Generic Earth Station Architecture for CubeSats (GESAC)

Reference Ground Station Hardware Architecture

Revision P1

CCP-CSA-00101-DEV-SP-P1

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REVISION HISTORY

Revision	Revision Date	Author	Review by	Revision Description
P1	2020/01/24	P. Kazakoff		Draft Revision

1.0 APPLICABLE AND REFERENCE DOCUMENTS

1.1 Applicable documents

The requirements contained in the applicable documents listed below shall be complied with. If requirements contained in the applicable documents are conflicting with those present in this document, the latter shall take precedence.

[AD1] CCP-CSA-00058-REQ-P2: GESAC Reference Ground Station Requirements

1.2 Reference documents

[RD1] "Computed Maximum Wind Gust Speeds," National Research Council, February 1958

[RD2] ITU Radio Regulations, Edition of 2016

[RD3] Radio Amateurs of Canada – 2m band plan

[RD4] Radio Amateurs of Canada – 70cm band plan

2.0 INTRODUCTION

2.1 Background

The Generic Earth Station Architecture for CubeSats (GESAC) is a universal reference ground station architecture. It provides support for a superset of up/down frequencies, modulations, and protocols to support Canadian academic CubeSat communications systems. Key features include:

- A novel software defined radio approach which leverages OS containerization to provide a modular, low-impact method to deploy and host all the ground segment software for a particular mission.
- A comprehensive set of documentation and software allowing academic team to build and operate their own ground station using GESAC features with minimal effort.
- Clearly defined RF figures-of-merit (G/T, EIRP) to support the development of link budgets by satellite operators.
- Developed using interchangeable hardware modules wherever it is reasonably possible to do so, enabling customized variants of the GESAC architectures to utilize existing infrastructure.

2.2 Purpose of This Document

This document is intended to capture the high-level hardware architecture for the GESAC prototype. A discussion of the existing ground station located at the John H. Chapman Space Centre is provided for context. Modifications required to convert the ground station to meet the requirements outlined in [AD1] are presented. Finally, calculated figures of merit are provided and compared with the requirements, with any deviations noted and justified.

3.0 EXISTING GROUND STATION

The existing amateur radio ground station installed at the John H. Chapman Space Centre is the result of several years of ad-hoc upgrades. The station, as designed, is primarily intended to support CSA ARISS operations (Amateur Radio on the International Space Station). While CSA ARISS operations currently use other facilities, maintaining FM voice support with the current station for ARISS work remains an important requirement.

A diagram of the existing station as it was configured in July 2019 can be found in Figure 1.

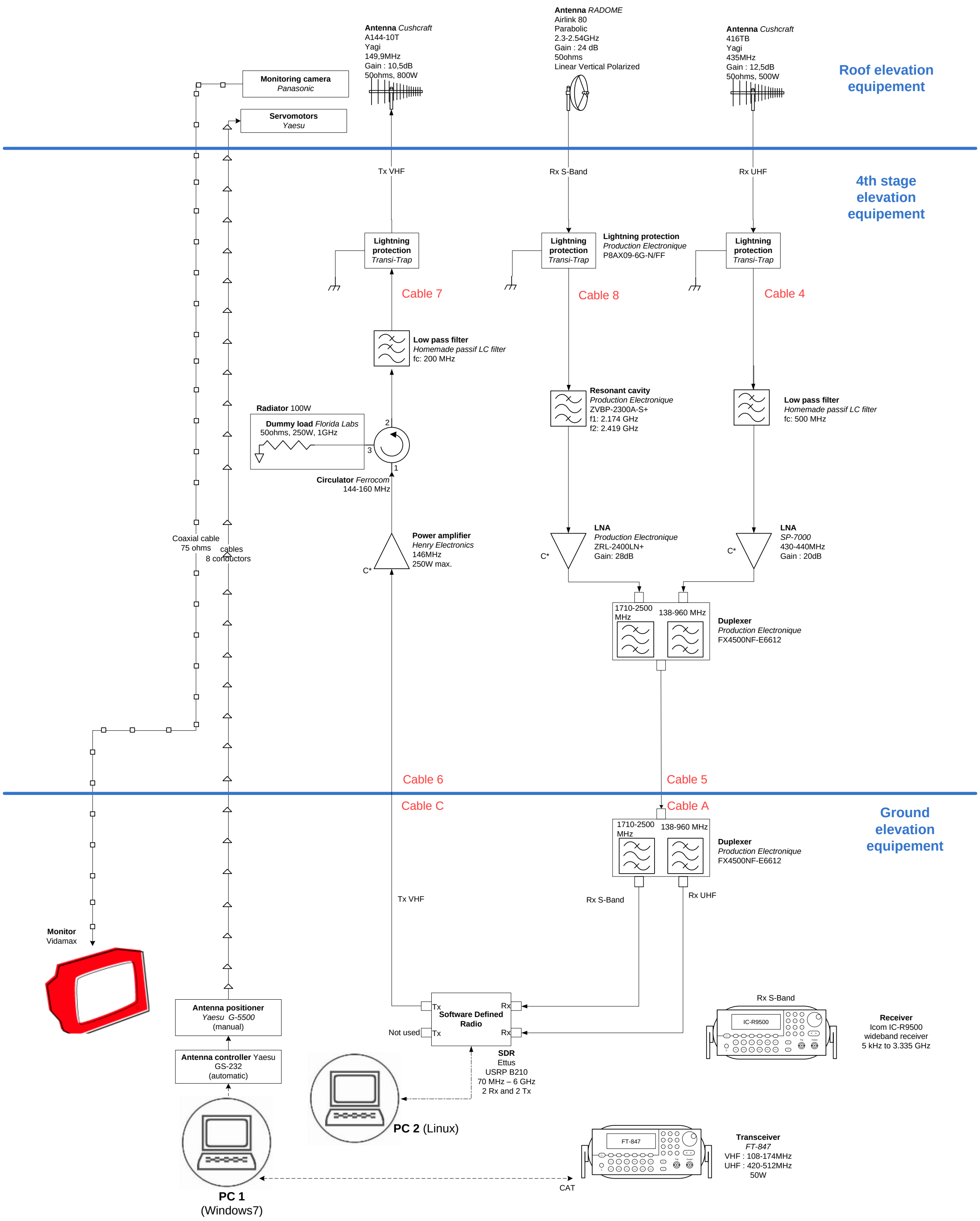


Figure 1 - Existing St-Hubert ground station

The July 2019 configuration is split into three zones: a ground level room containing the radios, PCs, and antenna controller, a rack in a fourth floor machine room containing amplifiers and filters, and a rooftop antenna tower.

The previous supported VHF uplink (nonlinear modulation schemes only), and UHF and S-band downlink. The S-band downlink currently only supported vertical polarization, which limited its usefulness. The primary transceiver was a USRP B210 software defined radio transceiver, with an ICOM FT-847 available as an auxiliary transceiver when needed.

The previous system exhibited several drawbacks which rendered it unsuitable for meeting GESAC requirements:

- Uplink was fixed to the 2 m band, with nonlinear modulation only due to the Class-C amplifier used on the uplink. GESAC requirements specify both UHF and VHF uplink, with linear modulation support for both.
    - Additionally, there was no driver amplifier at the input to the VHF power amplifier, so the USRP was not able to drive it – only the ICOM FT-847 had sufficient output power to drive the amplifier.
- No VHF downlink support was available.
- The antennas had polarization switches fitted, however, they are not connected, so the operator cannot select an antenna polarization on demand.
- There was a long coaxial cable run between the antenna and the UHF LNA on the fourth floor, impacting the system noise figure and thus achievable G/T.
- No duplexing support was provided in to allow for half-duplex in-band operation.

To address these issues, a new ground station architecture is provided in the next section.

4.0 MODIFIED GROUND STATION HARDWARE ARCHITECTURE

A modified ground station architecture was developed to attempt to meet the requirements presented in [AD1]. A schematic is presented in Figure 2 and Figure 3.

