Boeing AMSS System License Compliance Report

This License Compliance Report is submitted in accordance with paragraph 19(h)(5) of Boeing's transmit/receive licensing order,[1] and verifies that the Boeing AMSS system satisfies the conditions of the licensing order and complies with the specific design guidelines set forth in paragraph 19(h)(1)-(5). These design guidelines derive from work conducted in ITU-R Working Party 4A that was later incorporated into ITU-R Draft New Recommendation M.[AMSS].[2] Section 1 of this Report covers the overall control and monitoring functions of the system (¶19(h)(3)-(4)). Section 2 covers the control of aggregate off-axis EIRP (¶19(h)(1)). Section 3 covers factors that affect off-axis EIRP (¶19(h)(5.1)-(5.3)), including mis-pointing of Aircraft Earth Station ("AES") antennas in Section 3.1, variations in AES antenna pattern in Section 3.2, and variations in AES transmit EIRP in Section 3.3. Resistance to being "pulled off" to adjacent satellites (¶19(h)(2)) is also covered in Section 3.1.

1 Control and Monitoring Functions

The Boeing AMSS system includes a variety of control and monitoring functions to ensure that AES transmissions always remain under positive control, and to identify and shut down any malfunctioning AES, as described in Boeing's license application.[3]

The Boeing AMSS system monitors and controls the AESs using a network operations center ("NOC"), which is equivalent to a network control and monitoring center ("NCMC").[4] The NOC is responsible for managing the aggregate off-axis EIRP levels of the system (*see* Section 2). All AES transmissions are under positive control of the NOC. This control includes admitting all AESs into the network, authorizing transmit frequencies, authorizing changes to the transmit power/data rate, and removing an AES from the network.

No AES may transmit until it receives a poll message from the NOC, which is equivalent to an "enable transmission" command.[5] The NOC periodically polls inactive

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[1] *See The Boeing Company*, Order and Authorization, 16 FCC Rcd 22645, File No. SES-LIC-20001204-02300, Call Sign E000723, DA 01-3008, (Int'l Bur./OET 2001) ("*Order*"). Paragraph 19(h)(5) of the *Order* requires Boeing to submit a report verifying its ability to comply with the conditions set forth in ¶19(h) no later than 60 days prior to commencing commercial operations. *See id.,* ¶19(h)(5).

[2] *See Draft New Recommendation M.[AMSS], Technical and operational requirements for aircraft earth stations of the aeronautical mobile-satellite service networks operating in the 14-14.5 GHz (Earth-to-space),* ITU-R Study Group 8, Document 8/78 (July 1, 2002).

[3] *See Application of The Boeing Company for Blanket Authority to Operate up to Eight Hundred Technically-Identical Transmit and Receive Mobile Earth Stations Aboard Aircraft in the 11.7-12.2 and 14.0-14.5 GHz Frequency Bands*, File No. SES-LIC-20001204-02300 (December 4, 2000, supplemented January 10, 2001) ("Boeing Two-Way AMSS Application"), Technical Supplement at 5, 8-9, and 12-13.

[4] *See Order* at ¶19(3).

[5] *See id.,* ¶19(h)(4.1).

AESs individually using the forward link. The polling message specifies a return link transponder for which the NOC has reserved sufficient capacity to allow the AES to transmit. When an AES receives its polling message, it transmits a response to the NOC over the assigned return link transponder, and the NOC then assigns the AES "active" status. An AES inhibits transmission when:

- The NOC sends a "disable transmission" command;
- The AES loses the forward link from the NOC; or
- The AES detects an anomalous condition that may indicate loss of positive control from the NOC.

The AES also inhibits transmission if it receives a "parameter change" command that may cause harmful interference to other satellite systems during the change.[6] For example, if an AES is commanded to switch satellites, it first inhibits transmission and then begins to listen to the forward link on the new satellite. The AES does not resume transmitting until it receives a poll message ("enable transmission" command) on the new satellite.

The NOC monitors the performance of the AES to identify malfunctioning terminals and shut them down. The NOC sends a "disable transmission" command to an AES if:

- The assigned return link is lost;
- The AES fails to properly respond to power control commands; or
- The AES fails to properly respond to data rate change commands.

