Academia Sinica, Institute of Astronomy & Astrophysics

Subject:
Photonic Noise Source Design Approach,
AMiBA Intensity Mapping Project
To:
Ming-Tang Chen

Date:
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cc:
AMiBA routing

From:
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Location/Phone:
Hilo Office/
808-961-2926

References:
[1] AMiBA_DBE_System_V2, 2014-Oct-31
[2] DK001_2014_Baseband_Noise, 2014-Nov-17
[3] Photonic Noise Design, 2014-Nov-24

I. System Description

The currently proposed design approach for the AMiBA digital correlator upgrade is described in *Fig. 1* [1]. The system begins with 7 dual linear polarization receivers, each operating over 86-102 GHz. The received signals are amplified by cryogenically cooled HEMT LNAs located in the Receiver Package then down converted in the IF/LO Module to an IF of 2-18 GHz utilizing warm sub-harmonic mixers with a fixed[1] LO frequency of 42 GHz. Unique Walsh phase switching (0, 90 degrees at 42 GHz) are applied to each of the 14 LOs for crosstalk and backend noise reduction. The IF signals are further down converted to baseband (approximately 10-2500 MHz) using an I/Q down converter that separates the signal into in-phase (I), and quadrature (Q) components. The advantages and details of the I/Q down converter approach are provided in sections 1 and 2 of reference [2].

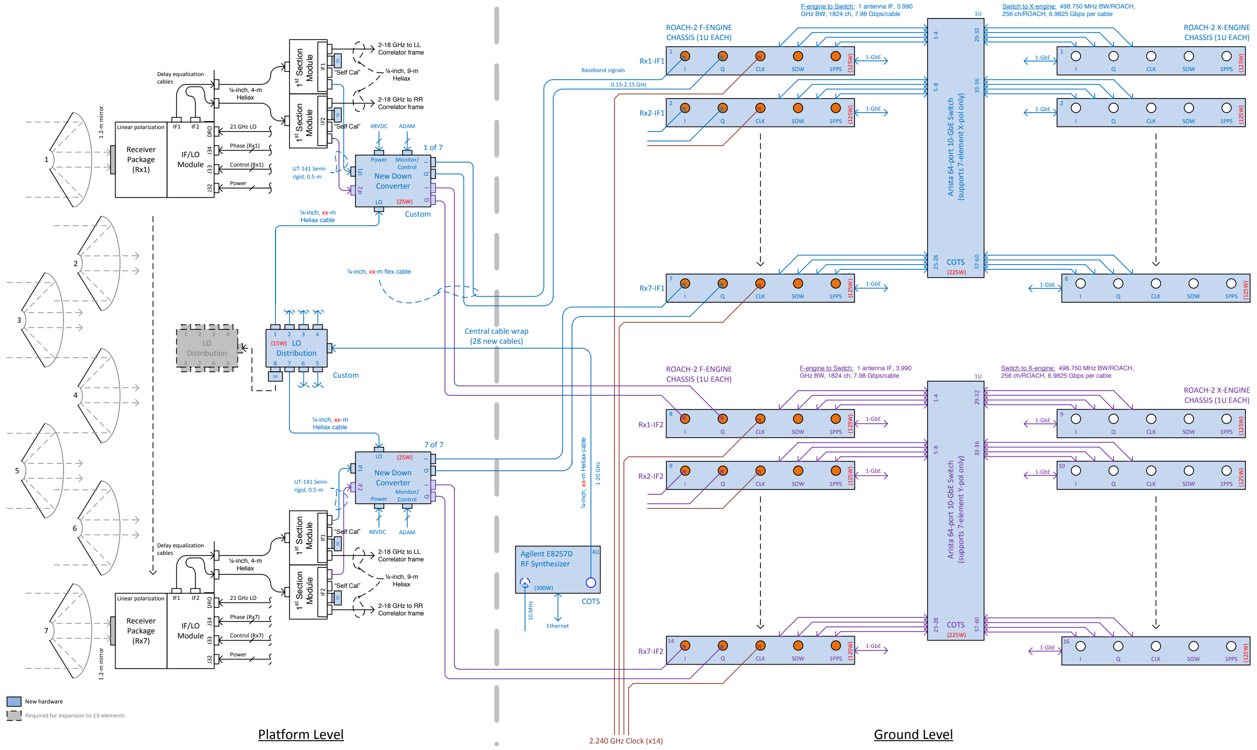

Fig. 1 System Block Diagram for Digital Correlator Upgrade. Hardware required for the digital upgrade is shown in blue. Each of the 7 New Down Converter assemblies provide I and Q baseband outputs for both X and Y polarizations. The 28 baseband signals are fed to 14 separate ROACH-2 F-Engine Chassis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

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[1] 42 GHz LO cannot be changed in frequency due to the phase switching method employed.

