FROM RF TO BITS WITH SYNTHETIC BEAMFORMING

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ABSTRACT

A Synthetic Beamforming antenna was built for Airborne Telemetry. Low-Noise Block-converters translated RF to IF suitable for direct analog-to-digital conversion. Then all telemetry functions were performed digitally via parallel FPGAs for 10 independent sources. Monopulse tracking and optimal diversity combination was performed using 4 antenna quadrants at two orthogonal polarizations. Novel estimation approaches drove digital demodulation, symbol- and bit- synchronization. Final telemetry outputs include: digital, analog (video), and analog IF (e.g., for downlink relay). This program has incubated several concepts that we believe have the combined potential to significantly improve the future of telemetry.

KEY WORDS

Synthetic beamforming, digital downconversion, multipath mitigation, digital receiver, digital demodulation, digital bit synchronization.

INTRODUCTION

The U.S. Air Force uses two modified De-Havilland Dash 8 aircraft for telemetry and sea surveillance range support primarily on the Eglin Gulf Range. These aircraft use a multi-beam electronically-scanned phased array antenna to receive S-Band telemetry. This paper discusses a recent antenna upgrade program that has provided an opportunity to introduce state-of-the-art advances to the field of airborne telemetry (and perhaps telemetry in general).

The legacy antenna is 33 feet long and weighs 3,200 lbs; it scans in azimuth only and uses a fixed 10-degree elevation beam aperture to search for, acquire and track up to 5 simultaneous spatially-separated, diversely-polarized sources. A conventional set of rack-mounted superheterodyne receivers and diversity combiners, demodulators, bit-synchronizers and data recorders serve to form the complement of onboard equipment for a mission.

Analysis of the required flight profiles generated a specification including tracking of 10 sources (up to 20Mbps) over a coverage volume from sea level to an altitude of 50K ft., with a 120-deg azimuth field of view. A conventional phased array was considered as a possible upgrade solution, but given the requirements and the state of technology, a Synthetic Digital Beamforming antenna subsystem was judged as the best solution to maximize performance and system longevity within the best cost constraints. Additional goals were: (i) to provide Bit Error Rate performance at least equal to the legacy antenna; (ii) to significantly reduce the weight in order to allow longer missions; (iii) to provide a platform for soft future upgrades; (iv) to
mitigate multipath since most of the range is over the Gulf of Mexico; (v) to reduce maintenance & calibration requirements.

THE DIGITAL BEAMFORMING SOLUTION

We interpreted the above goals to imply a requirement for forming 20 beams (10 for each orthogonal polarization). With a conventional approach, 20 sets of phase shifters would thus have been required, along with 20 receivers, 10 diversity combiners, 10 demodulators and 10 bit synchronizers. This approach was therefore considered prohibitive in many dimensions, including cost, power, weight, rack space, cabling, maintenance, etc.

Our approach postulated that computational capability per unit cost has increased sufficiently during the past decade to enable an all-digital solution. The design paradigm therefore shifted towards getting the telemetry information into a digital processor as quickly as possible and minimizing any RF processing. A block diagram of our solution is presented in Figure 1. As of this writing, the first deliverable system is in final integration and test after just 20 months of development.

Because of the many potential risk areas in an all-digital solution, we spent considerable time and effort on building an end-to-end simulation of our proposed approach, and many design decisions were based on its results. Initially, we used MATLAB to model high-level engagement scenarios, and separately used SIMULINK to investigate some details of the digital processing. However, we went further with our simulation-based design approach, by actually incorporating parts of this simulation into the software development process for the Antenna Control Computer (ACC). By this means, we were able to develop, investigate and verify the operation of the ACC using realistic engagement scenarios, well before any hardware was available. The following sections outline some of the areas in which this simulation and analysis provided guidance for the design evolution.
SYSTEM CONSIDERATIONS

Reducing the Required Number of Antenna Elements. In any Electronically-Scanned Antenna (ESA), the complexity and cost of the antenna are directly proportional to the number of “active” elements. These are elements whose output can be independently phase-shifted and combined in order to synthesize (and steer) a beam.