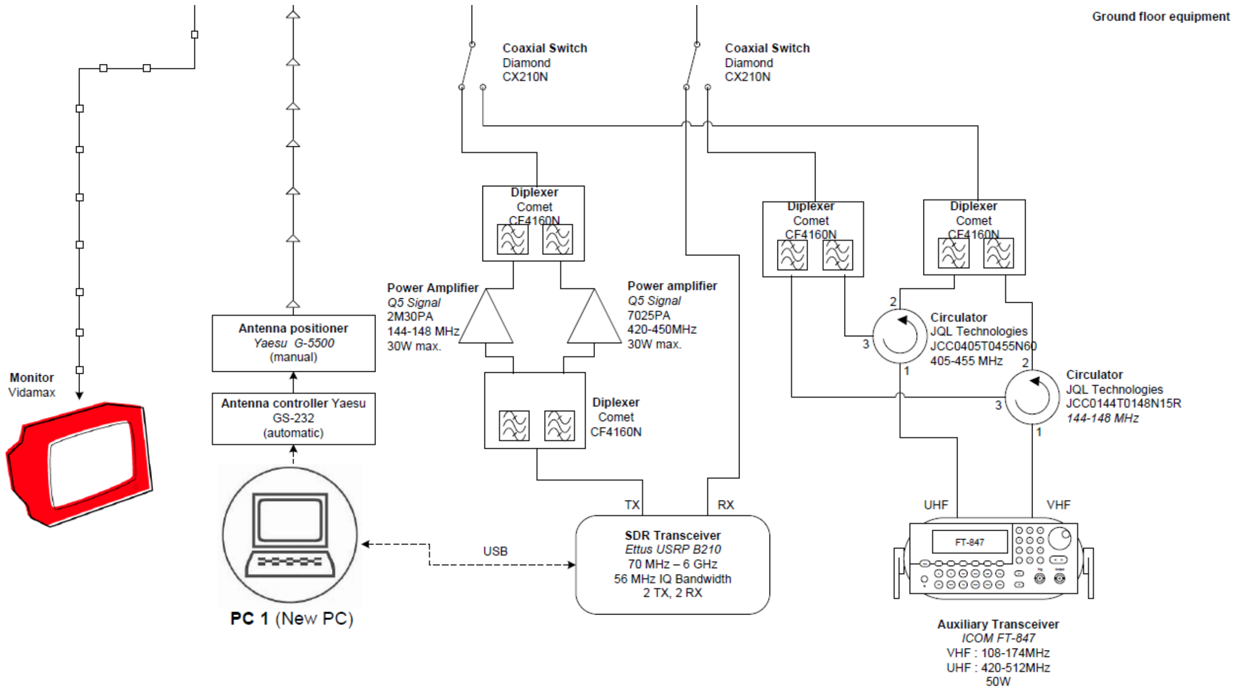


Figure 2: Modified ground station architecture - ground floor

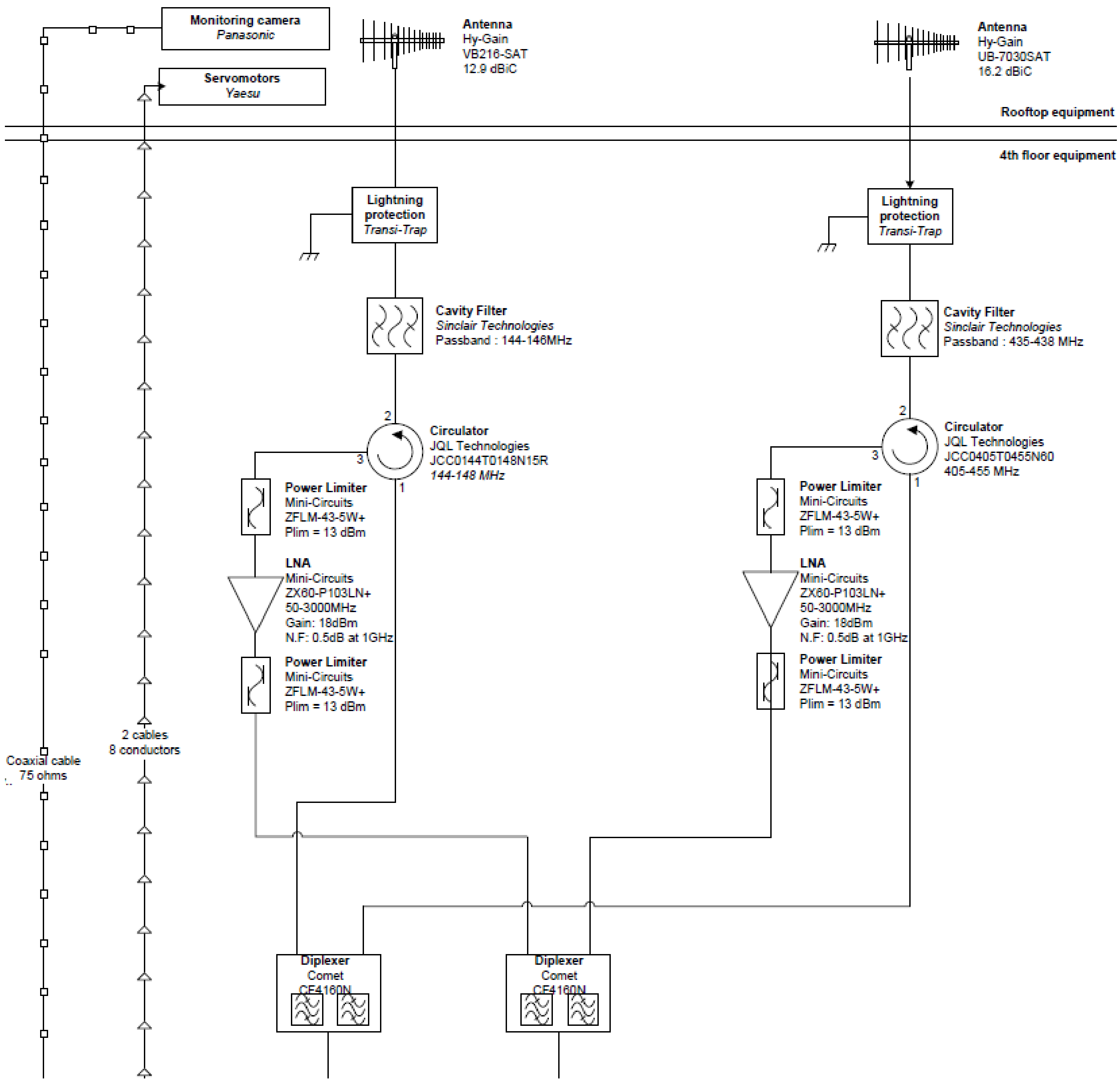


Figure 3: Modified ground station architecture - 4th floor and roof level

This ground station architecture makes several modifications to the original architecture. Key differences include:

- The existing VHF and UHF LMR-400 cable runs have been converted to TX and RX cable runs. VHF and UHF frequency separation is now performed using diplexers, not dedicated cables.
- High-Q cavity preselector filters have been added on the fourth floor to remove adjacent-channel interference and to optimize received noise figure by minimizing insertion loss prior to the LNA.
- Circulators are installed at each antenna to enable in-band half-duplex operation. As the circulators have only around 20 dB of isolation, PIN limiters are installed on the LNA inputs to protect them from damage.

- The class-C amplifier from the VHF path has been removed, and new 25 and 30 watt linear amplifiers for UHF and VHF have been installed at ground level.
- Manual SPDT RF switches allow the FT-847 to be switched in.
    - Since the FT-847 includes a built-in power amplifier, the PAs are bypassed in this mode.
    - As the FT-847 has separately switched UHF and VHF ports, these are converted to TX/RX through the use of two circulators and two diplexers.

4.1 Estimated Performance Metrics

The most critical figures-of-merit from the requirements (G/T and EIRP) are computed in the subsequent sections and compared against the nominal requirements.

4.1.1 VHF System G/T (GS-ANT-030)

From the VB-216SAT datasheet, the antenna gain is given as 10.7 dBd, and the beamwidth as 40-43 degrees in the E-plane and 50 degrees in the H-plane.

Antenna gain in dBi can be computed as:

$$G(dBi) = G(dBd) + 2.15 = 10.7 + 2.15 = 12.85\ dBi$$

A proper antenna temperature calculation requires multiplying the antenna gain and far-field noise temperature at each point and integrating over the entire unit sphere. However, we can arrive at a conservative approximation by the following procedure:

1. Compute the beamwidth of the antenna and assume a conical radiation pattern in the direction the antenna is pointed.
2. At the lowest elevation angle, find the portion of the cone which intersects with the unit sphere (a spherical cap).
3. Determine the solid angle of the portion of the spherical cap above the horizon, and the solid angle of the portion below the horizon.
    a. For the portion above the horizon, compute the sky temperature due to galactic noise (no-sun case).
    b. For the portion above the horizon, compute the sky temperature in the beam by taking into account the presence of the sun in the beam as well as galactic noise (sun case).
    c. For the portion below the horizon, assume a standard reference ground temperature of 290 K (both cases), plus a site-specific contribution due to city noise.
4. Perform an average (weighted by solid angle) of the portion above and below the horizon, for both the no-sun and sun cases. This is the ideal noise temperature excluding sidelobes.
5. Using the antenna temperature calculated in (4), compute the antenna's G/T for the sun and no-sun cases.

