IN-FLIGHT AUTO-TUNE OF AN AIRBORNE SYNTHETIC BEAMFORMING ANTENNA

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ABSTRACT

At ITC 2009, we described the real-world complications of fielding an airborne Synthetic beamforming Telemetry System, which simultaneously supports 20 individual beams (10 at each of 2 polarizations). We described how our layered Open-Source software approach helped us to modify the system rapidly after delivery without disrupting mission operations. Since then, we have further extended the software toolset that we developed to dissect the System behavior via post-mission replay and analysis, and to compare high-resolution in-flight measurements with our detailed physics simulations. This analysis has shown that the most significant factor affecting operational performance of the System was variation in the relative phase of the elements from day to day. These variations were traced to a variety of hardware issues, none of which could be resolved without major cost and effort. As an alternative approach, we developed a dynamic auto-tuning capability that optimizes the phase calibration of the System using each actual signal source as it is being tracked. This results in improved signal-to-noise performance while reducing the need for dedicated in-air calibration flights that we had previously created. We believe that the flexibility of digital beamforming, allied with a modular and easily-extensible software architecture, have again proven capable of quickly and cheaply mitigating real-world operational issues, without (so far) requiring any hardware modification of the delivered System.

KEY WORDS

Synthetic Beam-forming, Digital Telemetry, Antenna auto alignment, Open-Source software, Rapid Development, Operational improvement

INTRODUCTION

A prior paper entitled “Development of a Synthetic Beamforming Antenna – From Drawing Board to Reality” was presented at ITC 2009 (System Block Diagram shown in Figure 1). That paper described some of the areas of difficulty that were overcome during the pre- and post-delivery phases of an Airborne Digital Beamforming (DBF) Antenna, including: Specification Development, Hardware (LNB), Synchronization, Reliability, AGC, Software Development and Testing, Operational Issues in the Flight-testing Phase, In-Flight Antenna Patterns, and Vendor Coordination at the System Level. It then described our approaches to mitigating these difficulties, including: Data Collection and Post-Mission Analysis, Visualization Tools, and
Calibration. Although we were successful in demonstrating that the System was capable of achieving the desired specifications for mission performance relatively soon after delivery and installation, some of the above difficulties persisted throughout the flight-testing phase, and the subsequent challenges of real-world mission operations gradually shifted our focus from “achieving specification performance in the mission context” towards “maintaining day-to-day mission performance with minimal effort”. In turn, this required us (as the System Developers) to refocus the data-collection, analysis, and visualization tools on Mission Operations (i.e., mission setup, system configuration, and real-time use by the Operators during actual Missions). Many of the tools we had initially developed for developer use were therefore extended and adapted for use by Operators, as we undertook to simplify operations and maintenance. We also created new functions to automate routine operations, mainly using lower-level functions that we had first created during in-house development and testing.

**OPERATIONAL EVOLUTION OF ANTENNA CALIBRATION PROCEDURE**

**In-flight Antenna Patterns:** Since our antenna is electronically scanned, we were able to construct an operator test function (requested via the Quick Web Client – QWC) that performed a rapid High-Resolution Electronic Azimuth Scan over $\pm 60^\circ$. This “Hi-Res Scan” was logged for later analysis (along with all real-time measurements), but could also be viewed immediately by the operator using the QWC's graphical interface (initially constructed to simplify in-flight diagnosis and testing of the System). We also allowed the Hi-Res Scan to be requested even during track mode (causing a temporary interruption of tracking on that channel).

Early in the Flight-Testing Phase, we discovered by this means that the antenna azimuth patterns obtained in-flight were far from ideal when compared with those that had been demonstrated during Factory Acceptance Testing (on the ground, typically using a far-field source at boresight at an antenna-test range). Even after performing this procedure on the hangar throat (using a far-field source placed across the airfield), the subsequent in-flight antenna patterns were still not

![Figure 1 – Simple Block diagram of our Digital Beamforming Antenna](image.png)
acceptable. We therefore had to develop a calibration procedure that allowed the amplitude and phase \((A,\phi)\) of the antenna elements to be re-aligned for the in-flight situation. We therefore devised a set of user functions that could be run from the web-based Operators Console, including the following 4 components: Azimuth Scan, Boresight Snapshot, In-flight Recomputation of \(A/\phi\) values, and Database Update. These functions were typically utilized in the sequence now described.

**Full-up In-Flight Re-calibration Procedure:** Mission Operators already had a “Beam-Cut Mission” defined, consisting of a fly-by pass of the air base along a known path at a range of several miles from a ground source – a horn mounted on a Ground-Service Vehicle (GSV) emitting a CW signal within the telemetry band of 2200 to 2400 MHz. Three airborne locations \((A, B, C)\) were mapped on the path of this pass, such that \(B\) was “on boresight”, while \(A\) and \(C\) were respectively about 60 degrees in azimuth either side of boresight. This pass could either be configured as a “tracking pass” or a “staring pass”. The former provides a means of verifying the tracking capability of the System, since the tracking error can be logged as a function of SNR, and the signal amplitude can be measured as a function of scan angle. The latter provides an in-flight antenna pattern, since if the antenna is pointed at boresight while the aircraft flies from \(A\) to \(B\) to \(C\), then the signal amplitude traces the antenna pattern over approx. \(\pm 60\)deg.

