Subject: System Performance with I/Q Down Converter Plate SN001, AMiBA Intensity Mapping Project	**Date:** 2016 March 18 DK001_2016_I/Q_Plate_SN001	**From:** Derek Kubo
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1. System Description

The system design for the AMiBA digital correlator upgrade for CO Intensity Mapping is described in *Fig. 1* [1]. This system begins with seven 1.2-m dishes that feed dual linear polarization receivers operating from 86-102 GHz. The W-band signals entering each receiver are separated into pairs of orthogonal linear polarizations then are amplified by cryogenically cooled HEMT LNAs. The LNA outputs are routed via waveguide to room temperature sub-harmonic mixers (SHM) [2] for frequency translation to an IF of 2-18 GHz. The LOs for the SHMs are 42 GHz and are phase modulated with unique Walsh phase switching sequences (0, 180 degrees at 84 GHz). The IF signals are further down converted to baseband (10-2200 MHz) using an I/Q down converter (denoted as New Down Converter in the *Fig. 1*) that separates the signal into in-phase (I), and quadrature (Q) components. The I and Q signals are digitized within the F-Engine ROACH-2 chassis using a pair of 8-bit ADCs operating 4.480 Gsps[1]. The F-Engine provides demodulation of the LO phase switching sequences[2], PFB/FFT channelization (1024 spectral channels across 2.240 GHz), and sideband separation. The signal power profile for the overall system is shown in *Fig. 2* [3].

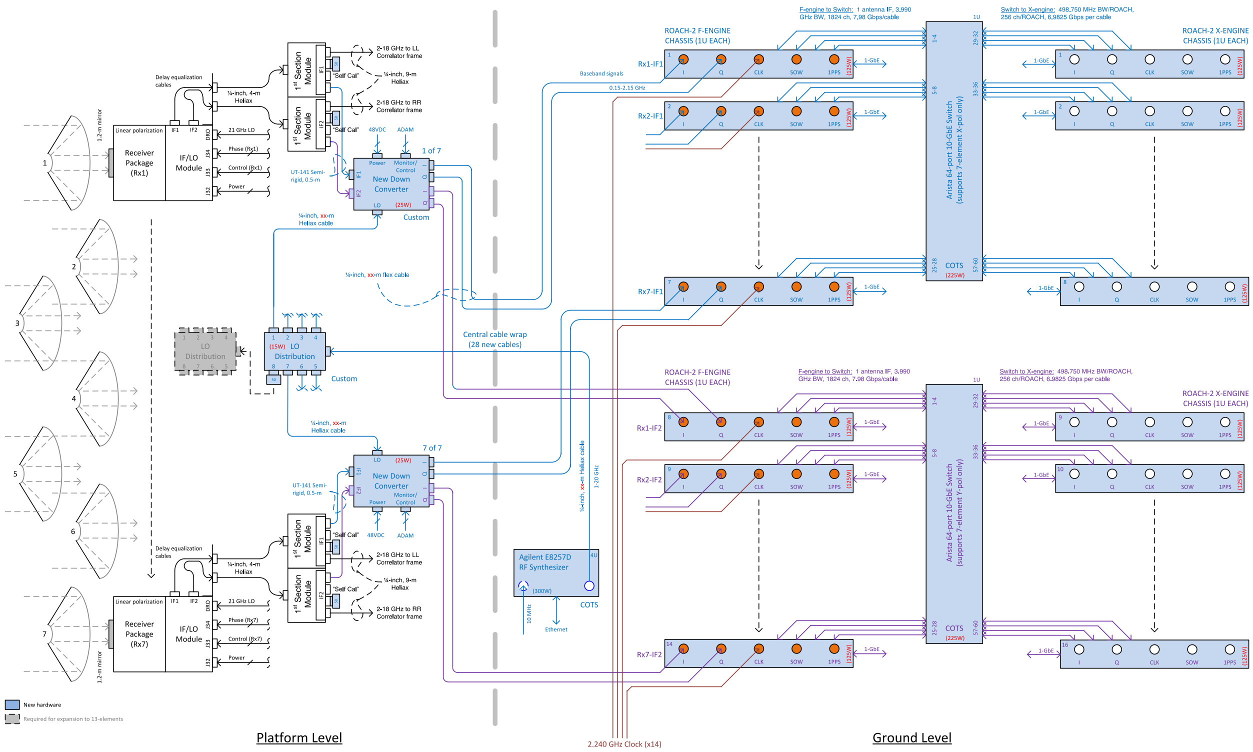


Fig. 1 System Block Diagram for Digital Correlator Upgrade. Equipment required for the upgrade are shaded in blue. Each of the 7 New Down Converter assemblies provide I and Q baseband outputs for both X and Y polarizations. The 28 baseband signals are fed to 14 separate ROACH-2 F-Engine Chassis that provide digitization, demodulation, PFB/FFT, and sideband separation functions.

[1] Current sample rate as of this writing is 3.2 Gsps (1.6 GHz clock).

[2] Provides reduction of crosstalk and noise introduced between the phase switch and ADC.