The beamwidth of the antenna is asymmetrical in the E- and H-planes (40-43 degrees in E, 50 degrees in H). To simplify the calculation we will assume that the E-plane and H-plane beamwidths are both equal to

50 degrees. Taking this beamwidth as the apex angle of the spherical cap which subtends the unit sphere surrounding the antenna, we have:

$$\theta = \frac{\theta_{beam}}{2} = 25°$$

$$\Omega_{beam} = 2\pi(1 - \cos\theta) = 0.5887\ sr$$

As per requirement GS-ANT-030, the minimum elevation angle is 5° above the horizon. Since we know the beamwidth, we can check if part of the beam includes the portion of the unit sphere below the horizon by:

$$\frac{\theta_{beam}}{2} \overset{?}{>} \theta_{elev}$$

$$25° > 5°$$

Thus, we know that part of the beam includes the ground, and we must account for ground temperature. We can calculate the solid angle of the portion of the beam above the horizon by using the formula for a spherical cap cut by a plane:

$$\Omega_{above} = 2\left[\cos^{-1}\left(\frac{\sin\gamma}{\sin\theta}\right) - \cos\theta\cos^{-1}\left(\frac{\tan\gamma}{\tan\theta}\right)\right]$$

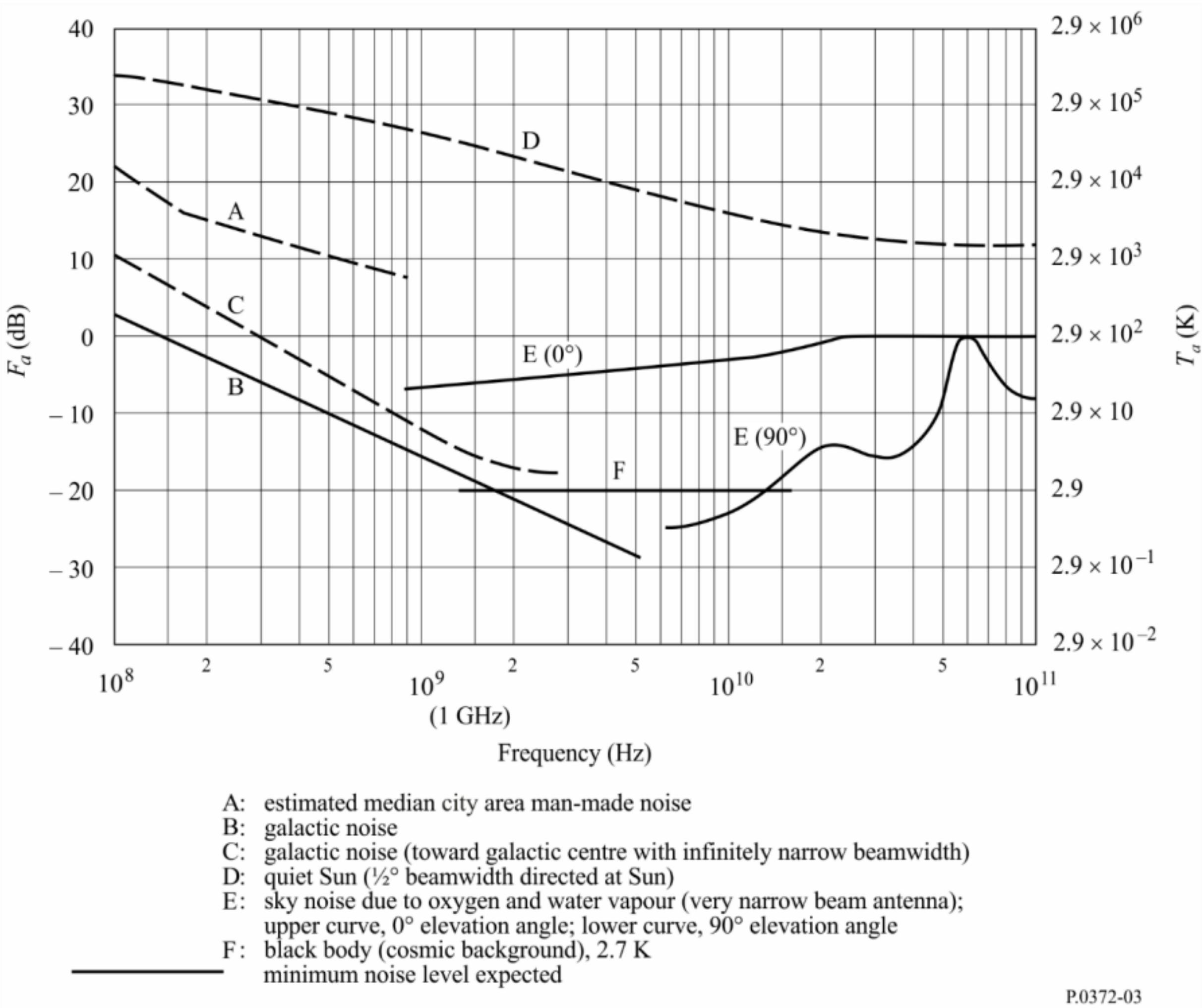
where $\gamma = -\theta_{elev} = -5° = -\frac{\pi}{36} rad$ and θ is the previously calculated half angle $\theta = 25° = \frac{5\pi}{36}\ rad$. The result of the above equation yields $\Omega_{above} = 0.3677\ sr$.

As we have the total solid angle subtended by the beam as well as the portion above the horizon, we can compute the portion below the horizon as:

$$\Omega_{below} = \Omega_{beam} - \Omega_{above} = 0.5887 - 0.3677 = 0.2210\ sr$$

We now need to know two pieces of information: the maximum sky temperature without the sun, and the maximum sky temperature including the sun. Reasonable approximations to these values can be obtained from ITU-R P.372-14, “Radio Noise.” We refer to Figure 3 from that standard, which is reproduced below.

F_a versus frequency (10^8 to 10^{11} Hz)



The dominant component of the sky noise is represented by line D, which provides the brightness temperature of the galaxy other than the galactic core. While using line C (galactic noise towards the galactic core) would be more conservative, using the overall galactic brightness temperature is more realistic as the angular extent of the galactic core is small. Picking the point off the graph using a plot digitizer, the galactic temperature at 140 MHz is approximately 313 K. Atmospheric noise can be neglected in the sub-GHz regime, as galactic noise dominates. Thus, we assume for the purposes of the analysis that the brightness temperature of the sky outside the sun is uniformly 313 K everywhere at 140 MHz. In reality, this temperature will only be reached when pointing towards the galactic ecliptic, but this is a conservative approximation for our purposes.

The brightness temperature of the quiet sun is given by line A. While the sun temperature will be higher during solar storms, this is an acceptable estimate for this analysis as the angular extent of the sun is small relative to beam width. Since the sun’s solid angle is so small relative to the beamwidth, it contributes minimally to G/T despite its very high brightness temperature.

Using a plot digitizer to pick a point off the graph, the brightness temperature of the sun at 140 MHz is approximately 610000 K.

The noise contribution of the galactic sky noise to the overall beam is thus:

$$\Delta T_{sky} = \frac{\Omega_{above}}{\Omega_{beam}} T_b = \frac{0.3677\ sr}{0.5887\ sr} \times 313\ K = 195\ K$$

To determine the brightness temperature of the portion of the sky below the beam, we once again refer to ITU-R P.372-14. While we could make the blanket assumption that the ground below the horizon is at the earth standard temperature of 290 K, this would be an underestimate. There is significant man-made noise (both intentional and unintentional) in the VHF band. The standard offers an approximation for the noise factor F_{am} for an outdoor environment in the frequency range 0.3 to 250 MHz:

$$F_{am} = c - d \log f$$

The factors c and d are determined empirically and given by a table, and f is the frequency in MHz. The standard provides four environments: city, residential, rural, and quiet rural. John H. Chapman Space Centre is located at the northeast corner of the St-Hubert Airport, approximately 1.5 km from the residential suburb of St-Bruno-de-Montarville to the east and approximately 1.0 km from the Longueuil borough of St-Hubert to the south. The vast majority of the area visible from the antenna site is farmland. Thus, the most appropriate category for this analysis is likely “rural.” In this case, $c = 67.2$ and $d = 27.7$. Using $f = 140\ MHz$, we obtain $F_{am} = 7.8\ dB$. F_{am} can be converted to a noise temperature by:

$$T = T_0 10^{\frac{F_{am}}{10}}$$

In the above equation, T_0 is the standard reference temperature of 290 K. Evaluating the expression yields $T = 1728\ K$.