In order to perform in-flight re-calibration, we adapted this Beam-Cut Mission to become a “Beam-Cut Calibration Mission”, requiring the fly-by pass to be performed several times. During the first pass, a Hi-Res Az Scan was performed at each point \(A, B, C\) (each hi-res scan takes a few seconds) – this provides the “Baseline” measurements. During the 2\(^{nd}\) pass, a Boresight Snapshot was performed at point \(B\), after which the In-flight Recomputation procedure was performed. During the 3\(^{rd}\) pass, another hi-res scan (“Verification” scan) was performed at \(A, B, C\), and if the operator was satisfied with the results, then the Calibration Mission was terminated. Otherwise, the 2\(^{nd}\) pass (snapshot and re-computation) and 3\(^{rd}\) pass (verification) were repeated until a satisfactory verification scan was achieved. Finally (after landing), the mission log was available for detailed off-line analysis, and the Database Update procedure was run to make the new \(A/\phi\) element calibration values permanent. The results of replaying such a datalog are shown in Figure 2 for the 3\(^{rd}\) pass of a Beam-Cut Calibration Mission. Figure 3 further shows a zoomed version of the hi-res scan taken at point \(B\) (boresight).

Even though this procedure was highly successful, we discovered that the underlying airborne element calibration values changed over time, and we identified several hardware factors that contributed to these changes. Since significant hardware redesign was not feasible at this post-

![Figure 2: Antenna Measurements from Live Beam-Cut Mission](image)

1 – instantaneous channel pointing angle  2 – tracking error
3 – slant-left polarization signal level  4 – slant-right polarization signal level
5 – SNR for each polarization computed by the optimal spatial combiner.

3
delivery stage, we therefore began development of a software-only calibration procedure that would become part of their set of standard maintenance functions. It was also necessary to provide a means to decide when this re-calibration procedure should be performed.

**Pattern Verification:** In order to determine when the Beam-Cut Calibration procedure should be rerun, the Operator performed an in-flight hi-res scan while tracking any source (ground or airborne) with sufficient SNR and dynamic stability. Once the scan was visualized, the operators decided whether a new Beam-Cut Calibration mission was needed. Typically, it was found that re-calibration was needed every few weeks, and a Beam-Cut pass was sometimes added on to the return path of an Operational Mission to provide efficient usage of flight and ground resources.

**Automatic Branch Tuning:** As can be seen in Figure 1, the antenna array consists of 8 segments (4 at each of two polarizations), and each of these 8 segment outputs was fed to our Spatial Combiner, which optimally combined them dynamically in amplitude and phase to maximize the SNR of the output signal (which was typically up-converted digitally and then downlinked to the ground station). In addition to this “output” path, the 8 segment outputs (filtered in amplitude and/or phase) were also provided to the azimuth tracker, which performed the proper vector (complex) combinations to provide highly-accurate monopulse tracking in azimuth. While the Optimal Spatial Combiner did an excellent job of maximizing the SNR (even through deep fades in either polarization due to multipath and/or source maneuvers), it became quite challenging to maintain solid monopulse tracking in highly-dynamic situations, particularly when the SNR dropped below about 15dB. It thus became clear that during normal operations, the average phase alignment between the 8 branches varied significantly, and we therefore developed an adaptive mechanism to align the branches optimally specifically for the monopulse tracker (which is separate from that for optimizing the combiner output SNR).
called this our “Branch Tuning” algorithm, and evolved this approach to increase the accuracy
and robustness of the tracker as our experience with live mission datalogs increased.

However, as mission operations continued, it became clear that even adaptive Branch Tuning
was insufficient to optimize dynamic mission performance between Beam-Cut Calibration
Missions. We therefore conceived a method of simplifying the in-flight calibration procedure
that would be amenable to automation. First, we investigated coarse phase-only recalibration.

Automatic Element Recalibration: Since Product Delivery, the System Developers have
continued product improvement activities in-house, and one such activity investigated the idea of
performing an abbreviated version of the above in-flight calibration procedure automatically
without operator intervention and without requiring a separate mission. Our approach was first
developed and tested in-house using the emulated version of the System, which is a complete
executable software-only version of the real-time system that is fully configurable and can run on
a standard PC requiring no external hardware. Figure 4 shows a hi-res Az Scan performed on a
simulated version of the full-up System in a “deteriorated” state, in which random amplitude and
phase errors have been introduced to emulate serious deterioration in calibration values (much
worse than experienced in normal operation). The top row shows first angle versus time, second
the monopulse tracking error (for a hi-SNR boresight target), and third a blowup of the same
error, plotted vs scan angle just in the boresight region. In all these plots, red represents the
Slant-Left polarization, green the Slant-Right. The 2nd row is as follows: first is the monopulse
amplitude, second is the monopulse SNR, and third is a blowup of the same SNR plotted vs. scan
angle just in the boresight region. Later, we will compare these panels to those obtained after
Coarse Auto-Tuning the antenna phase values only (not the amplitude).

