GPS Re-Radiation (Re-Rad) System to Support Military Aircraft Production

The Boeing Company
Boeing Field, Bldg. 3-390
Seattle, WA.

Reference: The current application is similar to the technical application for granted license with call sign WD2XMO (but at a different location) and file number 0239-EX-PL-2004

Submitted: 3/15/06

by

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Technical Description Exhibit

Boeing is presenting a technical description exhibit in this document showing compliance with all NTIA items in Chapter 8.3.28.

Purpose for the Application

The purpose of this application is to obtain a full 2-year experimental license to operate a GPS rerad system in a flight tests operation building in Seattle.
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Why we are Applying for a License

Boeing would like the ability to perform functional testing of the FMC requiring GPS signals inside a hanger in order to reduce delivery delays caused by the unavailability of GPS signals in the 3-390 Hangar in Seattle, Washington.

Location

Seattle (Building 3-390) at Boeing Field Flight Test. The building is located at NL 47.533214, WL 122.311614 (NAD83).

Military Contract Numbers

The facility is used to manufacture military aircraft (AITS, AWACS, MMA) as well as Commercial contracts such as Wedgetail and Peace Eagle, The following are the contract numbers:

1) F19628-01-D-0016 DO0042 for AITS Follow-on Contract (until 12/31/2009)
2) F19628-01-D-0016 DO0022,25-30 for AWACS Block 445 (until 12/31/2008)
3) N00019-04-C-3146 for MMA Program – SDD Contract (until 12/31/2009)
4) C338364 for Wedgetail System Acquisition (Australia)
5) SSM-SZ-4200-01 for Turkey Peace Eagle Program

The facility also supports other programs that make use of flight test operations co-located with the production operations.

Technical Description

System: GPS
Frequency: L1 1575.42 MHz
Emission: 20M4W7D (See Appendix)
Power into the re-rad antenna: Maximum -74.0 dBm/24 MHz or 39.8 Pico watts

The all metal building has both a highbay and a lowbay. The total size is 785 feet long by 280 feet 11 inches wide. The highbay ceiling down the middle is 98 feet high. The distance from the highbay floor to the lowest beams down the middle of the highbay is 60 feet. There are twelve telescoping canopy doors each 60 feet wide by 81 feet high, leaving 60 feet clear height when rotated up fully. There is also one horizontal rolling door that is 60 feet wide by 65 feet high.

The following analysis shows how the GPS re-radiating system is used with the doors open and still meet NTIA Chapter 8.3.28, item 7, the -140 dBm/24 MHz rule.

The system receives the GPS signals from a roof top antenna and re-transmits the signals inside the hanger to allow our production and flight test personnel to perform installation, testing and troubleshooting of the aircraft's GPS based systems. There are a maximum of 8 GPS re-rad antennas located inside the building, each one illuminates a corresponding aircraft test station. Each antenna is located 30 feet above the factory floor illuminating an area directly below it about 100 feet in diameter where the aircraft is located. The antennas are placed no less than 75 feet from any building outside edge perimeter. This provides an area of about 25 feet wide to the nearest exterior wall that has no detectable GPS re-rad signal using two GPS receivers. Boeing's intent is to have the GPS signal available 24/7 to production operations with or without the hanger doors open.

The roof mounted GPS antenna has a built-in band-pass filter. The manufacturer supplied plot shows a bandwidth of 27 MHz at the -3 dB pointing providing 38 dB of gain. An actual lab measurement of the GPS antenna was made to determine gain and bandwidth and found it to be 17 MHz @ -3 dB.[1] We analyzed the impact of this measurement using the following equation:

dB difference = log10 (BW1/BW2) x 10

We chose to disregard the gain/loss effects as it would present the worse case for compliance with item 7.[2] See figure 1. Using a MathCAD model to plot the dB difference range, we produced the following plot of all reasonable bandwidth values that might be encountered. The x-axis is the bandwidth range. Almost all systems will be at the far right of the x-axis. Systems at the mid to

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[1] We measured our sample GPS receive antenna and found the bandwidth to be 17 MHz @ -3 dB. We used a wide-band noise generator in an RF shield room and set the same sample antenna inside. We cabled out through a shielded cable connector port to a spectrum analyzer and used the video averaging mode to smooth out the noise. The bandwidth is about 10 MHz less than the manufacturer's value of 27 MHz. About all we can be sure of is that the approximate bandwidth is at least 17 MHz.

[2] 27 MHz will produce a <u>theoretical</u> +0.51 dB value with a 24 MHz bandwidth reference. However, since the natural GPS signal is limited to 20.46 MHz, it produces a bandwidth correction factor of -0.693 dB. This value can be ignored in practice. In addition, values above -0.693 dB are not possible. The actual measured 17 MHz bandwidth of the receive GPS antenna sample produces a calculated -1.498 dB value using a 24 MHz bandwidth reference.

far left of the x-axis would have lower modulation products for the receiver to decode and may not function properly, if at all, regardless of applying more signal. The y-axis is the corresponding gain/loss value in dB that is used to compute item 7.