The noise contribution of the ground below the horizon in the beam is simply:

$$\Delta T_{ground} = \frac{\Omega_{below}}{\Omega_{beam}} T_b = \frac{0.2210\ sr}{0.5887\ sr} \times 1728\ K = 649\ K$$

The total noise temperature in the beam, excluding the sun, is the sum of the two components:

$$T_{beam(no\ sun)} = 195\ K + 649\ K = 844\ K$$

To add the sun component, we need to multiply the sun’s brightness temperature by the ratio of the sun’s solid angle to the solid angle of the beam. Given the sun’s angular diameter of 0.53°, the solid angle occupied by the sun in the sky can be calculated as:

$$\Omega_{sun} = 2\pi(1 - \cos\theta) = 2\pi\left(1 - \cos\frac{0.53°}{2}\right) = 6.7 \times 10^{-5}\ sr$$

The additional noise temperature contribution from the sun is thus:

$$\Delta T_{sun} = \frac{\Omega_{sun}}{\Omega_{beam}} T_b = \frac{6.7 \times 10^{-5}\ sr}{0.5887\ sr} \times 610000\ K = 69\ K$$

Thus, our noise temperature when the sun is in the beam is given as:

$$T_{beam(sun)} = 844\ K + 69\ K = 913\ K$$

We can use the 844 K computed previously as $\Omega_{sun} \ll \Omega_{sky}$. Thus, we can neglect the slight effective difference in Ω_{sky} when the sun is in the beam.

The final step in determining our effective antenna temperature is the influence of sidelobes. In this case, we can make the assumption that since the main lobe is so wide and contains a significant fraction of the horizon, noise contribution from the sidelobes is neglibible. Thus,

$$T_{ant} = T_{beam}$$

Our antenna temperature is therefore approximately 844 K in the no-sun case and 913 K in the sun case.

The next piece of information required to determine system G/T is the effective noise temperature of the receiver, which can be derived from the noise figure cascade between the antenna and the receiver. The noise figure at the output of the low noise amplifier can be considered the system noise figure, as the gain of the amplifier dominates the noise figure of subsequent stages.

Between the antenna and the LNA, there are a series of passive devices:

- A cable run of approximately 30 m of Times Microwave LMR-600, with approximately 1.0 dB of insertion loss at 150 MHz
- A preselector filter (Sinclair model PH2040E-1-2) with approximately 1.0 dB of insertion loss
- A circulator (JQL model JCC0144T0148N15R) with approximately 0.4 dB of insertion loss
- A power limiter (Mini-Circuits model ZFLM-43-5W+) with approximately 0.2 dB of insertion loss

Since these devices are all approximately at room temperature, they can be lumped together into a single passive device before the LNA for the purpose of cascade analysis:

$$L_{total} = 1.0\ dB + 1.0\ dB + 0.4\ dB + 0.2\ dB = 2.6\ dB$$

The equivalent noise factor of a two-element cascade is given from Friis' equation as:

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1}$$

For a passive device at room temperature, noise figure in dB is equal to insertion loss. Thus, the linear noise factor for the passive devices is:

$$F_1 = 10^{\frac{2.6}{10}} = 1.82$$

The gain of the passive stage is given by:

$$G_1 = 10^{\frac{-2.6}{10}} = 0.55$$

The LNA is a Mini-Circuits model ZX60-P103LN+ with a noise figure of approximately 0.6 dB. This can be expressed in terms of noise factor as:

$$F_2 = 10^{\frac{0.6}{10}} = 1.15$$

Thus, the noise factor between the antenna and the LNA output is:

$$F_{total} = 1.82 + \frac{1.15 - 1}{.55} = 2.10$$

The equivalent noise temperature is:

$$T_{rx} = 290\ K \times (F_{total} - 1) = 319\ K$$

Assuming a near-perfect antenna efficiency, the total system noise temperature is given by:

$$T_{sys} = T_{ant} + T_{rx}$$

Which works out to 1163 K for the no-sun case, and 1232 K for the sun case.

Finally, we can determine our system G/T in decibels by:

$$G/T_{sys} = G_{ant} - 10\log T_{sys}$$

Evaluating the above for an antenna gain of 12.85 dBi yields a G/T of **-17.8 dB/K** for the no-sun case and **-18.1 dB/K** for the sun case.

This design thus fails to meet the target requirement for VHF G/T (GS-ANT-030) by approximately 2.8 dB in the no-sun case and 3.1 dB in the sun case. This deviation is discussed later in this report.

4.1.2 UHF System G/T (GS-ANT-040)

The UHF G/T calculation steps are essentially identical to the previous section, with the following changes:

- The antenna is a Hy-Gain UB7030SAT with 14.0 dBd (16.15 dBi) of gain and a 30 degree beamwidth.
- Figures for brightness temperature of galactic and sun noise were taken at 437 MHz from ITU-R P.372-14.
- As the extrapolation for man-made noise temperature is not valid above 300 MHz, $F_{am} = 3\ dB$ for 425 MHz was taken from Table 3 in P.372-14.
- Cascade losses were computed considering the additional cable run loss at UHF as well as the particular UHF circulator and filter in-use.

Performing these calculations yields a G/T of approximately **-13.1 dB/K** in the no-sun case and **-13.5 dB/K** in the sun case.

This design thus fails to meet the target requirement for UHF G/T (GS-ANT-040) by approximately 3.1 dB in the no-sun case and 3.5 dB in the sun case. This deviation is discussed later in the report.

4.1.3 VHF EIRP (GS-RF-100)

The VHF EIRP can be computed as:

$$EIRP = P_{PA} - Losses + G_{Ant}$$

The first term, the PA power, is constrained by requirement GS-RF-120, which states that the amplifier must be backed off at least 3 dB from its 1 dB compression point (P1dB) to ensure sufficient transmit linearity.

The amplifier selected is the Q5 Signal (formerly DEMI) 2M30PA 30 watt linear 2 meter band RF amplifier. To verify suitability to meet this requirement, the PA linearity was subjected to a single-tone test in the CSA RF engineering laboratory. The image below illustrates the test setup.

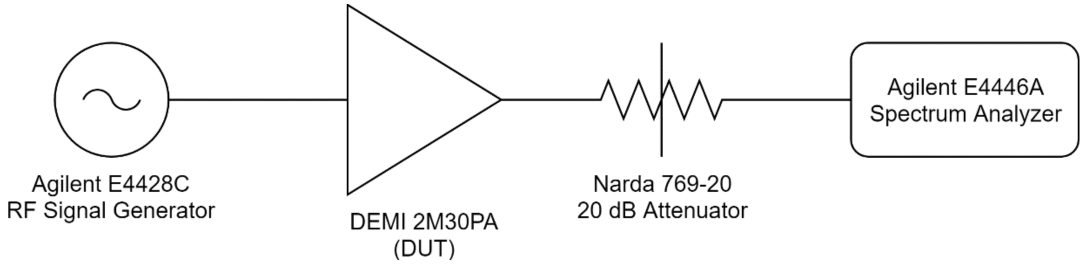


Figure 4: VHF gain compression test setup

The test was conducted by injecting a 146 MHz tone into the amplifier with the signal generator. The amplifier input power was swept while measuring the output power at the spectrum analyzer. The result, corrected to remove the influence of the attenuator, is given in the figure below. An extrapolation of the small-signal gain is also provided on the graph to illustrate deviation from ideal linear gain.