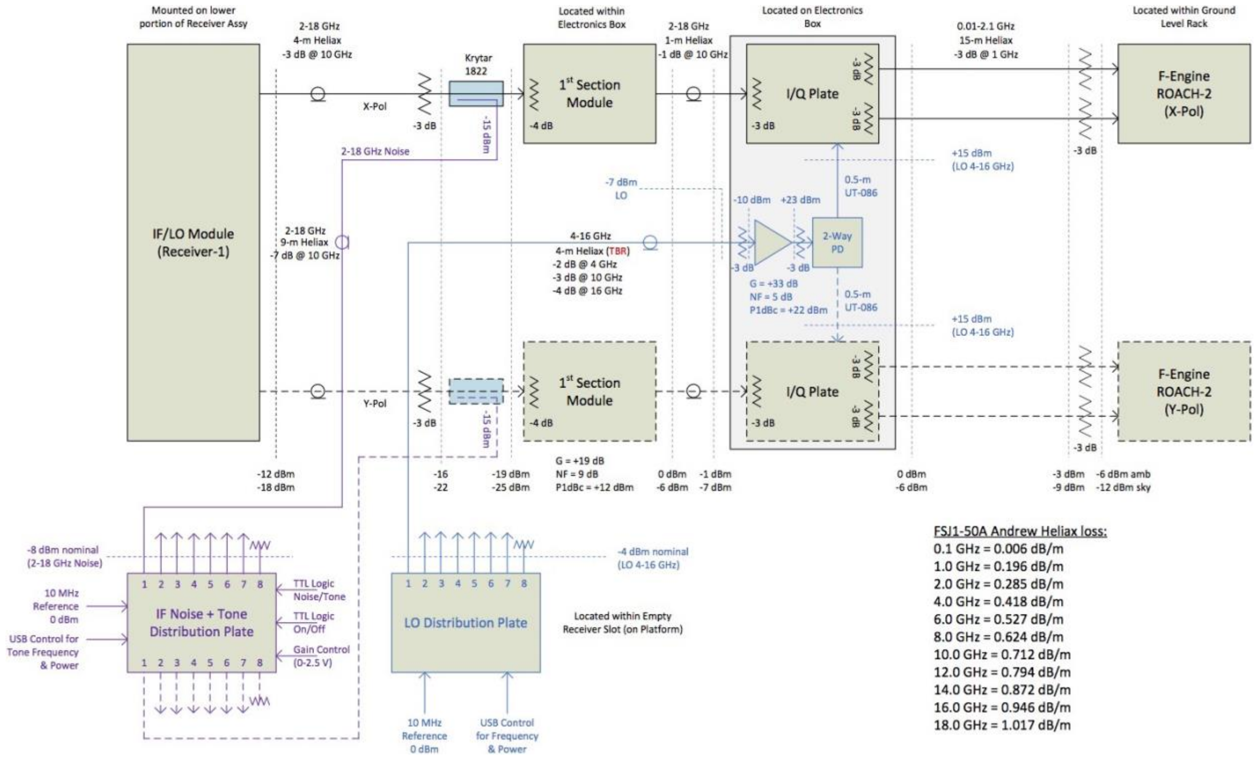


Fig. 2 System Power Profile Diagram[3]. *Note the two levels indicated for the IF and baseband paths represent ambient load over the receiver feed (higher power) and sky (lower power) with the shelter opened.*

2. Down Converter

2.1 Traditional Down Converter

The original down converter[4] for the 4-element prototype provided frequency translation over a fixed IF range of 3.6-5.6 GHz (F_{sky} of 87.6-89.6 GHz) using a LO of 5.85 GHz and is depicted in *Fig. 3*. Scaling this design to cover the full 2-18 GHz IF would require seven separate BPFs (1.95-4.05, 3.95-6.05, 5.95-8.05 GHz, etc.) and a pair of SP7T switches for selection. The design was considered undesirable due to the high hardware complexity and cost associated with the filter bank, and its inflexible nature of having fixed discrete frequency bands and LOs.

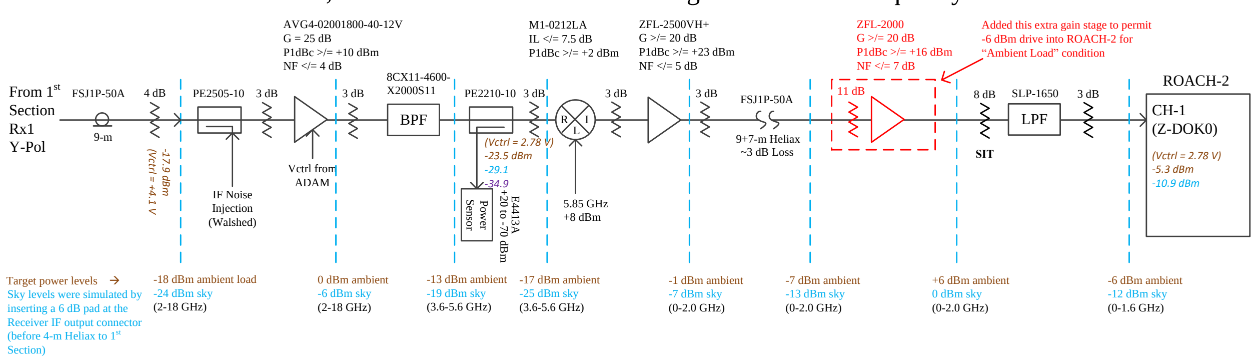


Fig. 3 Original Fixed Frequency Down Converter. The 2-18 GHz IF is bandpass filtered (BPF) to permit only 3.6-5.6 GHz to be heterodyne translated to baseband using a fixed LO of 5.85 GHz. The 0.25-2.25 GHz baseband signal is further lowpass filtered (LPF) to 0.25-1.6 GHz to allow for slower ADC sampling speed (goal is 2.24 GHz clock).

[3] Corrections for coaxial cable lengths in *Fig. 2*: 1st Section Module to I/Q Plate reads 1-m Heliax, should be 0.9-m. I/Q Plate to F-Engine ROACH-2 reads 15-m Heliax, should be 18.9-m. LO Distribution Plate to I/Q Primary Plate reads 4-m, should be 6.1-m.

[4] This original 4-element down converter was installed onto the AMiBA platform in February of 2013.

2.2. Selection of I/Q Down Converter

During the AMiBA Digital Correlator Workshop held in Taipei during March of 2013, I presented a Trade Study [4] that included four down converter options[5] and an agreement was made to select the hybrid analog-digital I/Q approach. This approach utilizes an analog I/Q down converter for frequency translation to baseband, and a digital I/Q to separate the sidebands within the F-Engine ROACH-2 chassis. The primary advantage of this hybrid approach is that quadrature phase errors (caused by delay imbalances) and magnitude imbalances produced in the analog I/Q section can be removed in the digital section using tone calibration for each channel bin (currently 1024 channels). *Fig. 4* [5] shows the relationship between phase errors and magnitude imbalances to sideband suppression. Magnitude imbalances, if held stable with respect to time, can be nearly eliminated (0 dB on the plot) within the F-engine using tone calibration leaving only phase errors caused by the quadrature hybrid used generate the 0 and 90 degree mixer LOs. The quadrature errors currently seen on SN001 I/Q plate are approximately +/- 2 degrees and conservatively indicate sideband suppressions of 36 dB can be achieved.