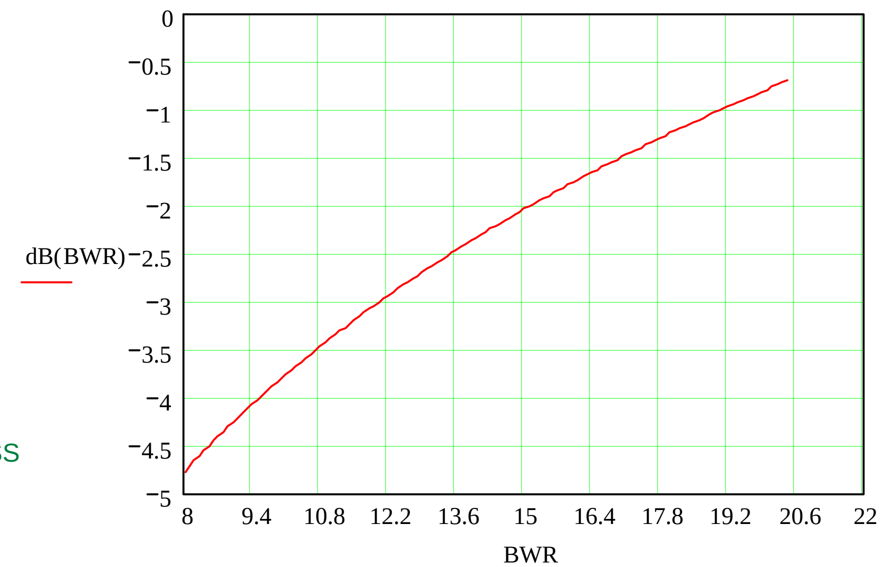

Figure 1 - Plot of bandwidth's effect on total system gain

From this plot, if the bandwidth values of all the system components are assumed to produce a combined bandwidth that is 24 MHz or slightly less (not limited) then the dB factor to correct for bandwidth gain is less than 2 dB (within the range of reasonable certainty in RF measurements) and can be ignored in most cases.

Boeing has the test equipment and the technical expertise to measure the system components and did not rely on published data alone. We used the above equation and analysis to evaluate options for the bandwidth considerations. This value can be used if the equation for calculating the total RF budget making the measurement for item 7 a little more reliable and compliant if needed. For our purposes, we were complaint without considering bandwidth effects in the total system to reduce uncertainties. The -1.498 dB would give us a better compliant result, if we used it.

Getting back to our system technical description, a variable attenuator follows and is used to calibrate the total system gain and maintain the NTIA maximum of -140 dBm/24 MHz at 100 feet from the building. The variable attenuator is a critical component to establish compliance with our method for item 7 and its use will be discussed in the following paragraphs.

There are several ways to calculate compliance for item 7. We chose a method that anyone can do with two hand-held GPS receivers and a scientific calculator. We focused on determining the RF power into the re-rad antenna that determines the signal level as defined in item 7 by a calibration procedure.

The calibration procedure begins with establishing the effective isotropic radiated power in the antenna's main lobe. This is done by using 2 GPS receivers (that are the same) to reduce ambiguous measurements that might be observed with just one receiver. The system gain was adjusted to a level where the receivers just barely detect the re-radiated signal at a measurement spot directly on the floor below. Since a minimum detectable signal is about –130 dBm and the 30 foot path loss is calculated as -56 dB, then the effective isotropic radiated power directed to the floor by the antenna's main lobe must be -74 dBm or 39.8 Pico watts. This includes the main lobe gain of about 3.0 dBi. The mathematical detail follows:

The equation for computing the isotropic free space loss is a ratio using the inverse square law and is derived from:

Pr / Pt = (c / 4*Pi * f * d) ^2

Where:
Pr = the received power by an isotropic antenna in watts
Pt = the transmitted power by an isotropic antenna in watts
c = the speed of light, 983.5710 feet/sec/MHz
Pi = 3.14159
f = the frequency in MHz
d = the distance in meters

The most common form for this equation is:

dB = FT + 20 log (d) + 20 log (f)
Where:
dB is the path loss in dB, since the equation is for isotropic transmit and receive elements
FT is the constant -37.87 to convert the distant unit to feet

In item 7, the phrase "isotropically radiated power" means to use the theoretical isotropic standard (single point equivalent of radiated power from a point source). This is to make the calculation simple by removing all possible antenna configurations and mounting positions.