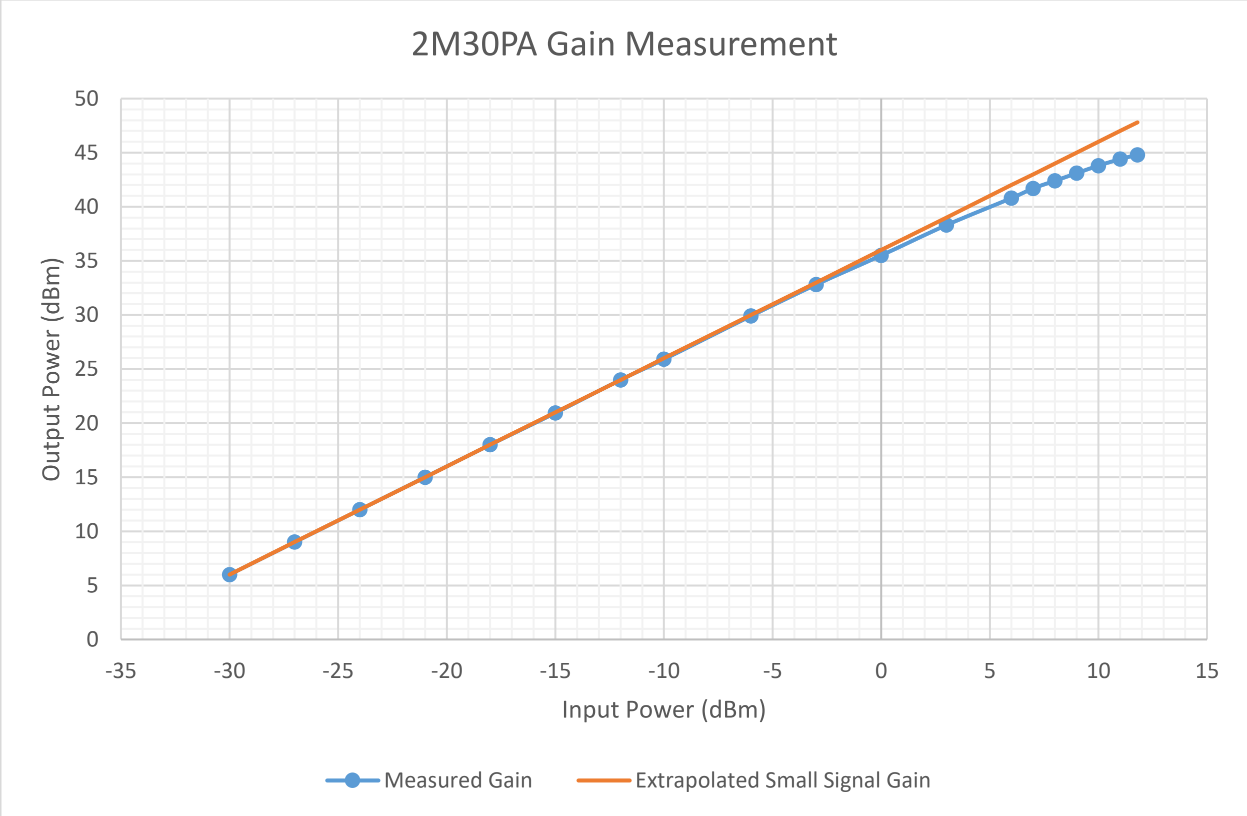


Figure 5: 2M30PA gain measurement

The same data is plotted below as a function of output power compared to realized gain. The dotted line in the below figure indicates where the amplifier deviates by 1 dB from the linear gain. The point at which the data series crosses the horizontal line is the P1dB point.

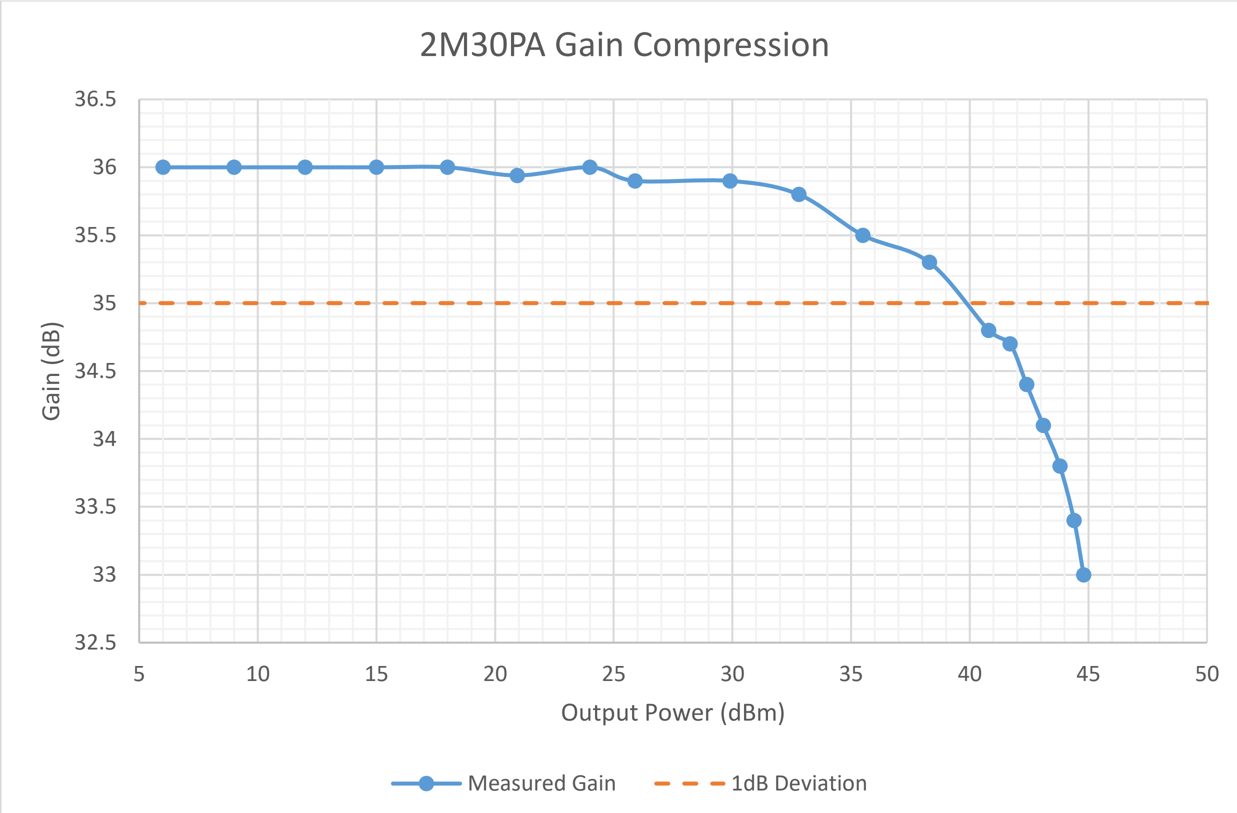


Figure 6: 2M30PA gain compression

The amplifier appears to have a 1 dB compression point of approximately 40 dBm, or 10 watts in linear units. Note that the datasheet for this amplifier indicates that the P1dB is ideally 30 watts (44.8 dBm), about 5 dB higher than measured.

This may be explained by the bias point of the amplifier – the amplifier draws approximately 2.3 A quiescent drain current, when the datasheet states that a value in the 3-6 A range is considered normal. Thus, to achieve the datasheet P1dB value, the bias point may need to be adjusted by modifying the voltage divider at the bias pin of the amplifier. However, this is considered an optional activity for the future, since this P1dB point is still sufficient to meet GESAC requirements as-is.

As requirement GS-RF-120 states the amplifier must be operated with at least 3 dB backoff from its P1dB, we can calculate the maximum operational power output of the amplifier in the system as:

$$P_{PA} = P1dB - 3dB = 40\ dBm - 3\ dB = 37\ dBm$$

The next step in determining the EIRP is accounting for the losses between the amplifier and the antenna input. The following losses are considered in the system:

- Connector losses
- Losses in the coaxial switch used to transfer to the auxiliary ICOM radio
- Cable run losses
- Lightning arrester losses
- Diplexer losses
- Circulator losses

- Filter losses

There are a total of 14 N-type connectors between the amplifier and the antenna. In general, a properly crimped N-type connector will have well under 0.05 dB of insertion loss at all frequencies below 1 GHz. We can thus conservatively approximate the connector losses as:

$$L_{conn} = 0.05 \times 14 = 0.7\ dB$$

The coaxial switch, a Diamond CX210N, specifies a maximum insertion loss of less than 0.05 dB below 500 MHz.

$$L_{sw} = 0.05\ dB$$

The cable run between the first floor radio room and the rooftop is long, approximately 80 meters of Times Microwave LMR-600 coaxial cable. Note that this figure is a conservative estimate – the cable is likely shorter, but TDR measurements of the cable length have not been done to arrive at a more precise figure. As per the datasheet for LMR-600, the attenuation is approximately 3.2 dB/100 m at 150 MHz (ie: 0.032 dB/m). We can estimate cable losses as:

$$L_{cable} = 80\ m \times 0.032 \frac{dB}{m} = 2.7\ dB$$

There are short (1-2 m) patch runs of RG-58 cable connecting adjacent components, however, the losses of these runs are negligible compared to the long run of LMR-600.

The lightning arrester, a Transi-Trap TT3G50, has an insertion loss of less than 0.1 dB under 1 GHz as per the datasheet:

$$L_{SA} = 0.1\ dB$$

There are two diplexers in the system, both model CF-4160N from Comet. The manufacturer gives the insertion loss as less than 0.1 dB below 170 MHz on its website. Thus, the expected insertion loss from both diplexers is:

$$L_{DP} = 2 \times 0.1\ dB = 0.2\ dB$$

The circulator, a JQL JCC0144T0148N15R, has an insertion loss of 0.4 dB as per the datasheet.

$$L_{circ} = 0.4\ dB$$

The cavity filter, a Sinclair PH2040E-1-2, states a maximum insertion loss of 1.0 dB in the passband.

$$L_{filt} = 1.0\ dB$$

The total loss is thus:

$$L_{total} = L_{conn} + L_{sw} + L_{cable} + L_{SA} + L_{DP} + L_{circ} + L_{filt} = 5.15\ dB$$

The last element required to determine the EIRP is the antenna gain. The antenna is a Hy-Gain VB-216SAT with 10.7 dBd of gain. We can convert the dBd gain to dBi by:

$$G(dBi) = G(dBd) + 2.15 = 10.7 + 2.15 = 12.85\ dBi$$

As the beamwidth of the antenna is very wide (>40 degrees), it is not necessary to degrade the gain to account for pointing loss. Pointing losses will be negligible in such a large beamwidth.