II. Noise Calibration Goals and Requirements

The primary goals for noise calibration are as follows:

1. *Magnitude and phase vs. frequency calibration for each of the 42 baseline products (21 X-pol, 21 Y-pol). The artificial noise must be flat, preferably with a Gaussian distribution, and be injected as early as possible at the antenna feed or equivalent at W-band (86-102 GHz). The calibration for the present analog correlator is being performed by periodically looking at astronomical sources during the track and takes into account Z-direction antenna movement caused by platform deformation. This astronomical calibration is still viable for the digital correlator upgrade.*

2. *Delay calibration for the ROACH-2 correlator. The ROACH-2 correlator chassis currently power up with arbitrary delays between the ADCs and causes a large number of phase wraps in the phase vs. frequency cross correlation product. A strong artificial correlated noise source is required to provide initial phase unwrapping. This noise source can be performed at W-band, IF or baseband.*

3. *ADC core offset, gain and phase calibration. Noise injection can be performed at either IF or baseband for DC offset and gain calibration. The noise drive level to the ADCs must be similar to the actual optimal drive level during observation. Phase calibration of the ADC cores requires tone injection. This noise and tone source can be performed at W-band, IF or baseband. The uncorrelated receiver noise can be used for the ADC offset and gain calibration.*

4. *Regardless of the approach taken, noise injection must not compromise the existing antenna-to-antenna isolation with a preliminary goal of >110 dB.*

III. Photonic Noise Source Design

A conceptual design for the photonic noise source is provided in *Fig. 2* [3]. This design involves combining the light from a narrowband laser at 192.643 GHz with a broadband super-luminescent diode (SLD) spanning 190.343-196.585 GHz. Manually variable attenuators, VA1 and VA2, are used to fine balance the power levels while monitoring at the CP2 test point. An erbium doped fiber amplifier (EDFA) provides variable optical gain and is controlled via RS-232. Optical switch, SW1, with minimum isolation of 55 dB, provides a means to redirect the optical power to the external test point for direct monitoring of the EDFA output power. The combined optical signal is routed up to the platform to a centrally located 8-way optical power divider. A set of 7 W-band photomixers generate the difference frequencies and radiates the receivers via WR-10 waveguide situated at the far side of the secondary mirrors[2].