The effective radiated power relative to an isotropic radiator is <u>normally</u> computed by:

$EIRP = P_t + G_t$

or

EIRP(dBi) = (transmitter power (dBm)) – (trans. line losses (dB)) + (antenna gain(dBi))

Where:
EIRP is the effective radiated power relative to an isotropic radiator.
P_t is the RF power in dBw or dBm at the input to the isotropic radiator.
G_t is the gain of the transmit antenna in dBi relative to an isotropic radiator.

The equation to <u>normally</u> solve for the receive power (item 7) is:

$\text{Receive Power}_{(\text{item } 7)}$ = EIRP – Isotropic path loss

However, we cannot calculate or measure P_t normally. The RF (link) budget that begins on the roof top GPS receiver and ends with the GPS re-rad antenna is variable from system to system. Only the -130 dBm signal at the receive antenna is a reasonable constant.[3] The use and inclusion of different antennas, filters, amplifiers and splitters with different gains and bandwidths from data sheets or measurement can be used. The coax type and length will vary. All of these will contribute to a wide variety of RF power input to the re-rad antenna and final EIRP. This will

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[3] The L1 frequency C/A code component has the highest level of -160.0 dBw and a maximum bandwidth of 2.046 MHz. The L1 frequency P(Y) code component has the highest signal level at -163 dBw and the maximum bandwidth of 20.46 MHz. See http://www.navcen.uscg.gov/pubs/gps/icd200/icd200cw1234.pdf, ICD Title: Navstar GPS Space Segment / Navigation User Interfaces, latest revision April 12, 2000 on pages 11 to 13.

affect the real coverage range of the system and the calculation for compliance of item 7. Therefore, the RF power into the re-rad antenna is uncertain. This value is P_t. It is critical for compliance to show an RF link budget to prove the value of P_t.

To solve the general equation above, we must first calculate P_t. Our method of determining P_t, follows:

The RF power into the isotropic re-rad antenna is uncertain and is determined indirectly from the received power level on the floor, 30 feet from the re-rad antenna. The system GPS radiated power is determined by a calibration procedure for two reasons. First, to radiate the minimal amount of RF power actually needed in the application of the system to the GPS system being tested and second to calculate the RF power, P_t, into the antenna for the EIRP equation above.

First, we must radiate a minimal signal to the aircraft's GPS system and adjust the variable attenuator to increase the signal level so that it provides a stable and reliable GPS receiver lock as indicated by two GPS receivers on the floor below the re-rad antenna. Using 2 GPS receivers (that are the same) reduces ambiguous measurements that might be observed with just one receiver. The system gain is adjusted to a level where the receivers just barely detect the re-radiated signal at a measurement spot directly on the floor below. A minimum detectable signal is about –130 dBm and duplicates the natural GPS signal level at the earth's surface.

The isotropic free space calculated path loss for L1 at 30 feet is 56 dB.

Therefore,

The RF power into the GPS re-rad antenna must be the best effort signal level measurement, less the path loss and less the isotropic forward gain of the GPS re-rad antenna using the standard equation:

P_t = (Signal level on the floor + 30 foot isotropic path loss) + (Isotropic antenna gain)

-77.0 dBm? = -130 dBm + 56 dB + 3.0 dBi?

However, we had some concern about how to properly handle the isotopic antenna gain. Some of our experts advised us not to consider the isotopic antenna gain again since it was factored into the measurement above. We performed an empirical measurement to physically observe the results, just to be sure. The empirical measurement showed we should not include the isotopic antenna gain and that it is factored into the measurement above. See Appendix A for details of the measurement. Therefore, we can remove the 3 dBi gain simply by changing its value to 0 dBi in the equation. We now have a very good isotropic equation for the re-rad antenna.

Therefore, the isotopic antenna gain in the equation is modified and the EIRP is calculated as:

-74.0 dBm = -130 dBm + 56 dB + 0.0 dBi

This equation calculates RF power P_t in dBm and coverts it to RF power in Watts.

$$\mathrm{dBm} := -74$$

$$\left[10^{\left(\frac{\mathrm{dBm}}{10}\right)}\right]\cdot 0.001 = 3.981\times 10^{-11}\ \text{Watts}$$

Or 39.81 Pico watts

The re-rad antenna is modified to minimize reflections and helps to contain the RF beam to radiate directly to the floor without altering the isotropic properties. Using the NTIA specification in item 7, these constructs are not considered in the calculation and are ignored.