The EIRP can finally be computed by:

$$EIRP = P_{PA} - Losses + G_{Ant} = 37\ dBm - 5.15\ dB + 12.85\ dBi = 44.7\ dBm$$

The required EIRP is 39 dBm as per requirement GS-RF-100. Thus, GESAC meets this requirement with approximately 5-6 dB of margin.

4.1.4 UHF EIRP (GS-RF-110)

The procedure for determining the UHF EIRP is essentially identical to the VHF case. The UHF EIRP can be computed as:

$$EIRP = P_{PA} - Losses + G_{Ant}$$

The first term, the PA power, is constrained by requirement GS-RF-130, which states that the amplifier must be backed off at least 3 dB from its 1 dB compression point (P1dB) to ensure sufficient transmit linearity.

The amplifier selected is the Q5 Signal (formerly DEMI) 7025PA 30 watt linear 70cm band RF amplifier. To verify suitability to meet this requirement, the PA linearity was subjected to a single-tone test in the CSA RF engineering laboratory. The image below illustrates the test setup.

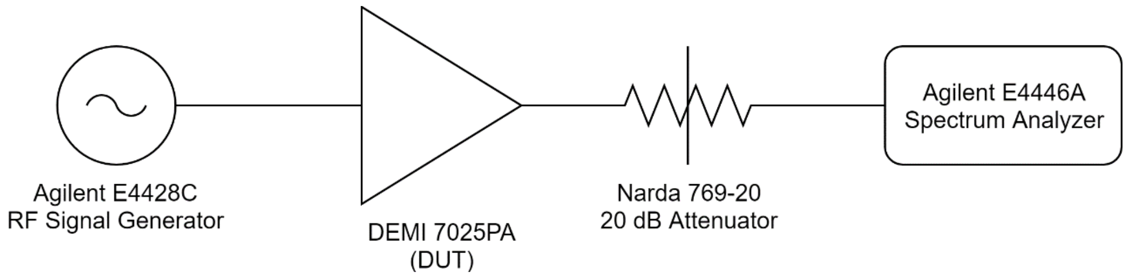


Figure 7: UHF gain compression test setup

The test was conducted by injecting a 437.6 MHz tone into the amplifier with the signal generator. The amplifier input power was swept while measuring the output power at the spectrum analyzer. The result, corrected to remove the influence of the attenuator, is given in the figure below. An extrapolation of the small-signal gain is also provided on the graph to illustrate deviation from ideal linear gain.

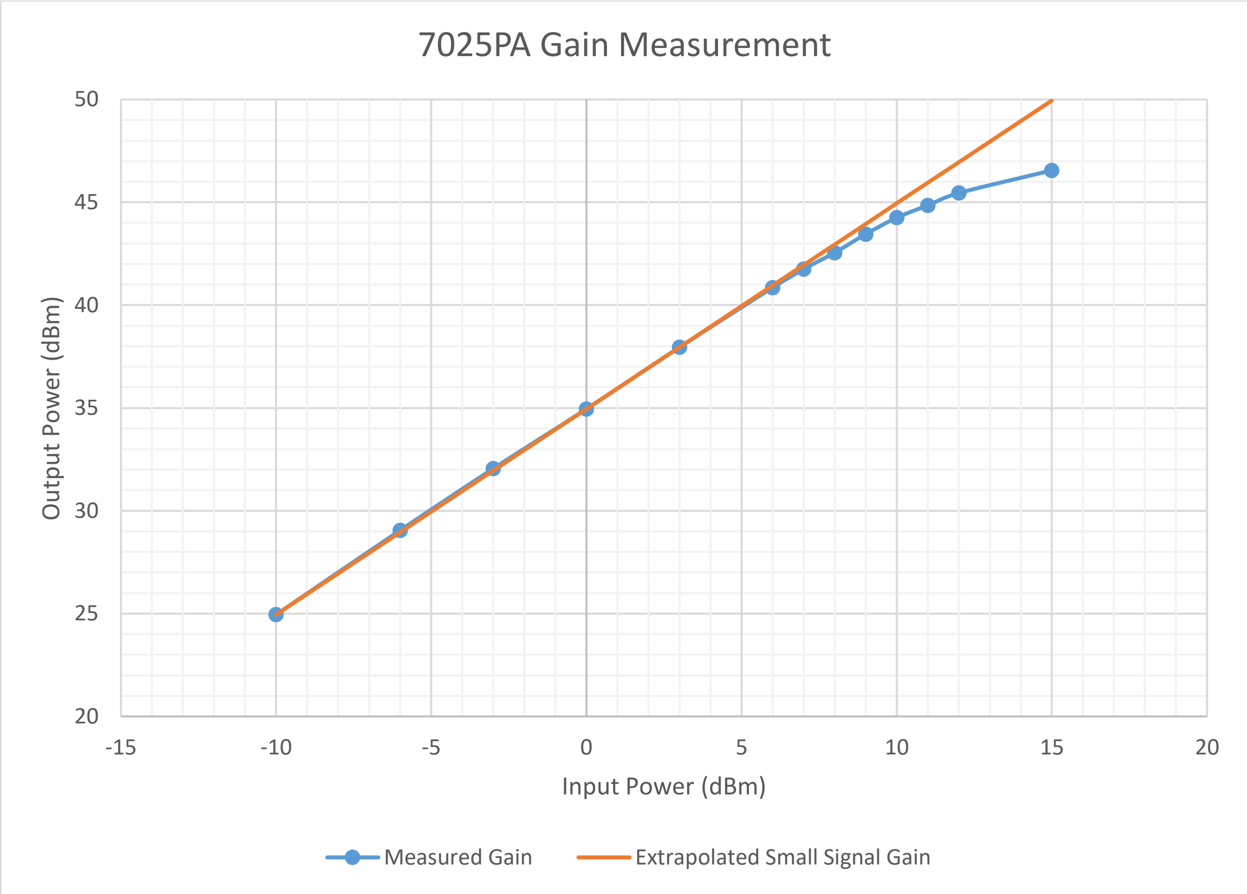


Figure 8: 7025PA gain measurement

The same data is plotted below as a function of output power compared to realized gain. The dotted line in the below figure indicates where the amplifier deviates by 1 dB from the linear gain. The point at which the data series crosses the horizontal line is the P1dB point.

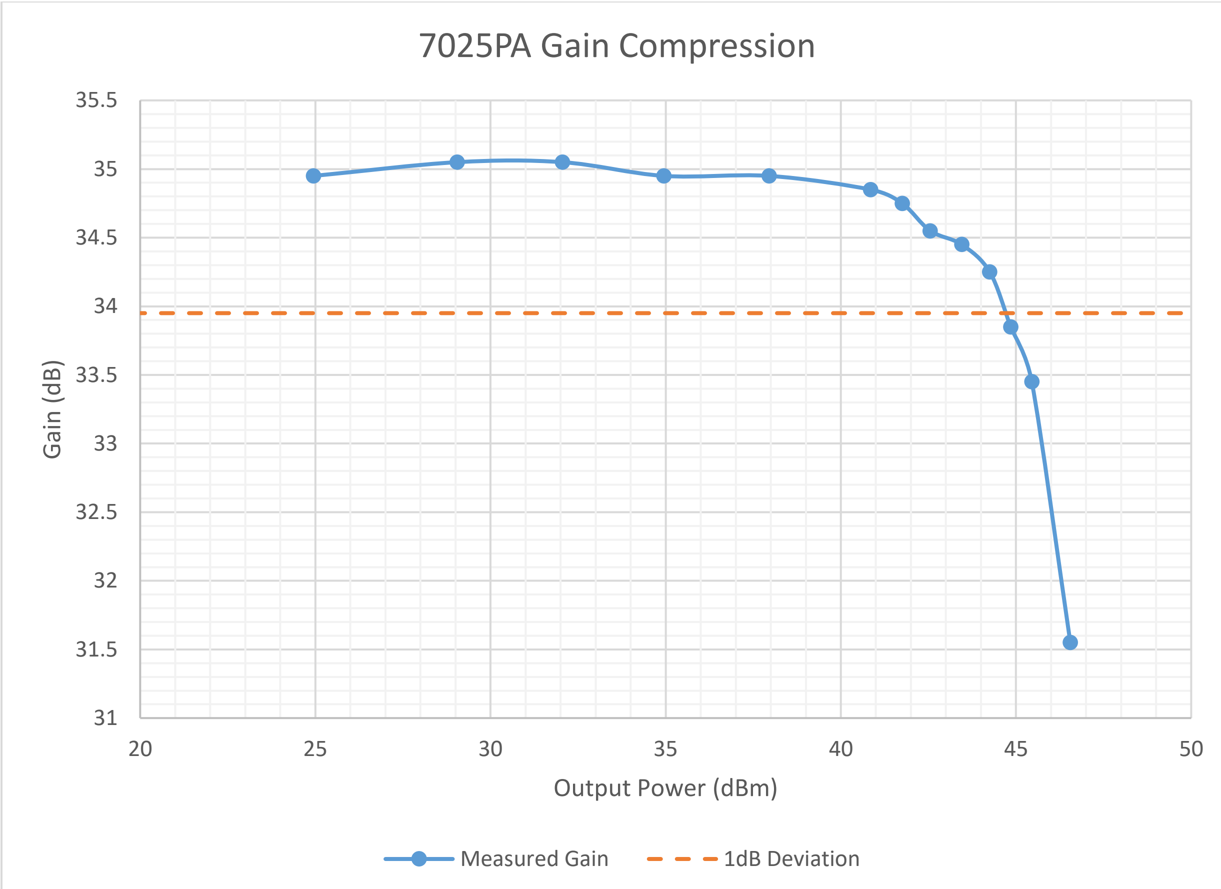


Figure 9: 7025PA gain compression

The amplifier appears to have a 1 dB compression point of approximately 44.5 dBm, or 28 watts in linear units. This agrees with the datasheet which specifies a 1 dB compression point of 25 watts, or 44.0 dBm.