![Antenna Location](image)

**Pill shaped coverage desired**

The system application profile required that the antenna coverage resemble a pill shape since the desired flight support was going to be contained within that volume, as shown in Figure 2. The resulting G/T (Gain/Temperature) requirement is shown alongside. We realized that rather than have a beam that was able to scan the required angular extent with full gain everywhere (requiring each radiator to be an active element), we could provide more than adequate coverage by strategically partitioning the aperture into fewer active elements. Due to the digital multi-point nature of our approach, we were able to investigate optimal-diversity combination from a portion of the process where there was spatial diversity available. With this technique, the elevation aperture is broken into 2 parts that divide the aperture into 1/3 and 2/3 portions approximately. A conventional antenna, where each diversity input requires a receiver, can be cost prohibitive, especially for multi-beam applications. In our approach, a digital “mini-receiver” implementation for each beam is made available at the output of each active element as part of the digital beamforming process. The result of this digital diversity combining is shown in figure 2 as well. Details of the downstream digital diversity combiner operation are provided later. Due to the architecture of the system, the combiner operation is transparent to whether the inputs originate from sources that are diverse in either space or polarization.

![Coverage volume](image)

**Figure 2 - Coverage volume (left), Resulting G/T requirement and diversity combining improvement (right)**
**Antenna Array.** The array is a planar structure mounted on existing horizontal rails that run the length of the aircraft. We use 56 active vertical “sticks” (2.5 feet high) that are arrayed in the horizontal plane forming an antenna surface 12.5 feet in length (cf. 33 feet for the legacy antenna). Each stick has 11 dual-polarized radiating elements combined into two vertical groups, with a feeding arrangement illustrated in Figure 4. A feed manifold partitions each stick into 2 individual sections, each with dual orthogonally-polarized outputs. The entire array weighs about 1100 lbs (cf. 3,200 lbs for the legacy antenna).

The Array Surface consists of a grid of individual patch radiators with a 2.5-inch square pattern as shown in Figure 3.

The Radiating Element consists of two concentric metal disks, or patches, positioned above a ground plane. The first disk is 1.54” in diameter, etched from the copper clad surface of 0.080 Rogers RO 4003 printed circuit material, which provides the spacing between the disk and an aluminum ground plane. The back side of the RO 4003 is stripped before bonding to the aluminum. Using this thin dielectric spacer for the first disk suppresses the monopole mode so that the element can be fed with a simple unbalanced coaxial probe. There is actually one feed for each of the two orthogonal linear polarizations. The second disk is .01” smaller and is separated from the first disk by a Rexolite spacer. The disk is machined from 0.031 copper sheets and then bonded to the Rexolite, which in turn, is bonded to the RO 4003. While there is no direct connection between the two disks, they are coupled electromagnetically. The resonances of the two disks coupled in this way provide a much larger impedance bandwidth than would be possible with a single disk at the same height.

Low loss design techniques are prevalent throughout the array design from the radome to the input to the LNA. The “A”-sandwich radome has been optimized for low loss over the entire field of view, and is spaced more than ¼ wavelength from the radiating elements. The radiating element employs ultra-low-loss components, while the RF combiner uses closed-cell foam supporting a low-loss strip-line circuit. The output of each RF combiner feeds the signal through a very low-loss filter to reject out-of-band interference. The 4:1 manifold combiner attaches directly to a combline filter as shown in Figure 4A. The combline filter characteristic is also shown in Fig. 4B, and it has a loss of approximately 0.25 dB.

**The Low-Noise Block-converter (LNB).** The LNB utilizes a dual-downconversion process, requiring a single 486-MHz local oscillator (LO). This downconversion plan was chosen after the spur performance of various available mixers was tested, ensuring that any significant intermodulation spurs fell well outside the IF pass band, thus retiring one risk.

In a beamforming application, control of group delay (inter-unit phase variation) is another critical risk area. For the IF (image-rejection) filter, we chose a combination of band-stop and
band-pass filters that operate after the first down-conversion. We minimized the variation of group delay by moving the frequency corners of all filters well away from the edges of the pass-band and into the guard space and its image around the Fs/2 spectral point. A functional block diagram of the resulting LNB design is provided in Figure 5. The production unit contains two LNBs in each enclosure (one for each polarization), thus reducing the volume, weight and number of cables required. Using the unique band-pass/band-stop approach provided excellent image rejection (50 dB goal vs. 30 dB spec.). Consequently, the overall selectivity of the LNB provided an effective pass-band for the desired 200-MHz telemetry information band, while keeping variation of group delay in check. The IF signal was then transported via low-loss cable to the first stage of the Data Acquisition and Signal Processing system (the DSA board).