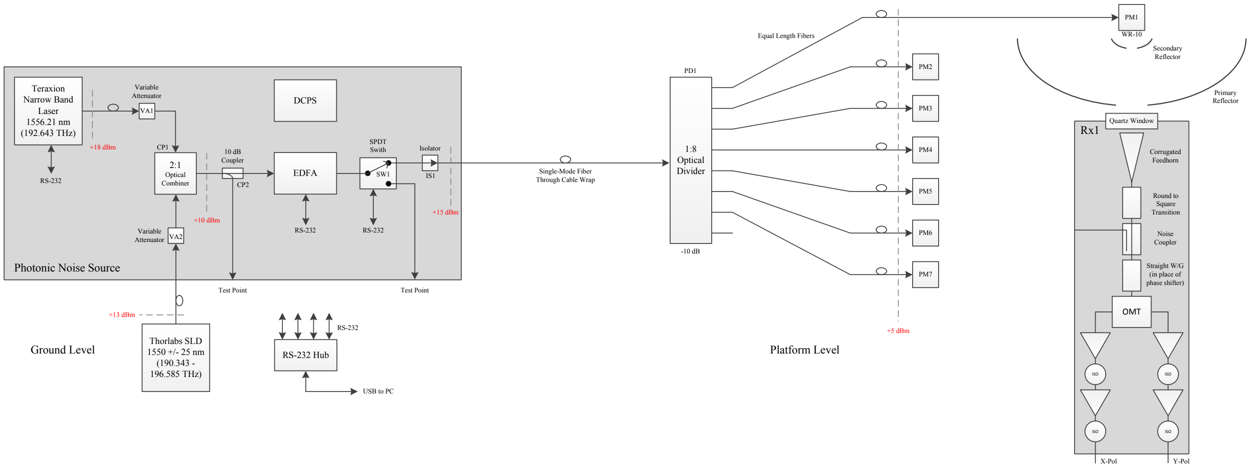

Fig. 2 Photonic Noise Source Design. A broadband SLD is combined with a narrowband laser at optical coupler, CP1, then amplified through an EDFA. The combined signal is transmitted up the cable wrap via a single optical fiber (single-mode) to a centrally located 1:8 optical power divider, PD1. The outputs of PD1 are fed to W-band photomixers, PM1-PM7, that generate the difference frequency for illumination of the receivers.

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[2] The diameter of the hole in the secondary is estimated to be 0.25" or about twice the operating wavelength.

Each of the 7 photomixers require an external DC voltage bias and careful monitoring of the photomixer current, both not shown in *Fig. 2*. Based on our experience with the NTT photomixer[3], a maximum output of approximately -10 dBm tone power is obtained by applying a fixed voltage bias of -2 V and slowly increasing the optical power until a photomixer current of 7 mA is achieved. For this noise application, the photomixer output power will be significantly reduced due to discarding a large fraction of the SLD noise bandwidth. An illustration of the wide spectral width of the SLD relative to the AMiBA receiver bandwidth is shown in *Fig. 3*.

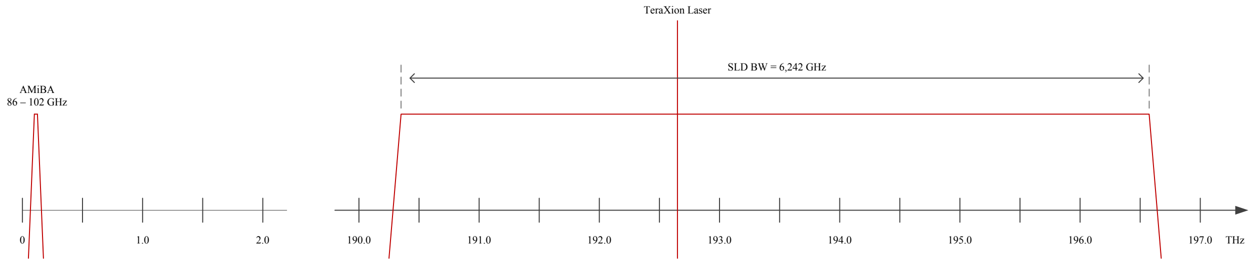

Fig. 3 Spectral Width of SLD vs. AMiBA Receiver. Only a very small portion of the SLD is translated down to the AMiBA 86-102 GHz band.

The W-band photomixer and AMiBA receiver together intercept only 16 GHz of the total SLD bandwidth of 6242 GHz. The loss due to the bandwidth reduction is defined as:

$$\mathrm{Loss}_{\mathrm{BW}} = 10*\mathrm{Log}(6242/16) - 3\ \mathrm{dB} = 22.9\ \mathrm{dB} \qquad (1)$$

A gain of 3 dB is introduced into the above equation to account for the double sideband contribution of noise power. In addition to the bandwidth loss, there will be a physical coupling loss from the photomixer waveguide output to the receiver feed horn that is currently estimated to be 55 dB[4]. Since the feed horn receives both X and Y linear polarizations, we plan to orient the photomixer to illuminate both simultaneously with equal power. Thus the total noise power entering the receiver can be estimated as:

$$P_{\mathrm{feed}} = P_{\mathrm{tone}} - L_{\mathrm{BW}} - L_{\mathrm{coupling}} - L_{\mathrm{2pol}} = -10\ \mathrm{dBm} - 23\ \mathrm{dB} - 55\ \mathrm{dB} - 3\ \mathrm{dB} = -91\ \mathrm{dBm}\ (7.94\mathrm{e}{-13}\ \mathrm{W}) \qquad (2)$$