The NOC also continuously logs numerous aspects of system and terminal performance including: aircraft position, aircraft attitude (heading, pitch, roll), AES data rate, AES entry and exit from the system, power control commands and any other anomalies.[7] The NOC will use this data along with a number of specialized techniques including event correlation, transmit lobing, and power modulation to identify malfunctioning terminals and shut them down, as described during the license proceeding.[8]

Lastly, the AES contains self-monitoring functions and automatically inhibits transmission in the event of a fault that may cause harmful interference to adjacent satellites.[9] The AES inhibits transmission if it detects:

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[6] *See id.,* ¶19(h)(4.2).

[7] *See id.,* ¶19(h)(4.3).

[8] *See Response of The Boeing Company*, File No. SES-LIC-20001204-02300 (April 5, 2001) at 6-10.

[9] *See* Order at ¶19(h)(4.4).

- Any satellite transponder fault, transmit antenna subsystem fault, or on-board transmit control system fault; or

- A loss of communication between the transmit control system and the antenna subsystem.

2 Control of Off-Axis EIRP

The NOC employs an algorithm to control the aggregate off-axis EIRP of the system so that it is less than or equal to that of a routinely processed VSAT terminal.[10] The control algorithm accounts for variations in aggregate off-axis EIRP caused by, for example, mis-pointing of AES antennas, variations in AES antenna pattern, and variations in AES transmit EIRP (*see* Section 3). As described below, each element of the control algorithm is designed conservatively to compensate for each type of variation and to ensure that the off-axis EIRP of all AESs remain within the levels prescribed for routinely processed VSAT terminals even in anticipated worst-case conditions.

The Boeing AMSS system control algorithm uses the reported state of all the AESs operating in the network and the known variations (tolerances and uncertainties) in the system to calculate the aggregate off-axis EIRP and control the individual AES transmissions, as described in Boeing's license application and shown in Figure 1.[11] All AESs operating in the network report their position (latitude, longitude), attitude (heading, pitch, roll), and transmit EIRP to the NOC.[12] The NOC then uses the reported data, an AES antenna model, and the known tolerances in AES pointing, antenna pattern, and transmit EIRP to compute an aggregate off-axis EIRP envelope for the AESs operating in the network. This envelope is then compared to the off-axis EIRP limits for routinely processed VSAT terminals. Based on how closely the envelope approaches the limits, the NOC issues commands to allow additional AESs into the network, change AES data rates/power levels, or remove AESs from the network.

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[10] Loral Skynet, the operator of Telstar 6, has indicated to Boeing that it has coordinated Telstar 6 with the satellites adjacent to 93° W.L. for off-axis EIRP levels that are less than or equal to that of a routinely processed VSAT terminal. SES Americom, the operator of AMC-4, has also confirmed that it has coordinated AMC-4 with the satellites adjacent to 101º W.L. for similar off-axis EIRP levels.

[11] *See* Boeing Two-Way AMSS Application, Technical Supplement at 34-38.

[12] *See id.*, Technical Supplement at 37-38. The initial application indicated that the NOC would back-calculate the transmit EIRP of the AESs based on the received power at the ground. Subsequent analysis has determined that it is more accurate for the AES to determine and report its EIRP to the NOC directly.