Digital Data Acquisition and Signal Processing. After the ADC the digital processing was achieved entirely within commercial FPGAs, and was broken into 4 stages. The 1st-stage functions included digital downconversion (DDC), phase shifting, filtering and digital beamforming. The 2nd-stage functions included optimal diversity combining and monopulse error estimation. The 3rd-stage functions included demodulation and bit synchronization. The 4th stage functions handled output of the telemetry as analog or digital streams (e.g., for onboard recording, video display, or 70 MHz IF for downlink relay). The following subsections now provide a little more detail.

Acquiring the data. In our SBA design, a portion of the receiver is contained within the LNB, where the desired 200-MHz telemetry signal band is translated intact to a range of contiguous frequencies suitable for digitizing. Each LNB output is digitized by a single 500MHz ADC driving one signal path into a massively-parallel distributed digital subsystem which includes
receiver, diversity combining, demodulation, and bit synchronization. We believe that the digital processing can avoid many of the problems (such as image rejection, non-linearity and harmonic problems) that can plague the hardware components in analog telemetry systems. However, we recognized that many “new” problems need careful attention in the digital domain (such as synchronization, bit significance etc.), if the digital potential was to be realized in practice.

Data acquisition from the entire antenna array is performed through 56 VME cards called Digital Sub Arrays (DSAs), each handling 4 of the 224 LNB outputs. Each DSA input has an ADC followed by a single FPGA that handles up to 10 telemetry streams in parallel. Each ADC output stream (500 Msamples/sec) is thus fed simultaneously to 10 identical digital receiver/filter processors (channels) located within the associated FPGA. While these cards were developed by a vendor specifically for this program, they are now available as a COTS product with many other potential applications, simply by reprogramming the FPGAs. This capability also provides us with a vehicle for ‘soft’ product improvements to the current application, including adaptation to changing requirements, without replacing hardware.

**Receiver Dynamic Range.** Figure 6 shows a block diagram of the receiver process we used. The LNB has an RF-to-IF conversion gain of approximately 50 dB, with a noise bandwidth of approximately 250 MHz, determined by the anti-aliasing filter. As can be seen in Figure 6, there is an analog Programmable-Gain Amplifier (PGA) in front of the ADC. This PGA has a bandwidth of 600 MHz and a Noise Figure of about 7.5 dB, thus ensuring that the System Noise Figure is not affected adversely by the digitizing process. The gain of the PGA must be set so that thermal noise “tickles” the ADC, ideally with about 3 LSB levels (RMS). The ADC is an 8-bit device with 7.3 effective bits. This limits the dynamic range of the ADC portion of the process to about 39.5 dB (when noise is integrated over the IF noise bandwidth). Of course, when the digital data is band-pass filtered and decimated downstream, there is a corresponding SNR gain of >11 dB (for a signal bandwidth <20 MHz). Next, because there are effectively 112 spatially-separated “receivers” for each polarization, there is an additional SNR gain of 20.5 dB. Consequently, the system receiver provides an aggregate dynamic range of more than 70 dB. 16-bit quadrature data paths are used throughout in order to ensure preservation of this dynamic range and care has been taken to minimize the numerical effects of bit significance everywhere.

**Downconversion and Band-Pass Filtering within the FPGA.** The DDC consists of a direct-conversion mixer and a four-stage decimating filter as shown in Figure 7. The first filtering stage is a decimate-by-2 FIR filter. The second filter is a Cascaded Integrator-Comb (CIC) filter with a programmable decimation ratio, allowing adjustment of the output sample rate to the relevant signal bandwidth for that channel. The third filter is a decimate-by-2 FIR filter with a steeper response than the previous filters in order to flatten the overall pass-band. The final filter provides the final spectral shaping for the DDC, with a default 1:2 shape factor (which can be adjusted). The mixer and filter banks are duplicated for each of the 10 channels in the devices.
Serial Beamforming. The DSA FPGAs connect together via a cascade chain that passes “partial sums” for each of the 10 beamforming channels. The partial sums are time-multiplexed over a common 36-bit data channel (16I+16Q+4tag). All 224 DDCs for a particular channel are synchronized externally. Each sum is forwarded (with the tag) to the next beamforming node, which may reside either on the same card or on an adjacent card in the pipeline. The element phase shift for each channel is determined through a series of lookups.