As requirement GS-RF-120 states the amplifier must be operated with at least 3 dB backoff from its P1dB, we can calculate the maximum operational power output of the amplifier in the system as:

$$P_{PA} = P1dB - 3dB = 44.5\ dBm - 3\ dB = 41.5\ dBm$$

The next step in determining the EIRP is accounting for the losses between the amplifier and the antenna input. The following losses are considered in the system:

- Connector losses
- Losses in the coaxial switch used to transfer to the auxiliary ICOM radio
- Cable run losses
- Lightning arrester losses
- Diplexer losses
- Circulator losses
- Filter losses

There are a total of 14 N-type connectors between the amplifier and the antenna. In general, a properly crimped N-type connector will have well under 0.05 dB of insertion loss at all frequencies below 1 GHz. We can thus conservatively approximate the connector losses as:

$$L_{conn} = 0.05 \times 14 = 0.7\ dB$$

The coaxial switch, a Diamond CX210N, specifies a maximum insertion loss of less than 0.05 dB below 500 MHz.

$$L_{sw} = 0.05\ dB$$

The cable run between the first floor radio room and the fourth floor is long, approximately 80 meters of Times Microwave LMR-600 coaxial cable. Note that this figure is a conservative estimate – the cable is likely shorter, but TDR measurements of the cable length have not been done to arrive at a more precise figure. As per the datasheet for LMR-600, the attenuation is approximately 5.6 dB/100 m at 450 MHz (ie: 0.056 dB/m). We can estimate cable losses as:

$$L_{cable} = 80\ m \times 0.056 \frac{dB}{m} = 4.5\ dB$$

There are short (1-2 m) patch runs of RG-58 cable connecting adjacent components, however, the losses of these runs are negligible compared to the long run of LMR-600.

The lightning arrester, a Transi-Trap TT3G50, has an insertion loss of less than 0.1 dB under 1 GHz as per the datasheet:

$$L_{SA} = 0.1\ dB$$

There are two diplexers in the system, both model CF-4160N from Comet. The manufacturer gives the insertion loss as less than 0.2 dB in the 350-540 MHz range on its website. Thus, the expected insertion loss from both diplexers is:

$$L_{DP} = 2 \times 0.2\ dB = 0.4\ dB$$

The circulator, a JQL JCC0405T0455N60, has an insertion loss of 0.25 dB as per the datasheet.

$$L_{circ} = 0.25\ dB$$

The cavity filter, a Sinclair PH3040E-1-3, states a typical insertion loss of 1.0 dB in the passband. As this is a typical value, not a minimum, the insertion loss was tested on the actual filter purchased for use using an Agilent E8363B Vector Network Analyzer and was confirmed to be under the 1.0 dB specification. To be conservative, the manufacturer’s value was used here.

$$L_{filt} = 1.0\ dB$$

The total loss is thus:

$$L_{total} = L_{conn} + L_{sw} + L_{cable} + L_{SA} + L_{DP} + L_{circ} + L_{filt} = 7.0\ dB$$

The last element required to determine the EIRP is the antenna gain. The antenna is a Hy-Gain UB-7030SAT with 14.0 dBd of gain. We can convert the dBd gain to dBi by:

$$G(dBi) = G(dBd) + 2.15 = 14.0 + 2.15 = 16.15\ dBi$$

As the beamwidth of the antenna is very wide (approximately 30 degrees), it is not necessary to degrade the gain to account for pointing loss. Pointing losses will be negligible in such a large beamwidth.

The EIRP can finally be computed by:

$$EIRP = P_{PA} - Losses + G_{Ant} = 41.5\ dBm - 7.0\ dB + 16.15\ dBi = 50.7\ dBm$$

The required EIRP is 48 dBm as per requirement GS-RF-110. Thus, GESAC meets this requirement with approximately 3 dB of margin.

4.2 Design Deviation Discussion

4.2.1 VHF G/T Deviation Discussion

As indicated above, analysis shows that VHF G/T does not meet the requirement initially laid out for the project. The G/T requirement (GS-ANT-030) is -15 dB/K, and the analysis shows a G/T of -18.1 dB with the sun in the beam, falling short of the requirement by 3 dB.

The reason for the deviation is due to practical constraints. Achieving a 3 dB improvement in G/T would require expensive rooftop installation of both LNAs and filters, as well as potentially the installation of a higher-gain antenna.

However, the achievable G/T is not a serious impediment. While it may be difficult to downlink very low-efficiency modulation schemes such as AFSK, even schemes with only moderate G/T performance such as non-coherent FSK with no forward error correction are well achievable considering typical CubeSat constraints. Re-computing the analysis used to generate the constraints at 410 km (maximum ISS altitude) yields a G/T requirement of -21.8 dB/K at the horizon for a 19200 bit/s non-coherent FSK satellite with an EIRP of -3.5 dBW. Under this condition, the link closes with approximately 3 dB of margin.

Realistically, CCP satellites are unlikely to use even 19200 bit/s on VHF due to frequency coordination difficulties – 9600 bit/s is a more reasonable upper limit. In this case, the required G/T is -24.8 dB/K, which the architecture presented here meets with slightly less than 7 dB of margin.

Thus, considering realistic CCP mission profiles, the degraded performance is acceptable for the near-future goal of supporting CCP satellites. Should interoperability with other missions with more strenuous G/T requirements be desired in the future, the system can be upgraded then.

4.2.2 UHF G/T Deviation Discussion

As with the VHF G/T case, the UHF G/T also does not meet requirements by analysis. The G/T requirement (GS-ANT-040) is -10 dB/K, while the predicted realized G/T is around -13.5 dB/K in the sun case. Once again, this is due to practical constraints (expensive rooftop work, and the potential requirement for a larger high-gain antenna).

However, analysis demonstrates that there is still sufficient G/T to operate with an ISS-orbit, -3.5 dBW EIRP, linear polarized reference satellite at 9600 baud uncoded FSK, which is sufficient for a CCP baseline. Higher rates data rates are possible at this G/T with better E_b/N_0 performing modulation, the addition of FEC, or higher satellite output power.

Thus, the degraded G/T is likely sufficient for the time being. If better G/T performance is desired, rooftop upgrades may be undertaken at a later date.

5.0 BUILD AND TEST

The GESAC prototype hardware was assembled in December 2019 in a bench test format in the ECD labs at John H. Chapman Space Centre. Initial bench testing was performed to assess functionality.