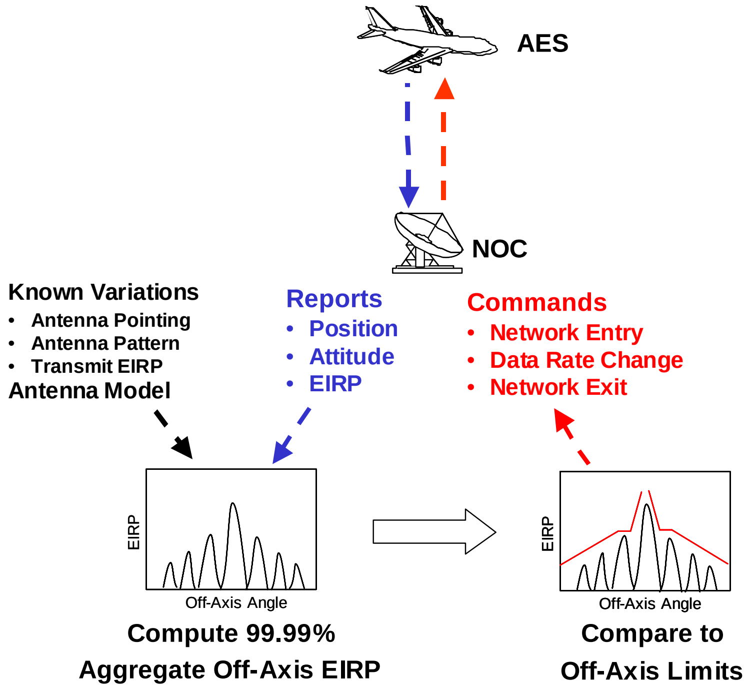

Figure 1. Control of Off-axis EIRP

An individual AES reports when its transmit EIRP, position or attitude (heading, pitch, roll) has changed sufficiently to cause its off-axis EIRP to change by more than 0.2 dB. The AES determines its position and attitude using information from the aircraft navigation data bus and concurrently calculates its EIRP based on the measured input power into the antenna, the antenna pointing angles, polarization, transmit frequency, temperature, and previously measured characteristics.

The NOC then calculates the antenna pattern gain envelope for each AES as projected along the GSO arc using an antenna model and the antenna-pointing angles computed from the reported aircraft position and attitude. The antenna model uses the array pattern of the antenna, the embedded element pattern, element amplitude and phase errors, and end-of-life element failure rate. Further, the NOC calculates the off-axis EIRP envelope for each AES by scaling the computed antenna pattern gain envelopes by the reported transmit EIRP.

A Monte Carlo method is used to combine the individual off-axis EIRP envelopes and the known factors affecting off-axis EIRP to calculate the aggregate off-axis EIRP envelope for the network. The Monte Carlo method allows for a combination of dissimilar factors that affect off-axis EIRP such as pointing tolerances (given in degrees) and power control tolerances (given in dB). The resulting envelope accounts for the 99.99% probability (or 3.7-sigma) combination of all of the tolerances and uncertainties. This is equivalent to accounting for 3.7 times the root sum squared ("rss") of the 1-sigma affect on off-axis EIRP of each tolerance and uncertainty. Each of these factors are characterized in Section 3 (antenna mis-pointing, *see* Section 3.1; antenna pattern variation, *see* Section 3.2; and EIRP variation, *see* Section 3.3).

The calculated aggregate off-axis EIRP envelope is then compared to the limits for routinely processed VSAT systems.[13] As designed and developed, Boeing's AMSS system will not exceed the maximum co-polarized components along the GSO arc, which are as follows:

Angle off-axis	*Maximum EIRP in any 4 kHz band*
$1.0° \leq \theta \leq 7.0°$	$15 - 25 \log \theta$ dBW
$7.0° < \theta \leq 9.2°$	-6 dBW
$9.2° < \theta \leq 48°$	$18 - 25 \log \theta$ dBW
$\theta > 48°$	-24 dBW

The NOC recalculates the aggregate EIRP envelope whenever an AES makes a report and prior to admitting any AES to the network or permitting an AES to increase its data rate. The NOC controls AES data rate and entry into the system so that the aggregate off-axis EIRP limits are always met.

3 Factors Affecting Off-Axis EIRP

There are a variety of factors that may cause unintended variations in off-axis EIRP. These factors can be grouped into three categories: AES antenna mis-pointing, AES antenna pattern variation, and AES transmit EIRP variation. The Boeing AMSS system has been designed to minimize each of these variations as well as to account for their effect in the control of the aggregate off-axis EIRP, as described in Section 2.[14] This section describes the testing that has been conducted which demonstrates that the Boeing system can and will adequately control these variations.

3.1 AES Antenna Mis-pointing

The Boeing AES uses a closed loop pointing algorithm to track the serving satellite as the aircraft maneuvers, as described in Boeing's license application.[15] AES antenna mis-pointing is caused by two sources, (i) closed loop pointing errors and (ii) mis-alignment between the transmit and receive apertures. Each of these error sources has been characterized and is accounted for by the NOC when computing the aggregate off-axis EIRP envelope. As described below, testing has shown that the AES can accurately track the serving satellite.