Converting the noise power presented to the feed horn as equivalent noise temperature yields:

$$T_{\mathrm{noise}} = P_{\mathrm{noise}}/(k*B) = [7.94\mathrm{e}{-13}\ \mathrm{W}]/[(1.38\mathrm{e}{-23}\ \mathrm{J/K})*(16\mathrm{e}9\ \mathrm{Hz})] = 3.60\ \mathrm{K}, \qquad (3)$$

where P_{noise} is the artificial noise power presented to the feed horn per polarization, k is Boltzmann's constant, and B is the noise bandwidth. Equation (4) is a modified radiometer equation[5]:

$$(T_{\mathrm{noise}}/T_{\mathrm{sys}})*\mathrm{sqrt}(B_{\mathrm{ch}}*\tau_{\mathrm{int}}) = \sigma_{\mathrm{det}} \qquad (4)$$

where T_{sys} is the receiver system noise temperature (average of 85 K or -77 dBm), B_{ch} is the digitized channel bandwidth (2.240 GHz/128 channels = 17.5 MHz/channel), τ_{int} is the integration time in seconds, and σ_{det} is the strength of the detection in terms of standard deviation. *Table I* shows the strength of the detection for various input noise power levels and integration times. At an expected input power level of -90 dBm, we can achieve a detection of 223 sigma in 1 second.

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[3] From ALMA Laser Synthesizer project.

[4] 55 dB loss is a pessimistic estimate, will be confirmed with empirical test using NTT photomixer.

[5] Email from Kai-Yang Lin, 5-Oct-2014, Subject – Re: Correlator Meeting Sept. 30 2014.

Table I Sigma Detection vs. Injected Noise Power and Integration Time

Receiver		Artifical Noise at Feed			
T_{sys}	P_{sys}	T_{noise}	P_{noise}	τ_{int}	Sigma
(K)	(dBm)	(K)	(dBm)	(sec)	
85	-77.3	45.3	-80	0.1	705
85	-77.3	14.3	-85	0.1	223
85	-77.3	4.5	-90	0.1	70
85	-77.3	1.4	-95	0.1	22
85	-77.3	0.5	-100	0.1	7
85	-77.3	45.3	-80	0.5	1576
85	-77.3	14.3	-85	0.5	498
85	-77.3	4.5	-90	0.5	158
85	-77.3	1.4	-95	0.5	50
85	-77.3	0.5	-100	0.5	16
85	-77.3	45.3	-80	1	2229
85	-77.3	14.3	-85	1	705
85	-77.3	4.5	-90	1	223
85	-77.3	1.4	-95	1	70
85	-77.3	0.5	-100	1	22
85	-77.3	45.3	-80	5	4984
85	-77.3	14.3	-85	5	1576
85	-77.3	4.5	-90	5	498
85	-77.3	1.4	-95	5	158
85	-77.3	0.5	-100	5	50

IV. ROM Cost

The Bill of Materials (BOM) for hardware (excluding the existing receiver) shown in *Fig. 2* is provided in *Table II*. The total cost is estimated to be \$19.4k + \$109.4k + \$15.1k = \$143.9k and excludes labor. The \$15.1k represents the cost of 14 + 1 spare Interface Panels described in section III of [2]. Note the total cost is dominated largely by the NTT photomixer at a quoted price of \$12,876 each (email quote Kozue Hasegawa, 2014 Dec 22).