Therefore,

The isotropic radiated power by the indirect method described above is:

P_t = -74.0 dBm or 39.81 Pico watts

Using the equation below to compute the isotropic free space loss for a GPS re-rad signal with a 175 foot path loss composed of a minimum of 75 feet from the re-rad antenna to the nearest building perimeter wall and 100 feet further to the distance specified in item 7, must be taken as a single distance and without regard to any obstructions:

Isotropic path loss in dB = FT + 20 log (d) + 20 log (f)

Isotropic path loss in dB = -70.94 dB

Returning to the general equation to compute a value for item 7:

Receive $\text{Power}_{(\text{item 7})} = P_t$ – Isotropic path loss

- 144.94 dBm = (-74.0 dBm) - (-70.94 dB)

Therefore, the GPS re-rad isotropic signal level with a 24 MHz reference for the bandwidth for item 7 is:

- 144.94 dBm/24 MHz

This value exceeds the requirements of item 7 by 4.94 dB. An additional 1.498 dB could be realized if we considered the small bandwidth factor created by the GPS roof top antenna. This demonstrates that compliance might be met in some systems that are slightly out of compliance when bandwidth of all the receive components are considered. We believe that the result is correct or very close and that it shows compliance with item 7 as best we can determine.[4]

Notes:

Adjustment or replacement of antennas, reflectors or other system components is not permitted without performing another calibration.

The re-rad antenna was designed and constructed by Boeing Engineers and Technicians at St. Louis. The details of the design are proprietary and are located in the Confidential Items Document.

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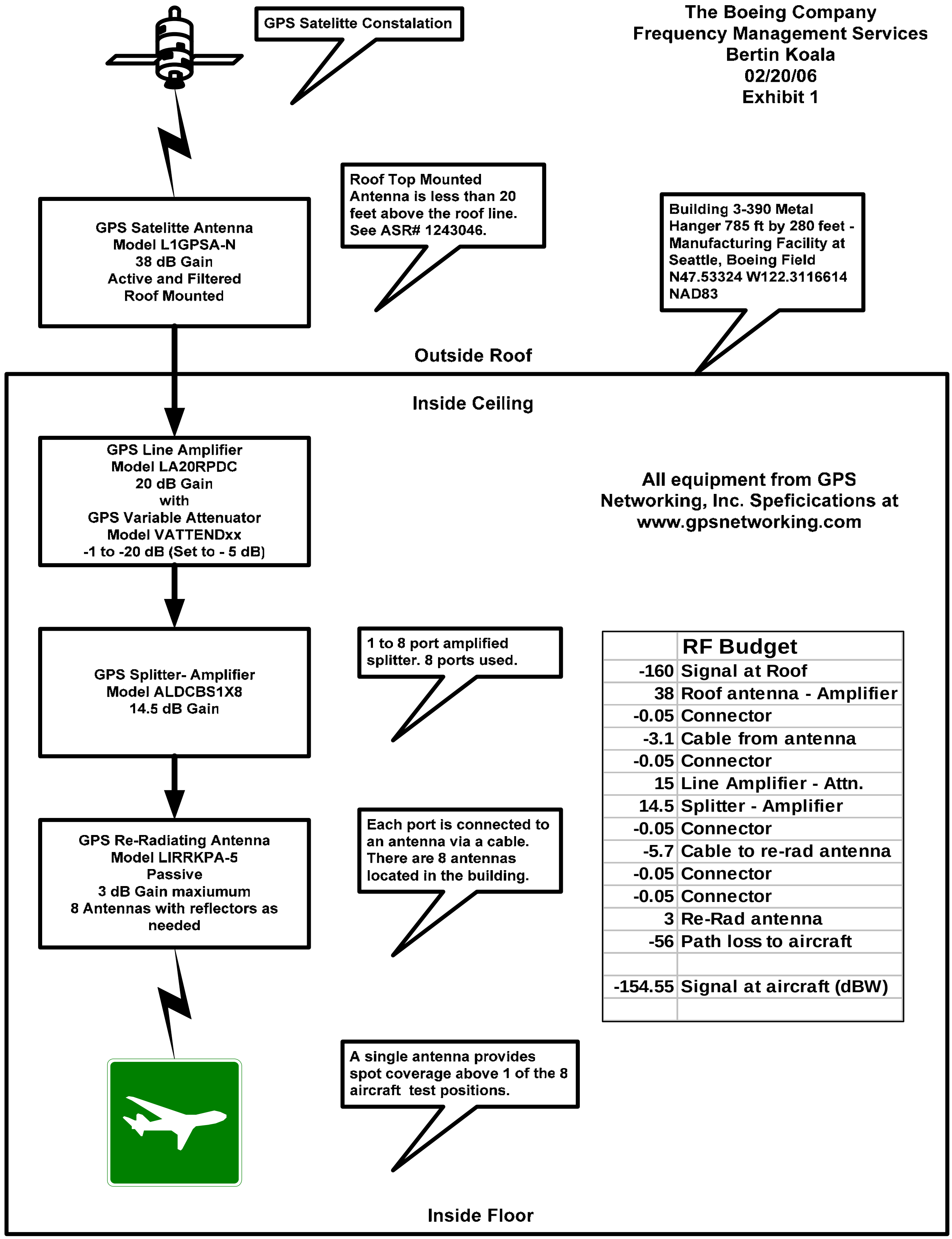
[4] Agilent Technologies technical support commented on our approach and measurement technique and found it to be correct. Please contact the author of this document to obtain contact information if any questions need to be asked of the applications engineer that was involved in this work.