Testing of the closed loop pointing algorithm was conducted in an indoor anechoic antenna range. AES transmit and receive antennas were mounted on a mechanical positioner that allowed them to be rotated through simulated aircraft maneuvers at controlled rates, as shown in Figure 2. Transmit and receive horns were mounted at the opposite end of the range. A primary transmit horn emitted a Boeing

[13] *See* 47 C.F.R. § 25.209(a).

[14] *See Order* at ¶19(h)(5.1)-(5.3).

[15] *See* Boeing Two-Way AMSS Application, Technical Supplement at 24-25.

AMSS system forward link signal for the AES antennas to track. A block diagram of a typical test setup is shown in Figure 3.

Figure 2. Transmit and Receive AES Antennas on the Mechanical Positioner

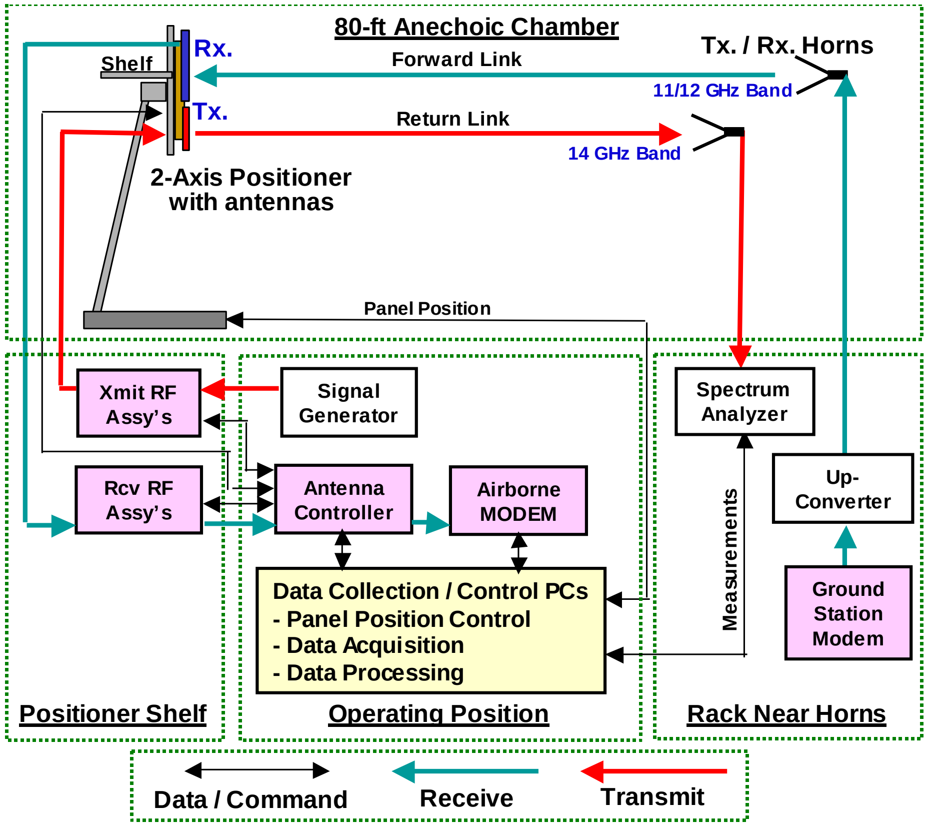

Figure 3. Test Setup Block Diagram

Representative test results are shown in Figure 4. In this case the AES antennas were rolled through 130 degrees, +65 to –65 degrees that are near the maximum operational scan angles for the antenna. Measurements were made at roll rates of 2 and 5 degrees per second. Five degrees per second is near the maximum roll rate for a commercial aircraft and occurs only very infrequently. A two degree per second roll rate is more typical. The AES antenna pointing angles were compared to the mechanical positioner pointing angles to compute a pointing error.