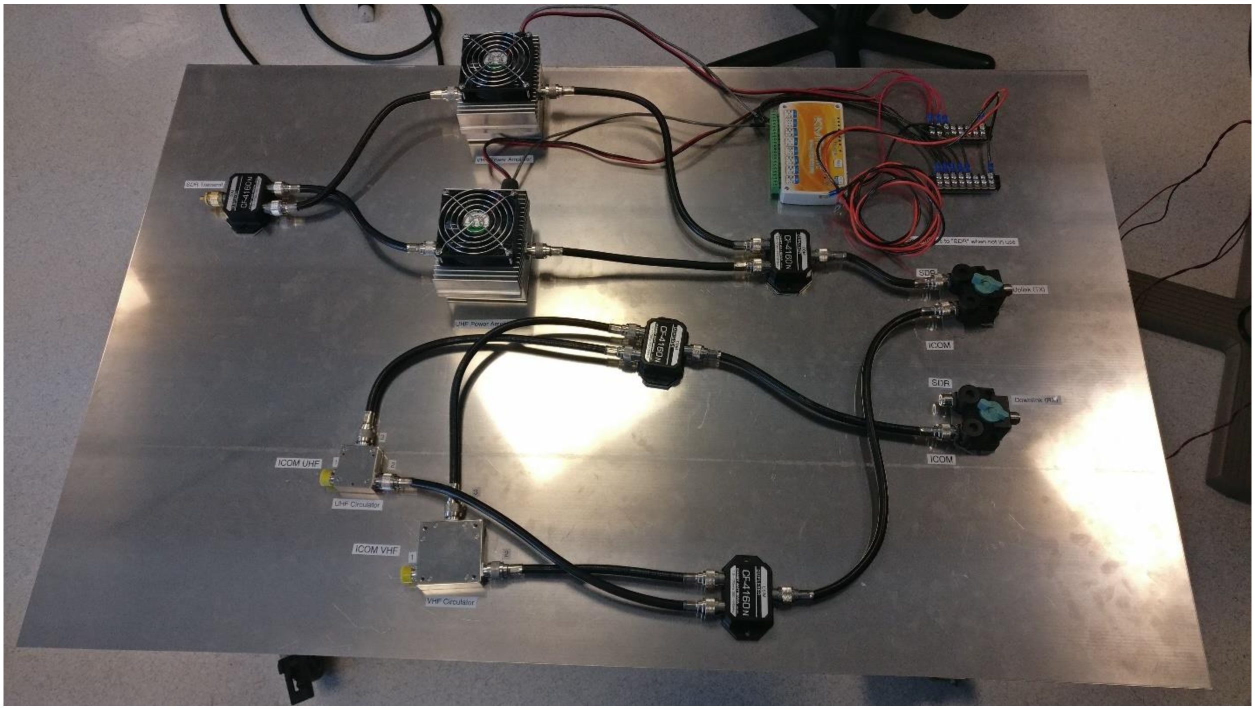


Figure 10: Ground-level equipment configured for bench testing

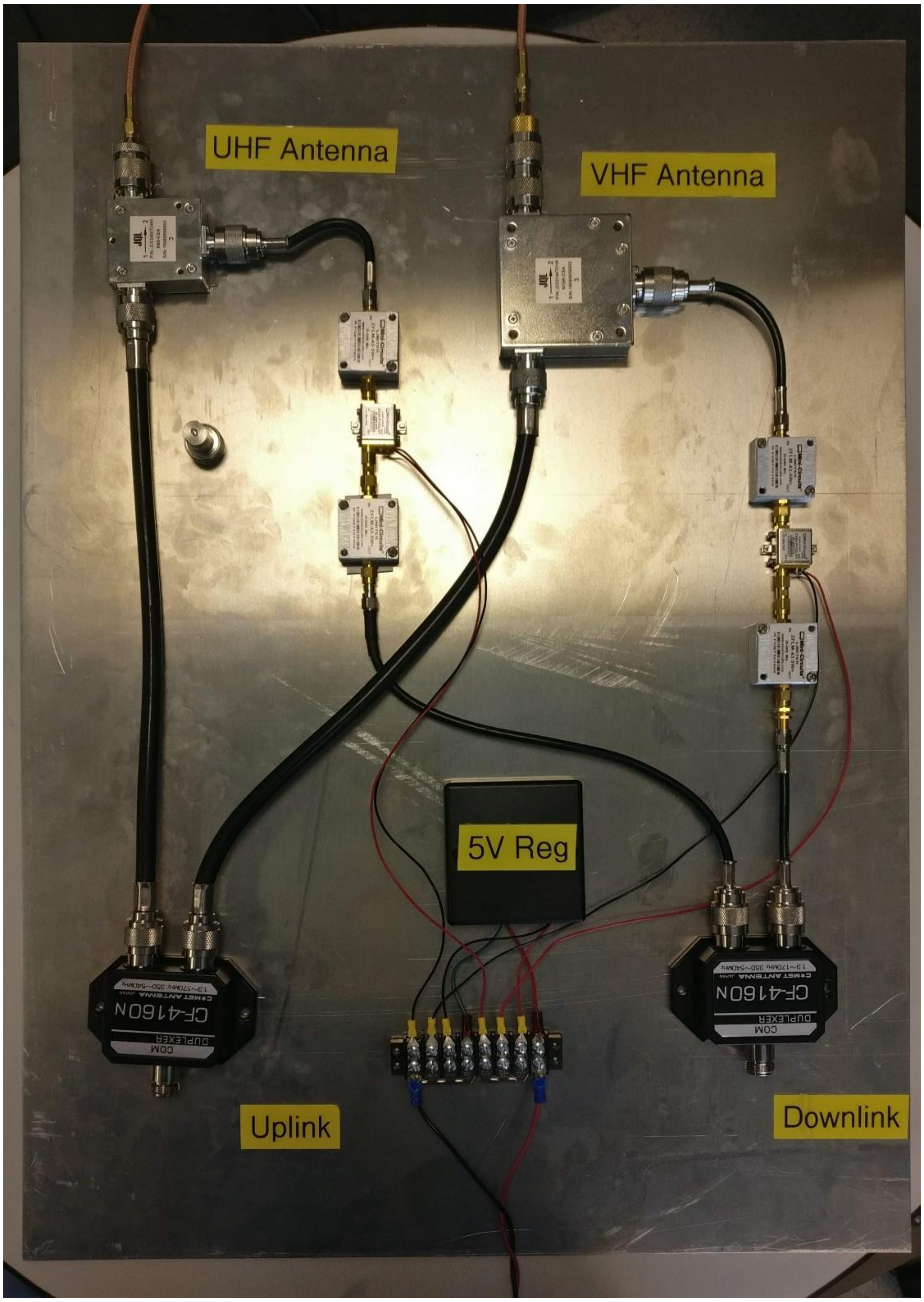


Figure 11: Fourth floor equipment configured for bench testing

5.1 Full Duplex Issues

During functional testing, two issues preventing full-duplex (cross-band) operation were identified. The transceiver selected, an Ettus Research USRP B210, has a maximum input power of 0 dBm. However, it was observed that driving the input above around -10 dBm was sufficient to drive the frontend into nonlinearity and deafen the receiver at moderate frontend gain settings. When transmitting, there are two parasitic paths which can present high return levels to the USRP receiver sufficient to cause this nonlinearity.

First, when transmitting full-duplex, some power is coupled from the transmit port to the receive port of the circulator on the transmit chain. This was anticipated in the design process, which is why power limiters were installed on the LNA inputs.

However, while the power limiters are sufficient to protect the LNAs, the LNAs themselves are still driven into saturation. This is not an issue for the LNAs (the LNAs can operate saturated without damage, so long as their input power is not exceeded). However, the saturated LNA output is more than sufficient to drive the USRP into nonlinearity, despite the fact that the strong interferer is well out-of-band.

The second issue relates specifically to the VHF uplink / UHF downlink case. When transmitting on VHF, a small amount of the VHF fundamental leaks into the UHF circulator section. Alone, this would not be a problem: there is sufficient filtering in the downlink direction to remove the parasitic out-of-band signal. However, the signal is sufficiently strong enough to drive nonlinearity in the UHF receive LNA, resulting in harmonic mixing products. Since the UHF amateur satellite band is an exact third harmonic of the VHF amateur satellite band, these mixing products are passed directly through the UHF receive chain and swamp the receiver.

6.0 DISCUSSION AND NEXT STEPS

At the present time, the GESAC prototype cannot operate full-duplex due to the issues identified in section 5.1. This greatly limits the prototype's usefulness, as many cubesats operate full-duplex cross-band, especially in the VHF Up / UHF Down mode.

Solutions have been identified to resolve the full-duplex issues, but not yet implemented:

1. To resolve the issue with the USRP nonlinearity, the receive chain will be split just upstream of the USRP input using a diplexer. This will route only the VHF signal to the RX1 input of the USRP, and only the UHF signal to the RX2 input of the USRP. This avoids the issue of a strong out-of-band interferer being present on an active receive chain.
2. To resolve the issue with the VHF transmit signal leaking into the UHF section, a UHF bandpass filter will be installed upstream of the TX input to the UHF circulator. This should suppress the VHF fundamental sufficiently so that it does not result in nonlinearity in the UHF LNA, allowing it to be removed by existing downstream filtering.

These solutions will be implemented in the coming weeks, and an updated version of this report will be issued after further testing.

7.0 LIST OF ACRONYMS

AD	*Applicable Document*
AFSK	*Audio Frequency-Shift Keying*
ARISS	*Amateur Radio on the International Space Station*
CCP	*Canadian CubeSat Project*
EIRP	*Effective Isotropic Radiated Power*
G/T	*Gain to Noise Temperature Ratio*
GESAC	*Generic Earth Station Architecture for CubeSats*
ITU	*International Telecommunications Union*
LNA	*Low Noise Amplfiier*
RAC	*Radio Amateurs of Canada*
RX	*Receive*
SPDT	*Single-Pole, Double-Throw*
TDR	*Time Domain Reflectometry*
TX	*Transmit*
UHF	*Ultra High Frequency*
VHF	*Very High Frequency*