Filter implementation. The filter response shown below was measured at an intermediate point within the DDC process discussed above. In this particular example, the channel frequency was
fixed at 39.5 MHz and the tuning frequency of the filter was swept across the band while the resulting amplitude was recorded. The stop-band:pass-band ratio is 2.4:1.3=1.85, and the sharpness of this filter is more than sufficient to satisfy the requirements of IRIG document 106.

**Figure 8 – Example measured filter characteristic**

**Diversity Combiner.** The Combiner weights the inputs from the 8 antenna segments according to their “signal quality” before summing them. A Signal Quality Measure (SQM) was developed to accommodate signals that appeared to have a large SNR, yet were unintelligible due to severe multipath contamination. Figure 9 shows how the polarization & spatial diversity combiner is able to recover from a fade (null in left pattern) that might manifest in a conventional antenna with no spatial diversity. Also included are the simulation outputs indicating the spectral content of the signal at the individual inputs (upper) and at the output of the Diversity combiner (lower).

**Digital Demodulation.** The Demodulator we have developed for this program is also completely implemented in firmware. The data stream arrives from the Diversity Combiner in the form of baseband I/Q samples at about 2.5 samples/symbol. Once in the Demodulator stage, the data is filtered and immediately re-constituted using a Farrow re-sampler. This allows the subsequent processing to run efficiently within the FPGA structure. In this firmware stage, we
have implemented: front-end filtering; AGC; frequency locking (via a PLL); AM, FM, and PM demodulation for analog and digital sources.

**FM & PM demodulation.** The approach for both types of modulation is similar. The absolute phases and slopes are estimated using a powerseries phase-trajectory estimator that is used to fit a sliding window of incoming data. The lowest-order coefficients of this process are separated into phase value, phase velocity and phase acceleration. Then the inter-relationship of these coefficients is used to extract data as well as time synchronization (bit sync) information. Simulation shows performance comparable to the current state-of-the-art using this approach, as shown in Figure 10.

![Figure 10 –Demodulator Performance](image)

**PRELIMINARY MEASUREMENTS OF PRODUCTION SYSTEM**

At the time of this writing, we are in Integration and Test of the first full-up deliverable system. We therefore can only present antenna pattern measurements in this paper, along with some of the filter and LNB performance measurements described above. We believe these already show the potential of our approach, and we intend to publish performance results for the complete system when it is fully operational.

**Measured Antenna Pattern.** Using this large concatenation of hardware and processing components, we were able to show that the efforts described above were effectively coordinated by demonstrating actual beamforming on the first antenna segment to come out of production. Actual range measurements are shown in Figure 11, demonstrating astonishingly successful results from these portions of this project so far.

**Inter-Element Mutual-Coupling Effects.** We were expecting mutual coupling effects to significantly affect the antenna pattern when we formed the beam at extreme scan angles. In practice, to our great initial surprise, we found that the theoretically-derived values worked well even at extreme scan angles. Further, we noticed we could compensate for the absence of the parasitic elements that were placed at the edges of the array to accommodate mutual element coupling discontinuities at the edges of the aperture. By properly calibrating and accounting for the cable lengths and the relative losses/gains of each component, we were able to produce an almost ideal antenna pattern that kept its sidelobe integrity over the entire scan volume required. The measured antenna patterns are compared to their theoretical counterparts in Figure 11 below.
CONCLUSION

We are building what we feel is a sensible solution to a system requirement using the latest in available technology. In that process, we introduced and implemented novel approaches to classic airborne telemetry problems which we hope will benefit the telemetry industry in general. Our cautious development approach has involved extensive simulation from the study level to the Hardware-In-Loop operational software development level. This investment has paid well as evidenced by the initial rapid successes during the Integration & Test phase of the program.

Besides developing a flexible telemetry acquisition system for airborne applications, we feel we have successfully iterated on an efficient technique to create a requirements driven solution with a minimum of hardware boundaries.

The first production unit is expected to be delivered within a few months of this writing, and hardware integration results so far are extremely encouraging. We hope to provide more complete and detailed performance results in the near future, particularly on the more controversial aspects of our design.

Figure 11 – Measured vs. Predicted Antenna Patterns

Left Side: Measured patterns
   Top:  0 deg. (calibration position)
   Bottom:  -60 deg.

Right side: Simulated Ideal Patterns for Comparison