The Boeing Company
Frequency Management Services
Bertin Koala
02/20/06
Exhibit 1



	RF Budget
-160	Signal at Roof
38	Roof antenna - Amplifier
-0.05	Connector
-3.1	Cable from antenna
-0.05	Connector
15	Line Amplifier - Attn.
14.5	Splitter - Amplifier
-0.05	Connector
-5.7	Cable to re-rad antenna
-0.05	Connector
-0.05	Connector
3	Re-Rad antenna
-56	Path loss to aircraft
-154.55	Signal at aircraft (dBW)

Certification of compliance for NTIA Chapter 8.3.28

Item 1. Comply.

Item 2. The GPS re-radiation system noted in this document will be used as an Experimental RNSS Test Equipment. The purposes include installing, testing and troubleshooting GPS receivers used in a manufacturing and production environment primarily for military aircraft and incidental independent research and development.

Item 3. NA.

Item 4. Boeing will accept a two-year grant with possible renewal.

Item 5. The operation is at a specific fixed location as is not mobile.

Item 6. The GPS re-radiation system noted in this document will be under the control the appropriate Boeing employees at all times. See item 10.

Item 7. As illustrated in this document, Boeing complies with a computed value of -144.94 dBm/24 MHz and exceeding by 4.94 dBm/24 MHz at a distance of 100 feet from the building [perimeter] where the tests are being conducted. The minor -1.498 dB due to the actual measured bandwidth of the roof top GPS received antenna that could be used to improve this margin was ignored.

Item 8. GPS users in the area of the potential interference to GPS reception will be notified that GPS information may be impacted for periods of time. The appropriate signage will be displayed in and around the building.

Item 9. The GPS re-radiation system noted in this document will be used only for the purpose of testing RNSS equipment/systems. See item 2.

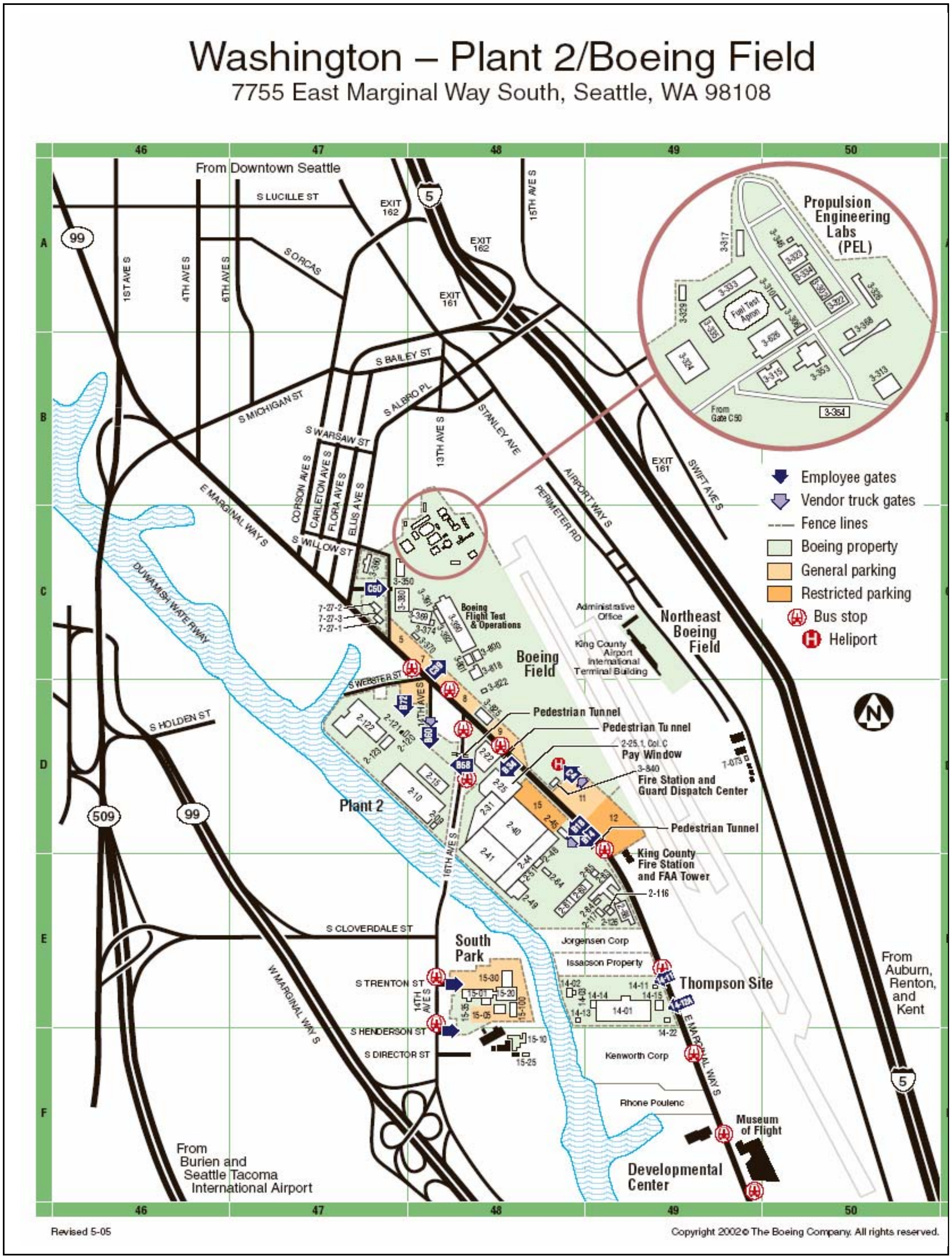
Item 10. The **"Stop Buzzer"** points of contact are:

Name	**Office Desk**	**Mobile**	**Office Pager**
Roger Klinger	206.655.2345		206.797.7101
Dan Downey	206.655.6030		206.797.7083
Janet S Booth	206-655-0566	425-308-0397	

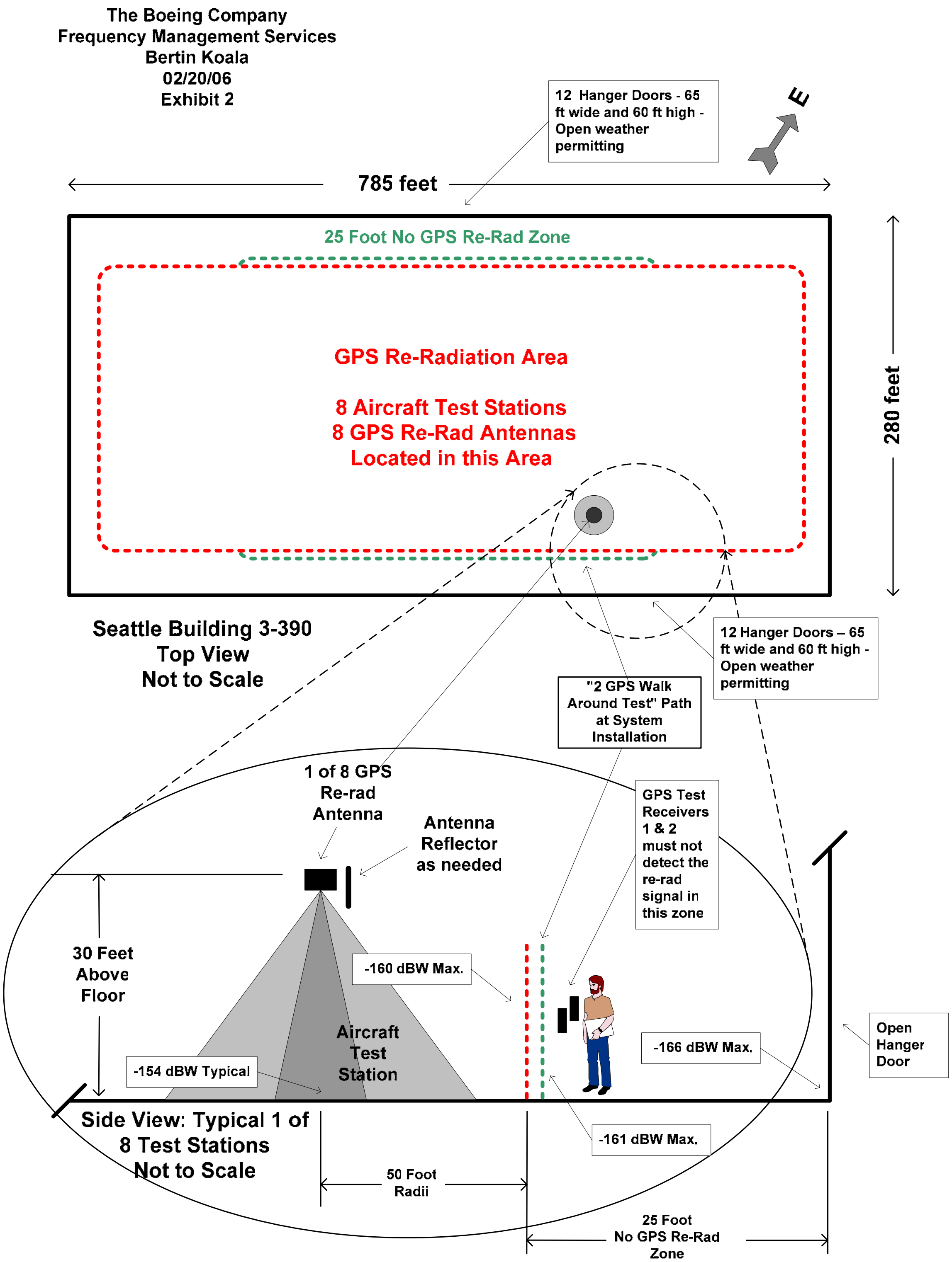
Boeing wishes to acknowledge significant contributions to this document:

Agilent Technologies, RF and Microwave Applications Support
James W. Daniels, Engineer, Electromagnetics, Boeing
James E. Hamlin P.E., Electromagnetics, Boeing
Robert Howard, Panasonic USA
Jason A. Koehn, RF / Microwave and Antenna Metrology, Boeing
Dennis Lewis, Engineer RF / Microwave and Antenna Metrology, Boeing
Glen A. Seganfredo, Boeing
Brian E. Ward, Electromagnetics, Boeing
Frank L Whetten, PhD., Connexion by Boeing
Ted Ueno, Panasonic, Japan

Appendix 1: Boeing field 3-390 Building Location



Appendix 2- GPS layout description for 3-390 building



Appendix A

The bandwidth and emission is best described as 20M4W7D. Our logic for this choice follows.

The GPS signal is actually 20.4 MHz wide, so re-radiating bandwidth should also be the same, 20M4.

The emission part is more complex. It depends on the FCC definition for phase modulation and the number of channels being applied.

Before considering the first emission symbol, we must look at the second symbol. We believe that there are two bit streams for L1, one for the C/A code and the other for the P(Y) code. Each bit stream can be thought of as a channel if we use the FCC definition. According to NAVSTAR documents, the bit streams are combined, with the L1 carrier being offset by 90 degrees from the P(Y) code. The output is a single carrier (L1) that is phase modulated using bi-phase shift keying (BSPK) of the combined bit streams. The spectral view is a C/A code with 2.046 MHz wide and a P(Y) code that is 20.46 MHz wide, both centered on the L1 carrier of 1575.42 MHz. So, 2 channels and therefore the second emission symbol is 7, meaning 2 or more channels.

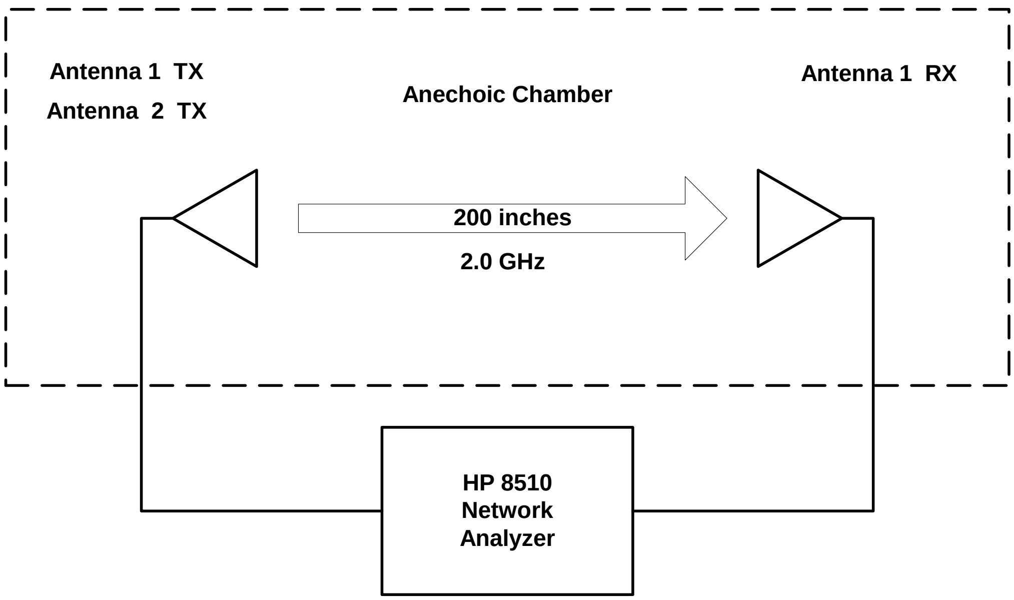
Using G (phase) as the first symbol of the emission designator is a simplistic description and somewhat correct. However, we see it defined as simple phase modulation of a single data channel. While W ("Cases not covered, in which an emission consists of the main carrier modulated, either simultaneously or in pre-established sequence, in a combination of two or more of the following modes: amplitude, angle, pulse.") describes a 2 or more channel modulation stream. We believe that W would be a better choice.

The third emission symbol is D, data. It speaks for itself.