The measured pointing error is caused by effects of RF beam to antenna command error, command quantization, bias, control loop latency, control processing error, and Received Signal Strength Indicator ("RSSI") errors. Based on extensive characterization of these errors, the NOC will use a 0.25 degree[16] (1-sigma) pointing error when computing the aggregate off-axis EIRP envelope. As can be seen in Figure 4, the pointing error always remains less than 0.25 degrees for the 2 degrees/second (typical) case. The pointing error is always less than 0.35 degrees for the 5 degree/second case (maximum roll rate) which is also easily accounted for within the 99.99% (3.7-sigma) envelope calculated by the NOC. This demonstrates that the AES can accurately

[16] *See id.*, Technical Supplement at 24-25. The measured pointing error is larger then the predicted pointing error included in the transmit application. However, the NOC accounts for the measured pointing error when calculating the aggregate off-axis EIRP envelope so that the Boeing AMSS system will continue to comply the off-axis EIRP density limits for a routinely processed VSAT network.

determine and control its antenna pointing even during extreme aircraft maneuvers. Under straight and level flight conditions the pointing error will, of course, be lower.

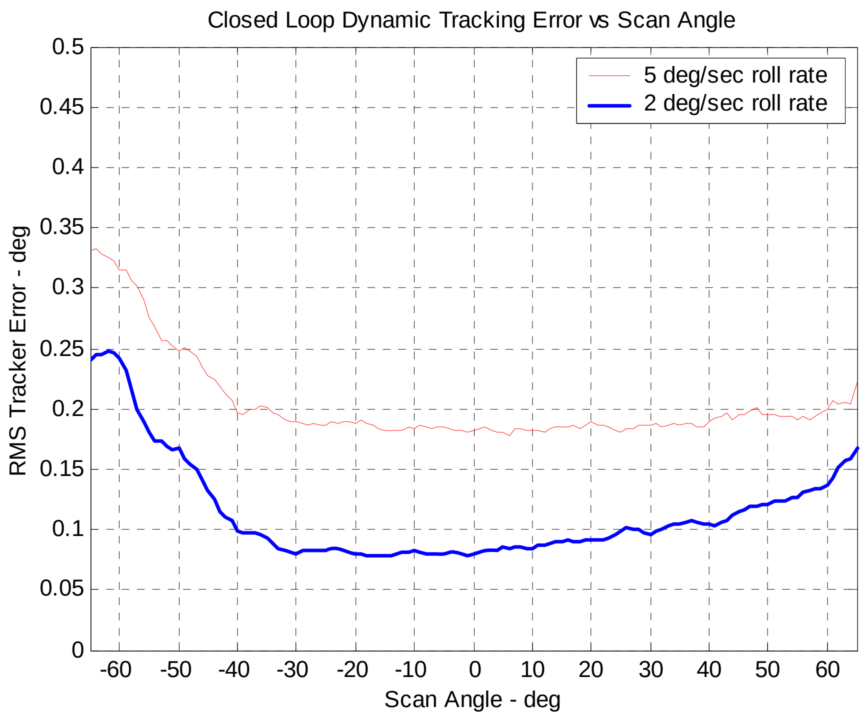

Figure 4. Transmit Antenna Pointing Error

The AES employs a tracking algorithm that is resistant to being "pulled off" to interfering signals from adjacent satellites. Additional tests have confirmed this. In these tests, two transmit horns were placed to one side of the primary horn so as to simulate adjacent satellites separated by 2 degrees of GSO arc. Comparison of the receive signal tracker performance with the interfering satellite sources on and off showed no shift or bias in the receive tracking performance.[17] In the unlikely event that an AES were "pulled off" to and adjacent satellite, it would automatically cease transmission.

In addition to the pointing errors associated with the closed loop pointing algorithm, there may be errors caused by mechanical mis-alignment between the transmit and receive apertures. These errors are caused by installation tolerances and flexure of the aircraft fuselage during flight and ground operation. Examination of the installation has determined that the pointing error due to installation tolerance is at most +/- 0.2 degrees. Analysis of the fuselage flexure by the Boeing Commercial Aircraft group has determined that the pointing error due to bias offsets between ground and flight is at most 0.13 degrees.[18] The pointing error due to fuselage dynamic flexure is at most 0.03

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[17] *See Order* at ¶19(h)(2).

[18] Values are given for a Boeing 737 aircraft. Different values will be used for each aircraft model.

degrees (1-sigma). The NOC uses these values when computing the aggregate off-axis EIRP envelope.