During normal operations, each channel of the antenna System constantly scans an azimuth
sector looking for a source to acquire. When the measured SNR exceeds the acquisition
threshold, a track is initiated, and the auto-tuning algorithm is run during track initialization (if
the operator has “turned on” this feature during Mission Configuration. The algorithm measures
the signal from each element in turn, while incrementing its phase by 45deg over the entire range
of 360deg (i.e., 8 values per element). Once the optimum is found for each element in a given
segment, it is fixed before moving on to the next element in that segment. After all segments
have been auto-tuned, the segments are then re-aligned with each other in phase, and subsequent
variations of phase between Segments are handled automatically by the Branch Tuning algorithm
previously described. The result of this procedure is shown in Figure 5, showing that almost
“ideal” calibration has been achieved, starting from what appeared to be an unworkable situation
for monopulse tracking shown in Figure 4. Since amplitude is not tuned in this algorithm (as it
would be in a full Beam-Cut Calibration Mission), and since phase is coarse-tuned only to the
nearest 45-deg quantized value, this procedure is very rapid (taking only a few hundred
milliseconds for the entire System), and thus does not significantly extend the source track
acquisition process (which normally takes about 1.5 sec).

Results of Coarse Auto-Tuning: Comparing Figures 4 and 5 is quite instructive. Starting with
the bottom row, the first panel of Figure 4 (“Before Tuning”) shows no recognizable monopulse
mainlobe, and the middle panel shows that a peak in slant-left monopulse SNR (red) rarely
coincides with a slant-right peak (green). The corresponding monopulse angle error (top middle

5
panel) shows that even in the mainlobe region around boresight (+2.5deg), there is conflicting information from the left and right polarizations (shown vs. angle in the top right panel). This is a very bad situation for monopulse tracking, and it is unlikely that the tracker could maintain lock on this source for very long in this condition, despite the high underlying SNR. Looking now at the same panels in Figure 5, we can not only see recognizable (almost ideal) antenna patterns, but the red and green patterns are almost overlays over the entire mainlobe region (which is all that matters for monopulse tracking). Note that the monopulse SNR has also increased from about 25dB (in only one or other polarization) to above 40dB for both polarizations simultaneously. Most impressive is the top right panel, showing that the monopulse angle error vs off-boresight scan angle is identical for both polarizations over the entire mainlobe region. This configuration (after coarse auto-tuning) thus produces highly accurate and robust tracking, as it should for a source with such a high SNR.

**Performance of Coarse-Tuning Algorithm vs. SNR:** As the source SNR reduces, the algorithm still works well, but it has increasing difficulty in recovering proper calibration reliably as the deteriorated SNR drops below 12-15dB. This finding thus also helps to determine when a full Beam-Cut Calibration Mission should be scheduled (as described above). If the “before” and “after” SNR are too far apart, then the initial acquisition potential of the System

**Figure 4: Simulated Hi-Res Az Scan with Deteriorated Calibration (Before Auto-tuning)**

**Figure 5: Hi-Res Az Scan from Figure 4 after Coarse Auto-Tuning**
will be compromised. Moreover, as the calibration deteriorates from day to day or week to week, tracking becomes progressively less robust, meaning the track will be dropped more often when deep fades occur in either polarization. Our procedures thus help to keep the tracking in top shape automatically, while indicating when a full-up recalibration is required.

SUMMARY

Over the first three years of Mission Operations, we have made continuous and significant improvements to the Airborne Telemetry DBF System that we first delivered in 2008. Some of these improvements were focused on user-operability issues (such as testing, diagnosis, and maintenance), others were focused on improving in-flight performance or dynamic robustness as our knowledge of the actual airborne signal dynamics improved – through detailed analysis of high-resolution datalogs taken (mostly automatically) during normal operations.

This paper described investigation of a persistent operational problem (misalignment of the antenna elements in amplitude/phase increasing over time), and the development of rapid software-only mitigations using our in-house simulation capability. Once each of our concepts had been developed and proven in-house, transition of the (software-only) updates to on-board hardware occurred very rapidly, minimizing the effort and cost of in-flight verification and validation, and avoiding any mission “downtime”.

The most surprising finding was that even serious performance degradation (due to dynamic misalignment of the antenna elements and/or branches) could mostly be recovered automatically with only minor software modifications. We believe these solutions provide further examples of the advantages of the flexible hardware and software architecture of our Digital Beamforming System, along with the utility of its emulated counterpart. One final note: all of the improvements developed over the past three years have been delivered, installed, tested and accepted remotely, requiring no on-site visits by our development personnel to the actual aircraft. This itself represents considerable savings in time, effort, and cost, and provides a new level of low-cost “on-line support” capability.