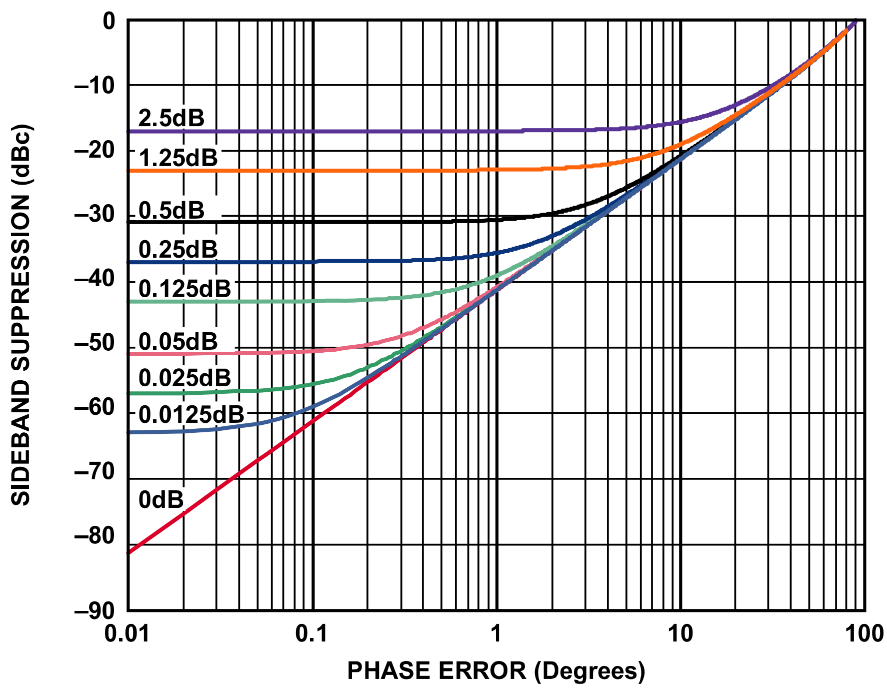


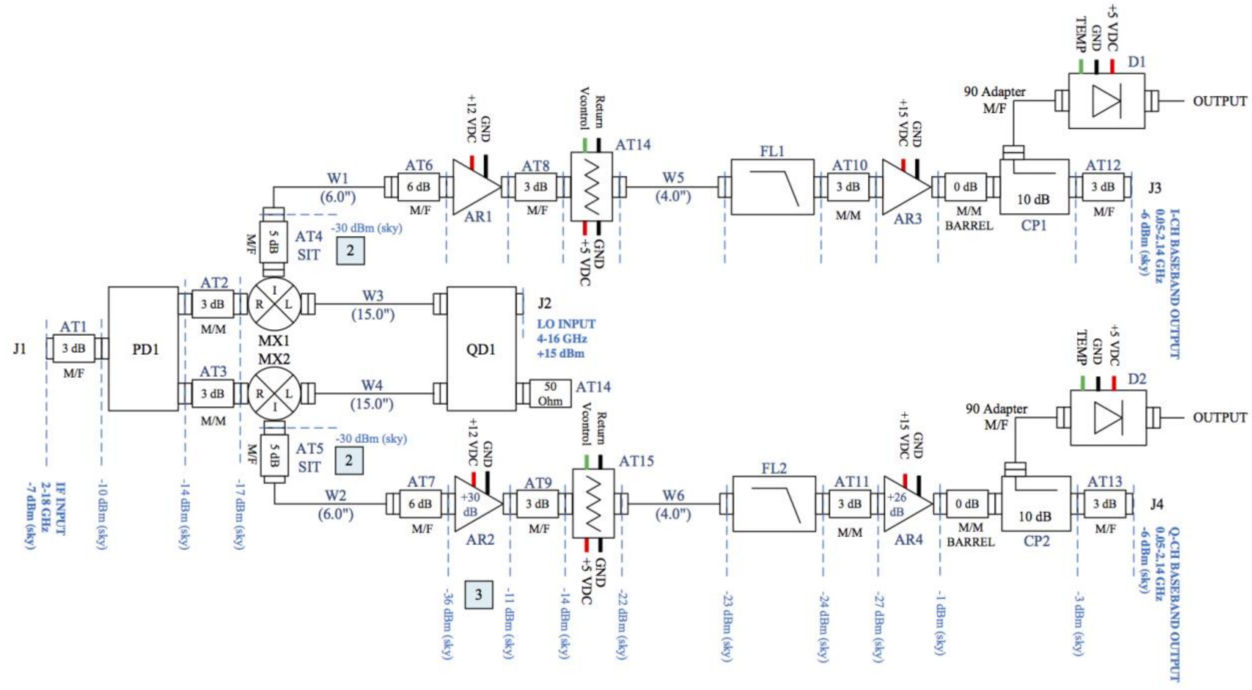
Fig. 4 I/Q Sideband Suppression Plot. Note that for quadrature phase errors of less then 2 degrees, sideband suppression greater than 36 dB can be achieved with calibration of magnitude imbalances.

2.3. Design of I/Q Down Converter

The electrical and mechanical designs for the I/Q plate along with fabrication, assembly and test were all performed in the ASIAA Hawaii office. A schematic diagram of the RF portion of the production I/Q down converter is provided in *Fig. 5* [6], and a photo of the completed SN001 I/Q plate is provided in *Fig. 6*. Consistent with the desire to maintain accurate quadrature phase over the LO frequency range of 4-16 GHz, we selected a Krytar, model 1830, which spans from 2-18 GHz and asked the manufacturer to cull for tighter phase specifications. And for the mixers, we selected Marki Microwave, model M2-0208LA, which supports 2-18 GHz on the RF and LO ports, and 1 MHz to 6 GHz on the IF port. We plan to complete the first eight (7 + 1 spare) I/Q plates in Hilo to support Y-polarization and are considering outsourcing the next eight assemblies for X-polarization toward the latter part of this year. In preparation for outsourcing, we have been formalizing all drawings that include: Schematic, BOM, Fabrication Details, and Assembly. Due to the complexity and iterative nature of alignment[6] and test, we will likely perform this in Hilo for all sixteen units.

[5] 1) Analog double sideband down converter with time series Walsh; 2) analog I/Q down converter with analog I/Q sideband separation; 3) analog I/Q down converter with digital I/Q sideband separation; 4) analog filter bank down converter.

[6] Involves hand selection of mixers and other components to produce overall quadrature errors of < 2 degrees.



[Fig. 5](#) Production I/Q Down Converter Schematic. The wideband 2-18 GHz IF input signal is presented to J1 then to in-phase power divider, PD1, and provides identical signals at mixers, MX1 and MX2. A continuously tunable LO of 4-16 GHz is fed to a quadrature hybrid and produces 0 and 90 degree LOs to the mixers. The baseband outputs of MX1 and MX2 consisting of both sideband spectra (LSB & USB), are amplified by AR1 and AR2, and signal leveled by PIN diode attenuators AT14 and AT15. Anti-aliasing low pass filters, FL1 and FL2, provide band limiting to 2.2 GHz (F_{3dB}). Final amplification is provided by AR3 and AR4 prior to transmission through the low loss Heliax cables. Power detectors, D1 and D2, provide feedback for controlling AT14 and AT15. The I and Q baseband outputs at J3 and J4, respectively, each drive 62 feet of FSJ1-50A Heliax cables consisting of two segments of 50 and 12 feet separated by an I/O panel at the cone level, 3 dB pads mounted to a second I/O panel at the rack level, and finally 18 inches of blue flexible cables prior to arriving at the F-Engine ROACH-2 chassis where the signals are digitized by 8-bit e2v ADCs.