3.2 AES Antenna Pattern Variation

The NOC uses an analytical model of the AES transmit antenna pattern to accurately calculate and control the off-axis EIRP envelope, as described in Boeing's license application.[19] The primary cause of variation in the antenna pattern is moving the beam pointing in elevation and azimuth. In addition to the pointing angles, the antenna model encompasses the array pattern, the embedded element pattern, element amplitude and phase errors (manufacturing tolerances, unit-to-unit variation), element phase quantization, and end-of-life element failure rates (aging).[20] As described below, testing has shown that the antenna model accurately predicts the gain pattern of the AES transmit antenna.

To test the accuracy of the antenna model, production AES transmit antenna patterns were measured for several scan angles and transmit polarizations in a compact antenna range, with representative results as shown in Figures 5 and 6. Figure 6 represents a worst-case scan angle and pattern cut. Superimposed on these measured antenna patterns is the 99.99% gain envelope predicted using the antenna model for the same conditions. In each case, the measured levels fall within the envelope of the predicted values of the AES transmit antenna pattern.

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[19] *See* Boeing Two-Way AMSS Application, Technical Supplement at 38.

[20] The only significant environmental effect on antenna performance is the change in electronic gain with antenna temperature. Since this does not affect the antenna pattern, it is accounted for in the AES transmit EIRP variation in Section 3.3.