With regard on how we considered isotopic antenna gain

The purpose of the empirical measurement is to validate that a 6 dBi change using two different transmitting antennas produces a corresponding 6 dB change in the receive antenna power regardless of the unit reference.   This proves that the 3 dBi transmit antenna gain can be computed as an absolute 3 dB, allowing us to calculate the RF power (P_t) into the antenna indirectly.

TX-1 and RX-1 Antenna horns are Scientific Atlanta 12.1.7 with a gain that is +/- 0.5 dB.
TX-2 Antenna horn is an EMCO 3115 with a gain that is +/- 1.0 dB.
All antennas and equipment are within calibration standards and operated within their respective specifications.



<table>
<tr><td rowspan="2">Base Reference Measurement</td><td>TX Horn Antenna-1</td><td>RX Horn Antenna-1</td><td>Reference Level Received RF Power</td><td rowspan="4">6.17 dB</td></tr>
<tr><td>Calibrated 16.0 dBi</td><td>Calibrated 16.1 dBi</td><td>-21.43 dB</td></tr>
<tr><td rowspan="2">Difference Measurement</td><td>TX Horn Antenna-2</td><td>RX Horn Antenna-1</td><td>Reference Level Received RF Power</td></tr>
<tr><td>Calibrated 9.7 dBi</td><td>Calibrated 16.1 dBi</td><td>-27.60 dB</td></tr>
<tr><td colspan="4">6.40 dB</td><td>6 dBi change in antenna yields 6 dB change in RX Power</td></tr>
</table>

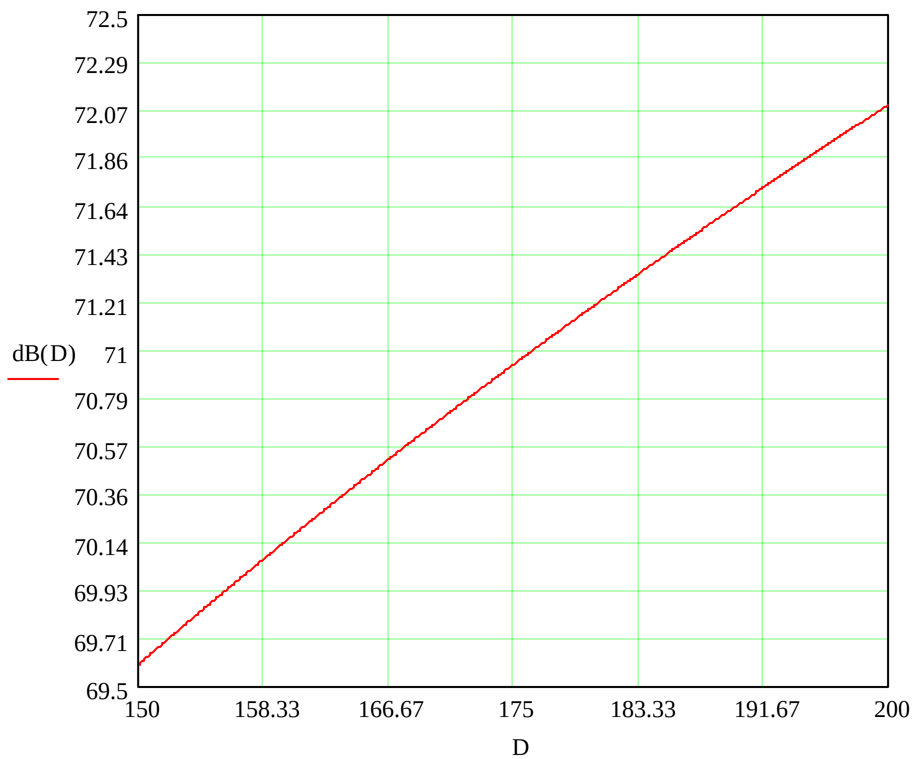
MathCAD Computer Model

MATHCAD COMPUTER MODEL THAT CALCULATES FREE SPACE PATH LOSS OF A GPS SIGNAL OVER DISTANCE EXPRESSED IN MHz, IN THE SELECTED DISTANCE UNIT BY MODIFYING THE EQUATION FOR A PARTICULAR RANGE OF DISTANCE FROM THE ANTENNA.

FREQUENCY MHz	RANGE	CHOOSE ONE	
$F := 1575.00$	$D := 150.0, 150.1 .. 200$	FACTOR MILES	$MI := 36.6$
		FACTOR KILO-METERS	$KM := 32.45$
		FACTOR FEET	$FT := -37.87$
EDIT EQUATION BELOW FOR DISTANCE UNIT		FACTOR METERS	$MT := -27.55$

$$dB(D) := FT + 20 \cdot \log(D) + 20 \cdot \log(F)$$

dB Loss



DISTANCE IN SELECTED UNIT