3. SN001 I/Q Plate Test Results

3.1 Characterization of Quadrature phase and Magnitude Performance

An Agilent E8257D synthesizer (250 kHz – 40 GHz) was used to inject a reference LO into port J2 at 4.0 GHz, +15 dBm power. A second Agilent 8720ET VNA (50 MHz – 20 GHz) was used to produce an IF signal into port J1 at 4.0 GHz +/- 0 to 2.0 GHz, in increments of 200 MHz, -7 dBm power. Voltage variable attenuators (VVA), AT14 and AT15, were adjusted and fixed to produce -6 dBm at outputs J3 and J4 for a LSB baseband frequency of 1.0 GHz. An Agilent 8508 vector voltmeter was used to measure the phase (Q-ch minus I-ch) and magnitude of the baseband outputs from J3 (I-ch) and J4 (Q-ch) for each IF frequency increment. This test was repeated for LO = 10 GHz and IF = 10.0 +/- 0 to 2.0 GHz, and LO = 16.0 GHz and IF = 16.0 +/- 0 to 2.0 GHz cases. The results for all three cases are shown in *Fig. 7*. Note the quadrature accuracy at the mixer outputs represented by the maroon traces in the left column are very good (90 +/- 2 degrees) and indicate an important measurement parameter because a quadrature error at this location cannot easily be compensated for by calibration within the F-Engine. The final outputs at J3 and J4 represented by the blue trace in the left column, however, shows a decrease from quadrature phase with increasing frequency offset from the LO. At 1 GHz offset, the quadrature error is approximately -8 degrees indicating that the I-channel baseband electrical path length is longer than Q-channel by 22 psec (~4.6 mm in Teflon dielectric). Fortunately this path delay imbalance can be calibrated out within the F-Engine. The output magnitude responses measured at J3 (I-ch, blue trace) and J4 (Q-ch, maroon trace) are represented in the right column. Imbalances in LSB to USB cause reduced sideband suppression according to the plot in *Fig. 4*, however, calibration within the F-Engine can remove these effects. The measurements presented here were performed manually and include only 21 frequency points over the 4 GHz IF bandwidth range (LO +/- 2.0 GHz). Future measurements beginning with SN002 will utilize automated software to set the IF synthesizer frequency in increments of 10 MHz (401 points) and collect the phase and magnitude from the vector voltmeter.

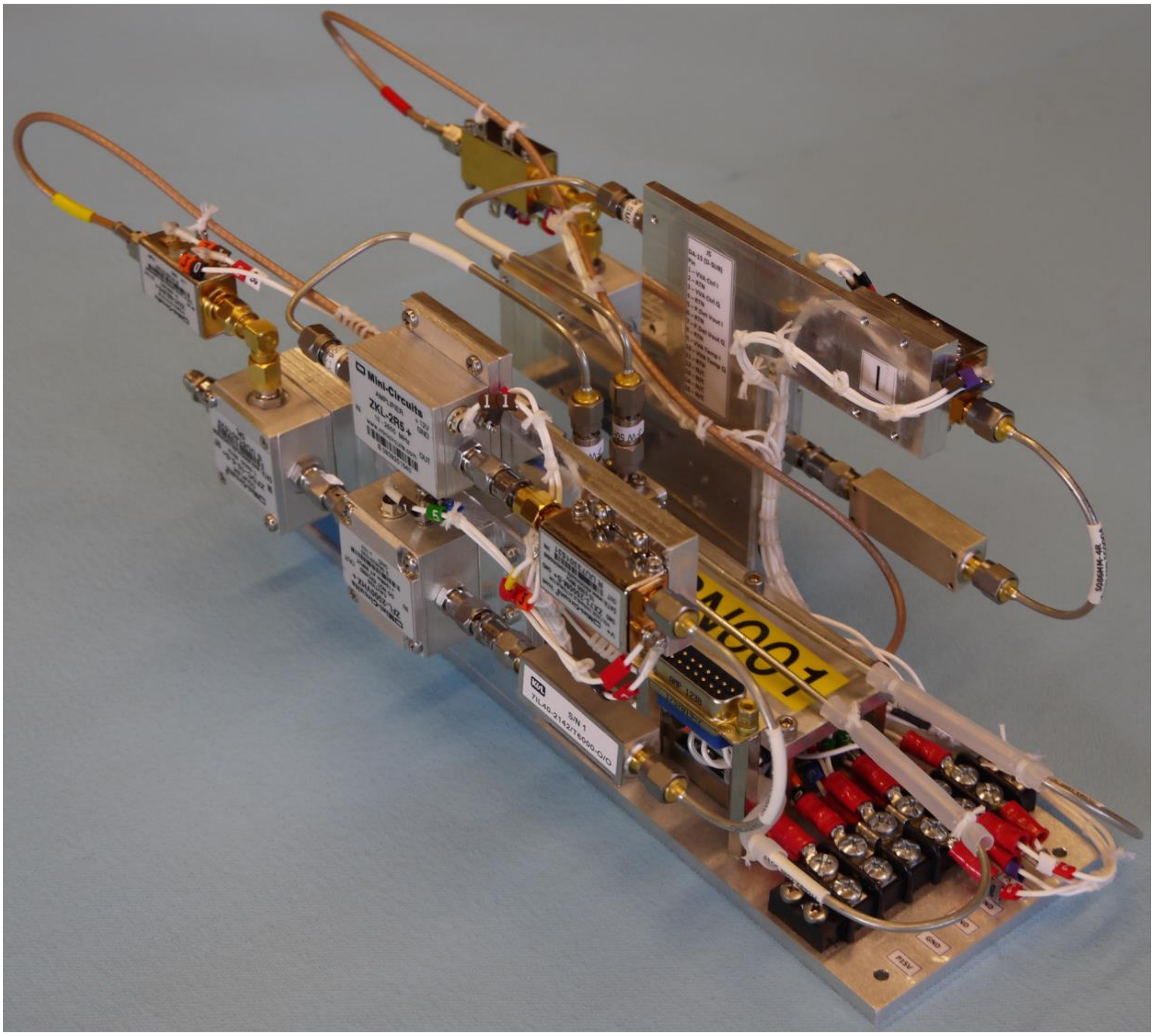


Fig. 6 Photo of the I/Q Down Converter SN001. The J1-J4 SMA connector signal input/outputs are provided on the far side (not visible) and will face downward when mounted onto the platform structure for access ease. This plate requires only +15 VDC power @ 800 mA via the terminal block and local regulation for +12 VDC and +5 VDC are provided onboard. The 15-pin D-connector provides the monitor and control input/outputs to the ADAM-5000/TPC controller. Note the two K&L LPFs are mounted in such a fashion as to be easily replaceable to accommodate different ADC sample rates.