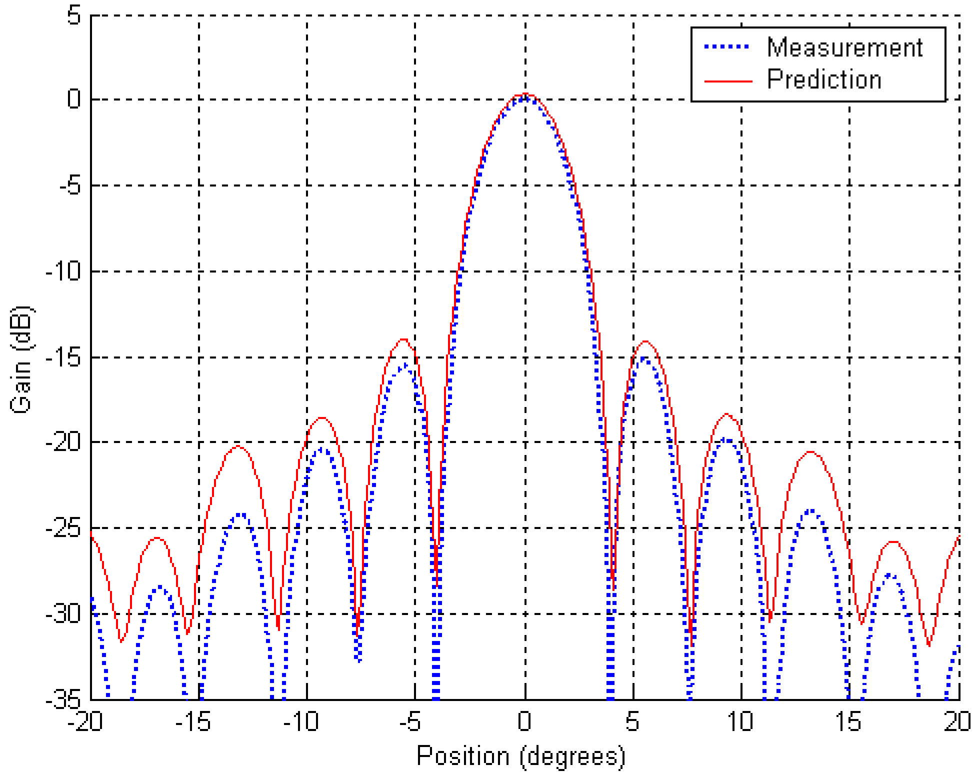

Figure 5. Predicted Versus Actual Antenna Patterns, 14.25 GHz at 0° Scan

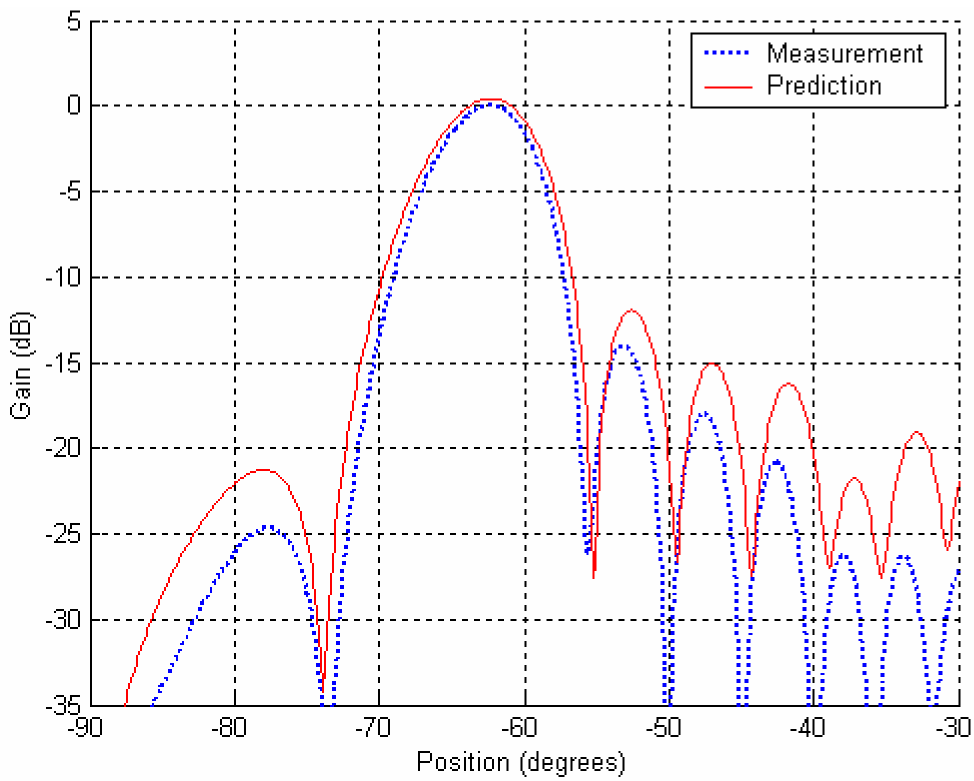

Figure 6. Predicted Versus Actual Antenna Patterns, 14.25 GHz at 63° Scan

3.3 AES Transmit EIRP Variation

The AES determines and reports its transmit EIRP to the NOC using the measured input power into the antenna, the antenna pointing angles, polarization, transmit frequency, temperature, and previously measured characteristics. Additionally, the AES is able to control its transmit EIRP so that it remains constant as the aircraft maneuvers, as described in Boeing's license application.[21] There are two sources of AES transmit EIRP variation, transmit EIRP determination error and latency between AES reports. Each of these error sources has been characterized and is accounted for by the NOC when computing the aggregate off-axis EIRP envelope. As described below, testing has shown that the AES can accurately determine and control its transmit EIRP and report it to the NOC.

Testing of the EIRP determination and control algorithm was conducted using a test setup similar to the one described in Section 3.1. The AES transmit and receive antennas were mounted on a mechanical positioner that allowed them to track a horn emitting a Boeing AMSS forward link signal. A receive horn was then used to measure the transmitted EIRP from the AES transmit antenna.

Representative results of the testing performed are shown in Figure 7. The AES equipment was commanded to maintain a constant EIRP as the transmit beam was scanned. The transmit EIRP reported by the AES equipment was plotted with the measured EIRP. The difference between the measured and reported EIRP is the transmit EIRP error.

The measured transmit EIRP determination error is caused by a combination of input power measurement error, cable loss calibration error, temperature compensation error, uncertainties in the antenna electronic gain and unit-to-unit variation. The transmit EIRP determination error decreases with increasing EIRP. Based on extensive characterization of these errors, the NOC uses a 1.43 dB (1-sigma) transmit EIRP determination error for the tested power level when computing the aggregate off-axis EIRP envelope. As can be seen in Figure 7, the actual transmit EIRP error is about 1 dB, demonstrating that the AES can accurately determine and control its EIRP during the most extreme maneuvers expected.

