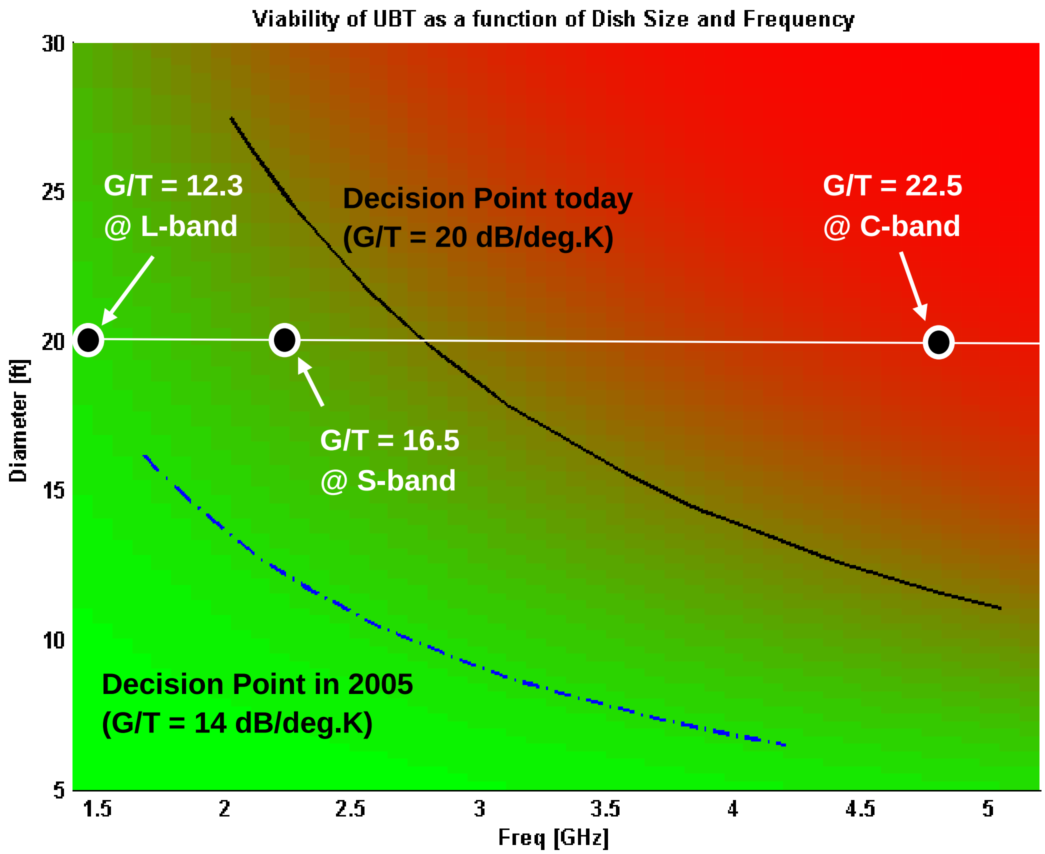

Figure 5 - Decision space for reflector replacement with DBF using available technology

For Example (referring to Figure 5) –

- A single-beam requirement for a 20 ft. reflector at C-band (G/T = 22.5 dB/deg.K) would immediately drive the decision to a reflector solution, but if the requirement included 2 additional simultaneous beams (e.g. one at S-band and one at L-band, or both at L-band), it would cement the case for UBT both in terms of performance as well as cost!
- A single-beam requirement for a 20 ft. reflector at S-band (G/T = 16.5 dB/deg.K) might result in a protracted pro/con arguments, but a requirement for only one additional simultaneous beam at L or S-band would tip the scale in favor of UBT.
- A single-beam requirement at L-band (G/T = 12.3 dB/deg.K) would indicate that UBT is the clear winner.
- A multi-beam requirement (e.g., > 3 beams) with an average G/T less than 20 dB/deg.K would also indicate UBT as the prudent choice.

As a point of comparison:, in 2005, when we designed were implementing the DBF system used in for the E-9A, the decision point below which DBF could be considered viable was at about G/T = 14 dB/deg.K as indicated by the dashed BLUE line in Figure 5. This indicates the fact that the black line in the figure is moving continuously to the right as the cost of the electronics continues to reduce (we estimate 3-5x reduction in the cost of the E-9 DBF electronics at today's prices).

10 Conclusions

Through our demonstrations and analysis, we have advanced Univeral Beamforming Technology to TRL6, and shown the suitability of UBT technology for a wide range of TM operations:

- We have demonstrated the functionality of a miniature UBT ground station.
- Low-cost commercially available components and algorithms from various vendors were used successfully.
- We showed near-theoretical performance, indicating the maturity of many of the signal-processing techniques and algorithms used in UBT.
- A novel beam-pointing approach demonstrated resilience in strong multipath conditions.
- Analysis has yielded a decision space to show that UBT, implemented with today's technology, can be a logical choice for any applications with a requirement of G/T < 20 dB/deg.K, including ground-based operations with mixed G/T requirements, some of which may exceed 20 dB/deg.K.
- We believe that UBT can be applied to airborne missions particularly effectively.
- CDSI has embarked on a path to design production hardware to support this promising UBT technology. Significant NRE remains to produce a mature DBM able to support a variety of operational TM applications.
- The state of the art for DBF applications has advanced to the point where it is now a viable alternative for many ground-based TM applications. We suggest that in 10 years or less, UBT will be able to economically out-perform all ground-based TM applications (and many non-digital beamforming applications) economically.

The authors:

Anand Kelkar, Chief Engineer, CDSI.
During his 35+ year career, Anand has developed several products in the Telemetry and Radar space. Anand has served as a key technical analyst for the US Army CECOM on the Firefinder Artillery and Mortar Locating Radar program. He has authored several patents in the fields of Radar Transmitters, Digital Beamforming and Antenna Positioners. He completed his BEE at Cooper Union in New York and his MSEE at the University of Southern California.

Brian Krinsley, Chief Engineer, Sea Range, NAWCWD, Pt.Mugu
Brian attended the University of California, Santa Barbara, receiving a degree in Electrical and Computer engineering. He has since received several certificates in Computer Programming and AI, as well as a Master's degree in Business from the University of LaVerne. He has worked for the Navy for over 25 years, supporting the EA-6B and F-14 aircraft, as well as NASA on their Space Shuttle extension. He currently works for the NAVAIR Sea Range as Chief Engineer.

Norm Lamarra, President, CDSI
Norm has a 4-decade technical background in Radar Systems, Signal Processing, System Modeling and real-time software development. He spent ten years at NASA's Jet Propulsion Lab, working initially on integrated spacecraft design, and later on advanced space network architectures for science gathering. His academic experience began in Mathematics, and evolved through engineering to a decade of pre- and post-doctoral work in the Schools of both Engineering and Medicine at UCLA. There he applied modeling and signal-processing principles to the analysis of dynamic physiological systems, eventually spending a short time as Adjunct Faculty.

Tom Young, Executing Agent, Test Resource Management Center (TRMC)
Tom supports the TRMC's, T&E, S&T Spectrum Efficient Test Technology Area. He is also a Systems Engineer in the 412th Test Engineering Group, Instrumentation Division, Edwards AFB, California. As EA, he directs the efforts for strategic roadmap development and execution of technology efforts to meet critical DOD spectral needs through high-risk, high-payoff Science & Technology projects. As a Program Manager, he has steered several key technologies to successful application. Tom has a BS in Computer Science (1999) from Chapman University, and an MS in Systems Architecting and Engineering (2008) from the University of Southern California.

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