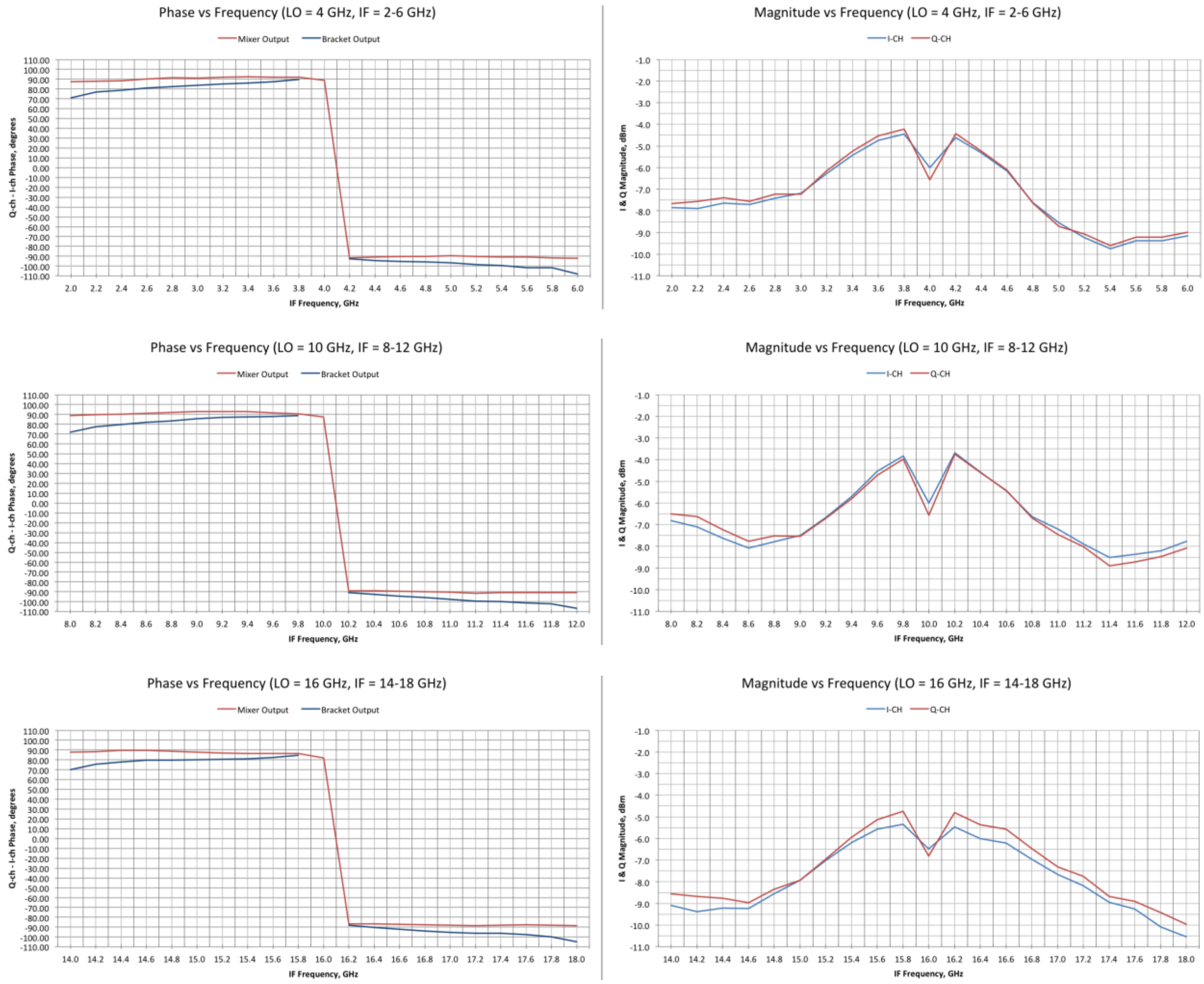


Fig. 7 Phase and Magnitude Response. Left column – Quadrature performance, maroon trace represents measurements taken directly at the I-port outputs of MX1 and MX2, blue trace represents J3 and J4 outputs. The test cables to the vector voltmeter were calibrated out to remove test setup errors. Right column – Magnitude response of I-channel represented by blue, and Q-channel represented by maroon traces.

3.2 Characterization of Linearity Performance

The IF input (J1) to the I-channel (J3) and Q-channel (J4) baseband output power linearity was measured for an LO of 4.0, 10.0, and 16.0 GHz. With the IF input power set to -7.0 dBm, VVAs AT14 and AT15, were set to produce -6.0 dBm for 1.0 GHz baseband outputs at J3 and J4. The input power level at J1 was swept in 1.0 dB increments while monitoring the J3 and J4 outputs using a power meter. The results for LO = 10 GHz, IF = 11 GHz are shown in *Fig. 8*. Note that the I and Q channels are nearly indistinguishable and show an output 1 dB compression point (P1dBc) of +17.0 dBm. This value of +17 dBm is 11 dB above our nominal operating point of -6.0 dBm (refer to power profile in *Fig. 2*) and verifies that we are indeed operating in the linear regime. The output P1dBc values for the two other LO frequencies are as follows:

LO = 4 GHz, IF = 3 GHz	P1dBc = +16 dBm
LO = 10 GHz, IF = 11 GHz	P1dBc = +17 dBm
LO = 16 GHz, IF = 17 GHz	P1dBc = +18 dBm