Table II Bill of Materials

ITEM	REF DES	MAKE	PART NO	DESCRIPTION	RQD QTY	SPARE QTY	$/EA	TOTAL $
1	-	TeraXion	TBD	Laser, narrowband, 1556.21nm	1	0	$0	$0
2	VA1, VA2	OzOptics	TBD	Optical attenuator, variable, 1550nm	2	0	$500	$1,000
3	CP1	General Photonics	TBD	Optical coupler, 50/50, 1550nm	1	0	$850	$850
4	CP2	General Photonics	TBD	Optical coupler, 10/90	1	0	$850	$850
5	EDFA	OEQuest	TBD	EDFA, 1550nm	1	0	$10,000	$10,000
6	SW1	Leoni	TBD	Optical switch, SPDT, 1550nm	1	0	$0	$0
7	IS1	Thorlabs	TBD	Optical isolator, 1550nm	1	0	$710	$710
8	Misc	ParMetal	TBD	Chassis, EMI, 3U	1	0	$175	$175
9	Misc	Dan Evans Mach.	-	Custom fabrication for chassis	1	0	$500	$500
10	DCPS	Daitron	TBD	DC power supply, 15 V, 150 W	1	1	$200	$400
11	Misc	Qualtek	880-03/005	AC power inlet, EMI	1	0	$50	$50
12	Misc	Orion	TBD	Fan, +24V	2	0	$20	$40
13	Misc	Orion	TBD	Fan guard, mesh	2	0	$3	$6
14	Misc	Orion	TBD	Fan guard, wire	2	0	$3	$6
15	Misc	TDK/Lambda	LS25-24	Power supply, 24 VDC, 1.1 A	1	0	$20	$20
16	Misc	Thorlabs	ADAFC2-PMW	Panel mount feedthrough, FC/APC	4	2	$48	$288
17	Misc	Thorlabs	TBD	Fiber cables, pigtail, FC/APC	10	2	$129	$1,548
18	Misc	TBD	TBD	D-sub, 9-pin, male	3	1	$20	$80
19	Misc	TBD	TBD	D-sub, 9-pin, female	3	1	$20	$80
20								
21				SUBTOTAL FOR PHOTONIC NOISE SOURCE CHASSIS				$16,603
22								
23	-	Thorlabs	S5SC1005S	SLD, 1550+/-25nm	1	0	$2,576	$2,576
24	-	TBD	TBD	RS-232 hub	1	0	$250	$250
25								
26				TOTAL FOR GROUND LEVEL HARDWARE				$19,429

ITEM	REF DES	MAKE	PART NO	DESCRIPTION	RQD QTY	SPARE QTY	$/EA	TOTAL $
1	PM1-PM7	NTT	IOD-PMW-13001	Photomixer, W-band	7	1	$12,876	$103,008
2	PD1	TBD	TBD	Optical power divider, 8-way, 1550nm	1	0	$2,000	$2,000
3	-	Thorlabs	TBD	Fiber cables, pigtail, FC/APC, 3m	7	2	$200	$1,800
4	-	Thorlabs	TBD	Fiber cables, pigtail, FC/APC, 12m	1	1	$300	$600
5	-	Dan Evans Mach.	-	Custom mount for photomixer	7	1	$250	$2,000
6								
7				Total FOR PLATFORM HARDWARE				$109,408

ITEM	REF DES	MAKE	PART NO	DESCRIPTION	RQD QTY	SPARE QTY	$/EA	TOTAL $
1	SW1, SW2	MiniCircuits	ZASWA2-50DR-FT+	SPDT switch, DC-5 GHz, 82 dB iso, absorb	2	0	$94	$188
2	FL1, FL2	MiniCircuits	VLF-1800+	LPF, DC-2125 MHz,	2	0	$22	$44
3	CP1, CP2	MiniCircuits	ZFSC-2-10G+	2-way power divider, 2-10 GHz	2	0	$70	$140
4	VA1, VA2	MiniCircuits	ZX73-2500-S+	Variable atten, 10-2500 MHz, 25 dB	2	0	$50	$100
5	D1, D2	MiniCircuits	ZX47-60LN+	Detector, active, 10-8000 MHz	2	0	$90	$180
6	Misc	MiniCircuits	SF-SF50+	Panel mount feedthroughs, SMA f/f	6	0	$5	$30
7	Misc	TBD	TBD	Blank 1U Panel	1	0	$25	$25
8	Misc	-	-	Fabrication, custom	1	0	$150	$150
9	Misc	MiniCircuits	VAT-3+	Fixed attenuator, 3 dB	2	0	$14	$28
10	Misc	MiniCircuits	TBD	Coaxial cable, flex	12	0	$10	$120
11								
12				SUB-TOTAL FOR INTERFACE PANEL				$1,005
13								
14				TOTAL FOR 14+1 INTERFACE PANELS				$15,075

V. Requirements Compliance

The requirements listed in section II are repeated below with the baseband noise source capabilities list below each item.