[21] *Id.,* Technical Supplement at 10-12

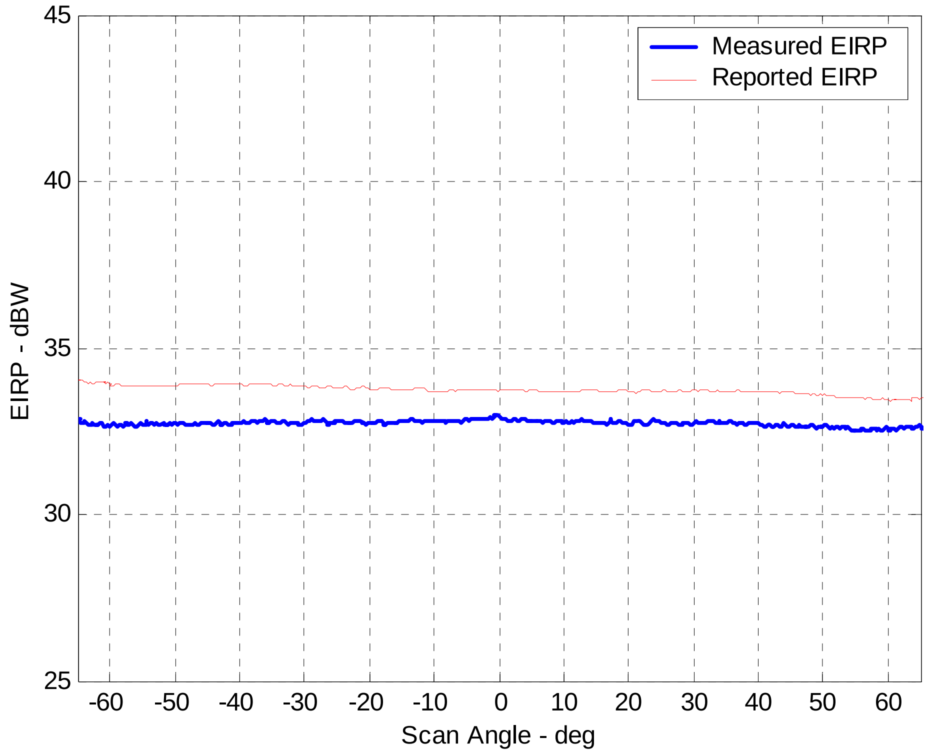

Figure 7. Measured and Reported EIRP vs. Scan Angle

In addition to the transmit EIRP determination error, there are also uncertainties caused by latency between AES reports to the NOC and the resulting control error. These uncertainties are caused by changes in the AES transmit EIRP between reports and changes in the aircraft position and attitude. An AES reports when its state has changed sufficiently to cause its off-axis EIRP to change by more than 0.2 dB. There is a finite latency for the report to traverse the GSO link, be processed on the ground, and a response made. The total error is limited by the maximum rate at which an aircraft can change position, roll, pitch, and heading. Based on extensive characterization of this uncertainty, the NOC uses a 0.5 dB (1-sigma) latency and control uncertainty when computing the aggregate off-axis EIRP envelope.

3.4 Summary of Factors Affecting Off-Axis EIRP

The design, control, and testing of the Boeing AMSS system has addressed a wide variety of factors that affect the aggregate off-axis EIRP density of the system:

- Antenna mis-pointing (Section 3.1)
    - Tracking error of closed loop tracking system
    - Bias and latency of closed loop tracking system
    - Pull-off to adjacent satellites
    - Mis-alignment between the transmit and receive apertures
        - Installation tolerances
        - Fuselage Flexure
- Antenna pattern variation (Section 3.2)
    - Scanning angle variation (elevation and azimuth).
    - Array pattern
    - Embedded element pattern
    - Element errors
        - Amplitude and phase (manufacturing tolerances, unit-to-unit variation)
        - Phase quantitization
    - End-of-life element failure rates (aging)
- Transmit EIRP variation (Section 3.3)
    - Measurement error
    - Cable loss calibration error
    - Antenna electronic gain uncertainty
    - Temperature compensation error
    - Unit-to-unit variation
    - Latency (of position and attitude inputs) and control error

By accounting for all of these factors, the Boeing AMSS system can and will control its off-axis EIRP density to within the limits for a routinely processed VSAT system.