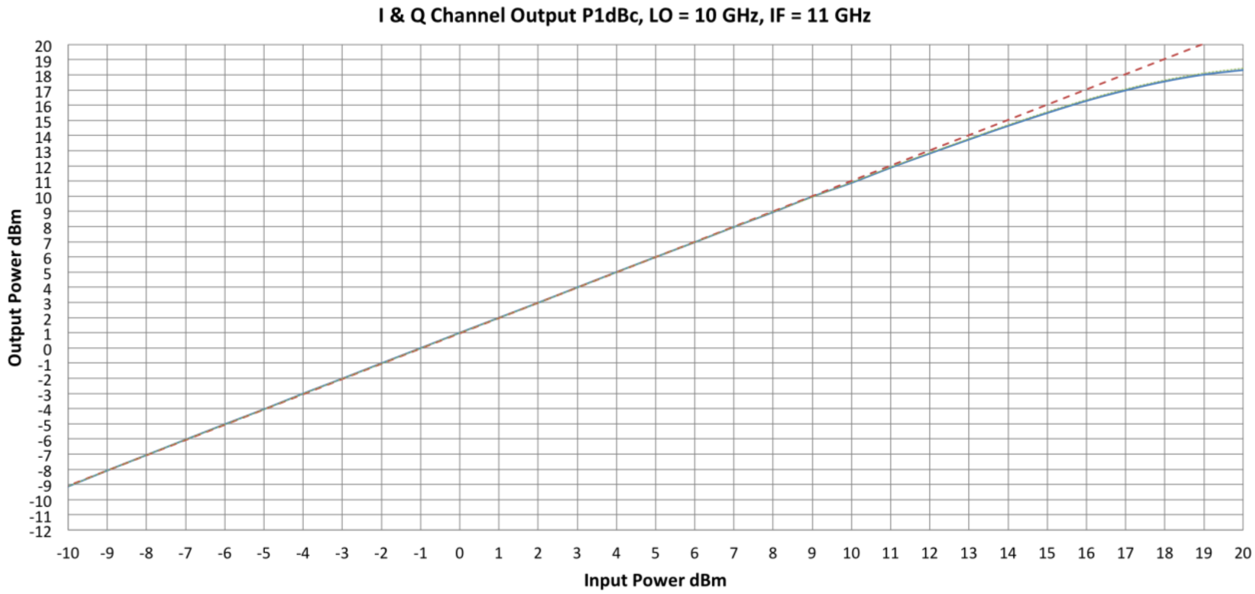


Fig. 8 I & Q Channel Output P1dBc, LO = 10 GHz, IF = 11 GHz. Maroon trace is ideal, blue trace is I-channel, dashed green trace is Q-channel. The nominal input operating point is -7 dBm.

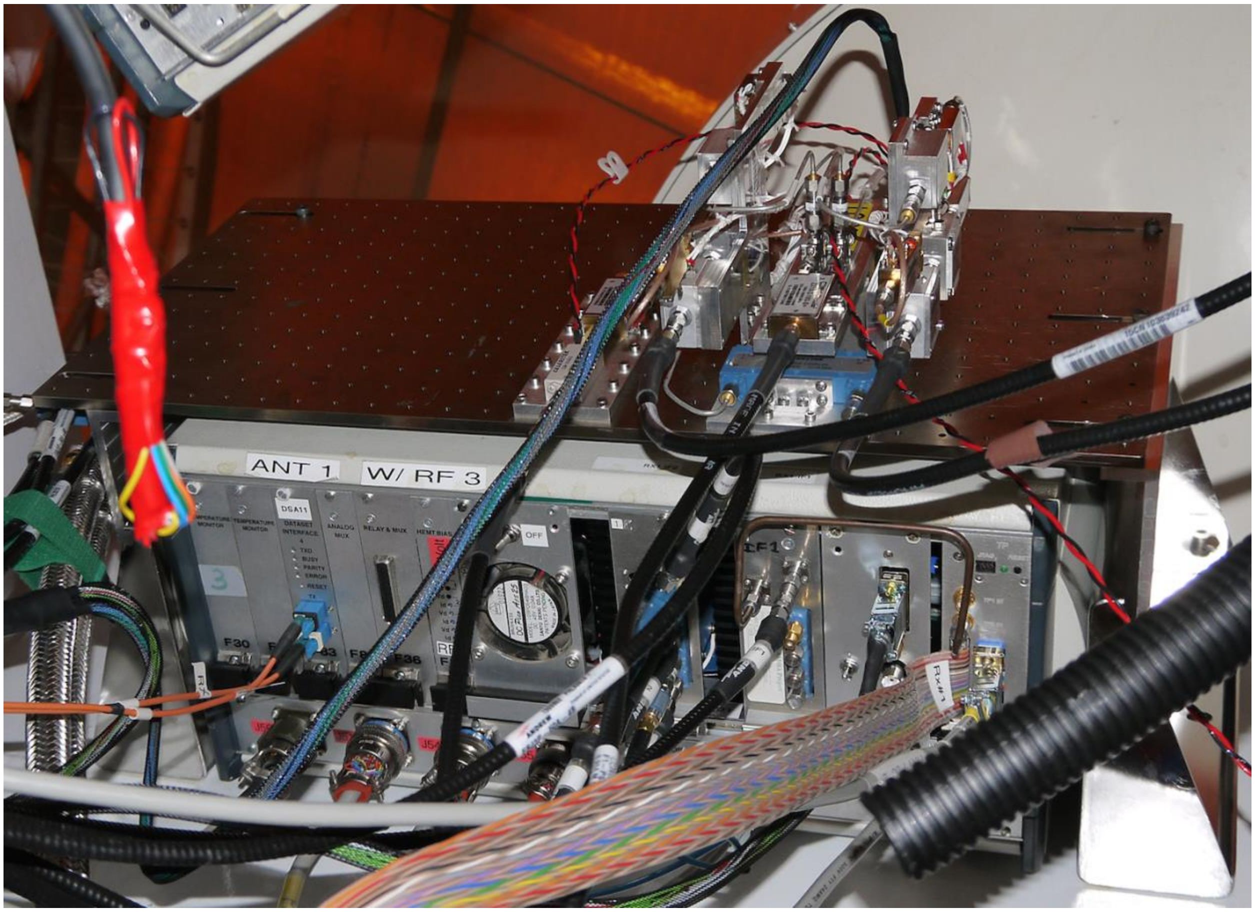
4. Installation of the I/Q Plate onto the Platform

A photo of the I/Q Down Converter plate installed on the platform is shown in *Fig. 9*. This SN001 I/Q plate was mounted to the Electronics Box for Antenna-1 that houses the Receiver Electronics (6 modules on left), cooling fan, 1st Section (x2), and Total Power Detector plugin modules for Rx1 (receiver-1). The X-Y calibration module within the Electronics Box was removed (no longer used) and replaced by a custom designed Power Detection plugin module (second plugin module from right). This module serves to detect the 2-18 GHz IF signal power exiting the 1st Section module and is used to set the VGA located within the IF/LO module to produce the desired -7 dBm level into the I/Q plate. A custom monitor & control Y-cable was constructed and installed to interface from a centrally located ADAM-5000/TCP to the new I/Q plate and Power Detection module. The +15 VDC power for both the I/Q plate and LO distribution assembly were temporarily connected from the XX analog correlator frame, however, in the future a set of dedicated Daitron low noise DC power supplies will be utilized. The LO input to the I/Q plate was temporarily provided by a fixed 5.85 GHz phase locked source used by the previous conventional down converter. Our initial commissioning tests on astronomical sources will use this LO frequency to repeat observations conducted with the 4-element prototype that utilized the traditional down converters.