1. *Magnitude and phase vs. frequency calibration for each of the 42 baseline products (21 X-pol, 21 Y-pol). Similar to the above, the artificial noise must be flat, preferably with a Gaussian distribution, and be injected as early as possible at the antenna feed or equivalent at W-band (86-102 GHz). The calibration for the present analog correlator is being performed by periodically looking at astronomical sources during the track and takes into account Z-direction antenna movement caused by platform deformation. This astronomical calibration is still viable for the digital correlator upgrade.*

   The most significant benefit for photonic noise source approach is that it closely simulates an astronomical source with white Gaussian noise properties. Based on the numbers provided in *Table I*, high SNR calibrations can be performed in a matter of seconds where as an astronomical source may require several minutes. Calibration does not require turning Walsh demodulation off, and if the telescope is pointing at a weak extended source one could simply perform calibration in-situ without moving off source. Another benefit is that calibration for maximum sideband separation can be performed and will be directly applicable to astronomical sources. One technical downside of the photonic calibration approach is that it cannot detect the effects of platform deformation. Another potential technical issue is the stability of the calibration source with respect to environmental temperature variation. The stability of the calibration system can be characterized by comparing to Jupiter, i.e., perform a 10 minute scan on Jupiter then point off source and perform a 1 minute scan with the noise source. This sequence should be repeated for several hours to see if there is drifting of the magnitude and phase (with respect to channel number) for each of the 42 baseline products.

2. *Delay calibration for the ROACH-2 correlator. The ROACH-2 correlator chassis currently power up with arbitrary delays between the ADCs and causes a large number of phase wraps in the phase vs. frequency cross correlation product. A strong artificial correlated noise source is required to provide initial phase unwrapping. This noise source can be performed at W-band, IF or baseband.*

   Though the delays from the photonic noise source may not exactly match the delays of the receivers looking at an astronomical source, a table representing the fixed delay offsets can be generated to accommodate the differences. As noted above, the Walsh demodulation should be left on.

5. *ADC core offset, gain and phase calibration. Noise injection can be performed at either IF or baseband for DC offset and gain calibration. The noise drive level to the ADCs must be similar to the actual optimal drive level during observation. Phase calibration of the ADC cores requires tone injection. This noise and tone source*

can be performed at W-band, IF or baseband. Receiver noise can be used for the ADC offset and gain calibration.

The ADC core alignment for DC offset and gain can utilize the inherent noise generated by the receivers. A tone injection source used for ADC core phase offset calibration is not included with this photonic noise source, however, a simple baseband tone injection scheme can be configured using the Interface Panels described in section III of [2].

3. *Regardless of the approach taken, noise injection must not compromise the existing antenna-to-antenna isolation with a preliminary goal of >110 dB.*

   This photonic noise source approach is not expected to degrade the antenna-to-antenna isolation.

V. Summary

The photonic noise source approach is attractive in that it is elegantly simple with injection at the receiver feeds. Though the telescope can be calibrated on strong astronomical sources, an artificial noise source such as the one presented here has the potential of reducing the calibration duty cycle without compromising the science data. This photonic approach, however, is currently expensive at $144k USD and is driven by the cost of the photomixers (quantity of 7 + 1 spare). This photonic noise source approach does carry with it some technical unknowns as follows:

(a) What is the conversion efficiency of the photomixer for noise vs. tone? We currently assume the same loss as for tone signals, however, to empirically demonstrate this we would need to purchase a Thorlabs SLD at a cost of $2.6k USD and perform a test using existing hardware in our Hilo office.

(b) What is the coupling loss radiating through the opening in the secondary mirror? We currently assume 55 dB, however, to empirically demonstrate this we would need to mount our existing NTT photomixer at the far side of the secondary and quantify the received signal power.

(c) In order to maintain high stability of the photonic calibration system, we plan to leave the laser, SLD source, and EDFA powered on and simply switch off the light to the photomixers via optical switch, SW1, during astronomical observations. The current Leoni switch that we have in hand has 55 dB isolation but we must verify whether this number is sufficient. Even a minute amount of correlated noise has the potential to corrupt the science data if permitted to leak through.

The physical implementation of the phototonics noise source approach is considered fairly straight forward and is expected to require approximately 1 week of labor for the identification and ordering of components, and another 2 weeks of mechanical design, fabrication and assembly labor for the Photonic Noise Source chassis and custom mounts for the 8-way optical power divider and photomixers. Expansion to support 13-elements for phase II of the AMiBA Intensity Mapping Project (30 GHz receivers) will require replacing the 8-way optical power divider with a 14-way, and replacing the 7 W-band photomixers with 13 Ka-band photomixers.