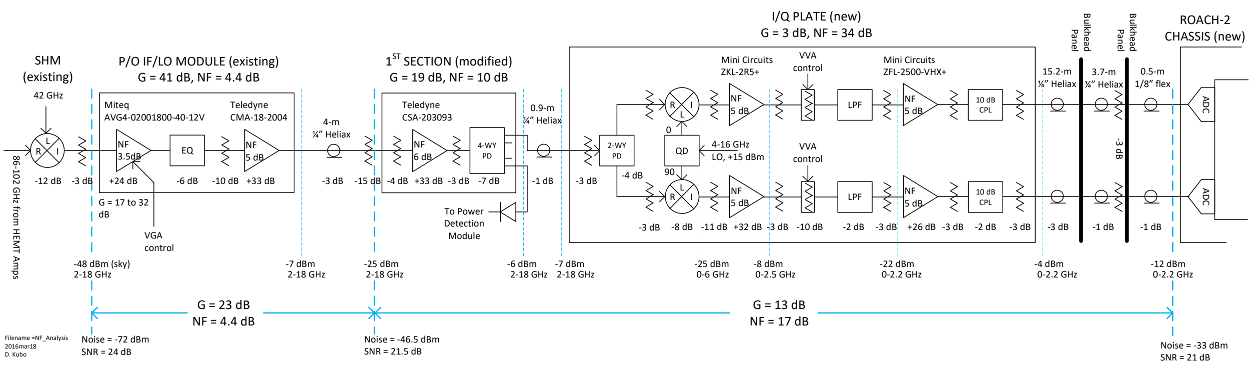
4.1 Description of Overall Signal Path

A simplified diagram of the overall IF and baseband signal path is shown in *Fig. 10*. An ambient temperature absorptive load was place over the feed of receiver-1 and the variable gain amplifier (VGA) located within the IF/LO module was adjusted[7] to produce -7.0 dBm at the I/Q plate J1 input. For this target value of -7.0 dBm, the associated Power Detection module output was 3.575V (-10.0 dBm → 2.83V, 0.0 dBm → 7.24V). The control voltages for variable attenuators, AT14 and AT15, were adjusted to 5.25V and 5.40V to produce -12.4 dBm and -12.2 dBm into the I and Q input channels of the F-Engine ROACH-2 chassis, respectively.

[7] When looking at the cold sky, the VGA will be adjusted to produce ~6 dB higher gain to achieve the same -7 dBm power level at the I/Q plate J1 input.



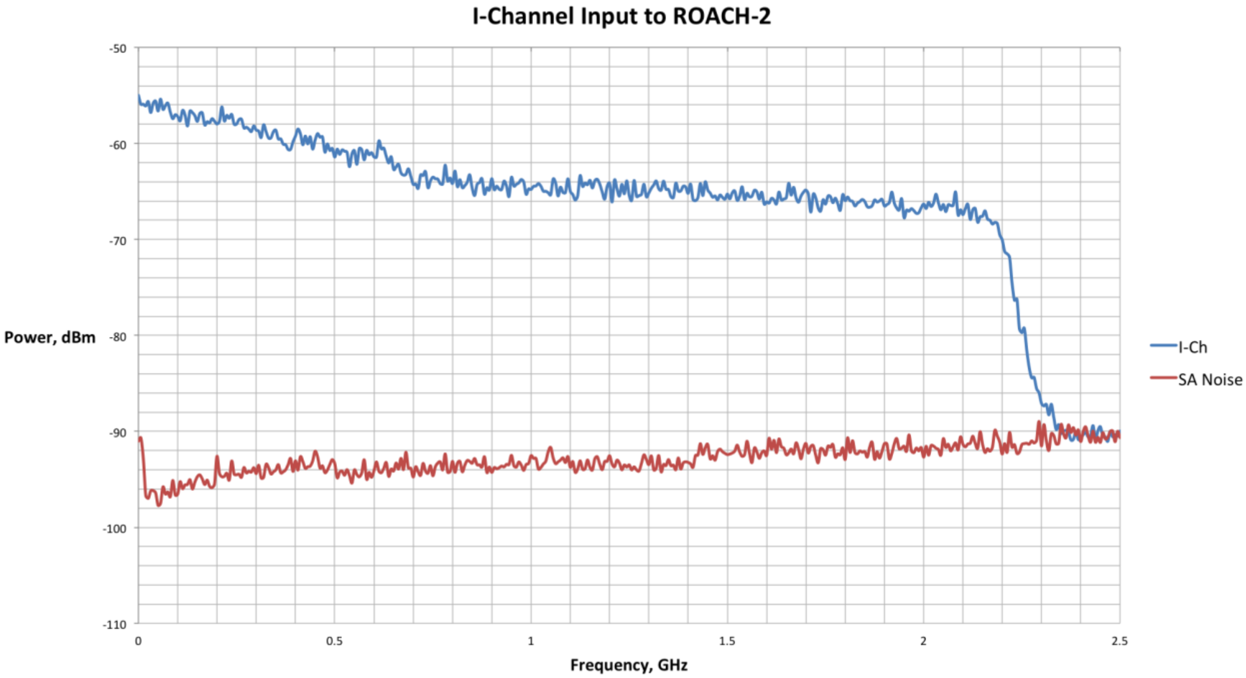
[Fig. 9](#) I/Q Down Converter Installed on Rx-1 Electronics Box. A custom adapter plate with universal mounting holes was mounted over the top of the existing Electronics Box and was secured to the platform using custom angle brackets. The I/Q plate was installed onto this adapter plate in the Y-polarization position with room on the left for a future X-polarization I/Q plate. The small assembly to the left of the I/Q plate houses an amplifier and 2-way power divider to divide the LO to the two eventual I/Q plates.



[Fig. 10](#) Simplified System Diagram of IF and Baseband Signal Path. The 86-102 GHz W-band signal from cooled HEMT LNAs is fed to a room temperature SHM (leftmost mixer) which provides frequency translation to the 2-18 GHz IF. The signal is processed through an existing IF/LO module, a modified 1st Section module, and the I/Q plate. The I and Q baseband outputs are transmitted through long segments of low loss ¼-inch Heliax cables to the ground level where they are digitized by a pair of ADCs located within the F-Engine ROACH-2 chassis.

4.2 Magnitude vs. Frequency Response

With the ambient load maintained over the receiver-1 feed, the VGA within the IF/LO module was adjusted to produce the desired input power of -7 dBm at the I/Q Plate J1 port. VVAs AT14 and AT15 were adjusted to produce -12.4 and -12.2 dBm at the end of the blue cables to the ROACH-2 chassis for I and Q channels, respectively. An Agilent N9918A spectrum analyzer was used to capture spectral plots (RBW = 3 kHz, VBW = 30 kHz) for I and Q channels and are shown in *Fig. 11*.



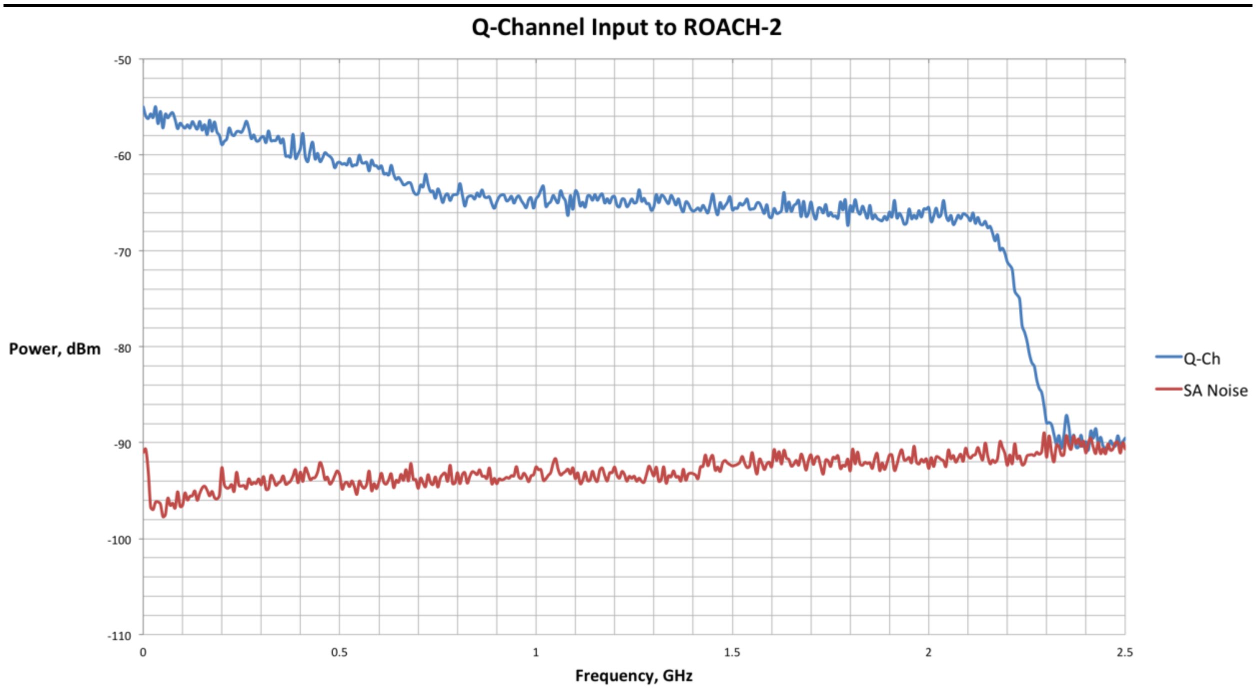


Fig. 11 Baseband Noise Power Spectra. Blue traces represent baseband signal, maroon trace is with the spectrum analyzer input terminated to 50 Ohms.

The important features to note are the near linear falling slope of 8 dB from 0 to 800 MHz, and 2 dB falling slope from 800 to 2100 MHz. The 3 dB roll-off point is located at about 2200 MHz and down by approximately 10 dB at the Nyquist frequency of 2240 MHz relative to the flat portion of the spectra. After the X-engine process, it is likely that we will discard the 2140 to 2240 MHz guard band portion of the spectra (channels 977-1023).

Note that these baseband spectra from 0 to 2.5 GHz represent the folded over double sideband spectra of 3.35 to 5.85 GHz (LSB) and 5.85 to 8.35 GHz (USB) at IF, where down the converter LO was set to 5.85 GHz. Translated to W-band, the actual frequencies are 87.35 to 89.85 GHz (LSB) and 89.85 to 92.35 GHz (USB). Since our Nyquist frequency is limited to processing a maximum baseband bandwidth of 2.24 GHz, and with the guard band mentioned above, the maximum frequencies represented at W-band are 87.71 to 91.99 GHz (84.0 + 5.85 GHz +/- 2.14 GHz).

4.3 Signal-to-Noise Ratio

Referring back to *Fig. 10*, a measurement of the signal-to-noise ratio (SNR) at the IF/LO output for receiver-1 was performed using a power meter with the ambient load over the receiver feed.

HEMT receiver bias on →	-8.4 dBm
HEMT receiver bias off →	-28.2 dBm

SNR @ IF/LO output →	19.8 dB

The modified + new hardware that exists between the IF/LO module and the ROACH-2 chassis (includes 4-m Heliax, 15 dB pad, 1st Section, 0.9-m Heliax, I/Q Plate, 15.2-m & 3.7-m Heliax, 3 dB pad, and 0.5-m flex cable) can be represented by a single block with G = -5 dB and NF = 35 dB. With this equivalent representation, the output noise with the input to the block terminated to 50 Ohms is calculated to be -47.6 dBm (measured P_N = -44.3 dB, $P_{I\text{-}ch}$ = -12.4 dBm, $P_{Q\text{-}ch}$ = -12.2 dBm). The backend noise contribution of the modified + new hardware results in a measured SNR of 32 dB, thus the overall SNR of the IF/LO system is dominated by the SHM and preexisting IF/LO module with a measured SNR of 20 dB for receiver-1.

5. Summary

The development of this I/Q downconverter plate allows selection and digitization of any 4 GHz portion of the 2-18 GHz IF band, or equivalently 86 to 106 GHz of the sky band. This can be done by simply selecting the appropriate LO frequency. E.g., to observe the 92 to 96 GHz portion of the sky we will select an LO of 10 GHz. The 94 to 92 GHz portion will be captured as the lower sideband (LSB) and the 94 to 96 GHz portion as the upper sideband (USB). Nyquist low pass filtering will be provided at baseband prior to the ADCs. One of the primary advantages of using the I/Q down converter over a traditional down converter is that it eliminates the need for an IF filter bank which is both physically cumbersome and costly. In addition, the use of fixed filter banks does not allow for frequency coverage agility, we would be locked into the frequencies of the filters themselves.

The drawback of the I/Q approach is that more attention to detail is required during the assembly stage to achieve and maintain >/= 20 dB sideband suppression across the entire 2-18 GHz band of operation. A total of 14 + 2 spare assemblies will be required to support the 2 polarizations and 7 antennas and will require a dedicated team of 2 skilled individuals to complete the task.

References:

[1] AMiBA DBE System, 2014-Oct-31, http://amibablog.asiaa.sinica.edu.tw/wp-content/uploads/2014/10/AMiBA_DBE_System_2014oct31.pdf

[2] W-Band GaAs HEMT MMIC Subharmonically Pumped Diode Mixers for AMiBA Receivers, http://www.ursi.org/proceedings/procga02/papers/p2161.pdf

[3] System Power Profile, 2015-Dec-10, http://amibablog.asiaa.sinica.edu.tw/wp-content/uploads/2015/12/System_Pwr_Profile_2015dec10.pdf

[4] Down Converter Design Trade Study, 2013-Mar-27, https://dl.dropboxusercontent.com/u/51016221/AMiBA_downconverter_2013mar26a.pdf

[5] I/Q Imbalance discussion, http://www.edaboard.com/entry1972.html

[6] Schematic, I/Q Downconverter, 2016-Feb-12, http://amibablog.asiaa.sinica.edu.tw/wp-content/uploads/2016/02/SCHEM_IQ_DOWNCONVERTER_2016FEB12.pdf