Final Report:

An ALMA Design Study Proposal for Production of the 4mm Band 2 Cartridges

P.I.: Eric Bryerton[1]

[1]NRAO Technology Center, Charlottesville, VA

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I. Introduction

This report summarizes the outcomes of the ALMA Design Study entitled “The undiscovered country: probing the formation of stars, the evolution of galaxies, and the origin of life—an ALMA design study proposal for the production of the 4mm band 2 cartridges.” The effective period of this design study was from Oct. 1, 2012 through Sept. 30, 2013. In the original design study proposal, we put forward the following list of deliverables to be completed by the conclusion of the design study:

- Band 2 Science Workshop report with enhanced band 2 science case
- Draft Specifications and ICDs for band 2 cartridge production
- Measured performance of prototype cryogenic LNAs (80nm CRYO3 hybrid and 35nm MMIC)
- Prototype 2SB downconverter module with 4-12 GHz IF outputs with measured data for conversion gain and sideband rejection
- Test data from the ARO 12m telescope using prototype band 2 80nm CRYO3 hybrid and 35nm MMIC LNAs
- Optics report, including measured data for feedhorn and OMT, with predicted performance, including investigation of cooled lens option

In the remainder of this final report, we summarize the progress toward each of these deliverables.

II. Band 2 Science Workshop

On May 29, 2013, twenty-five astronomers and students gathered at the North American ALMA Science Center for a workshop devoted to science which would be enabled by equipping ALMA with receivers covering 67-90 GHz, ALMA Band 2. The workshop was available via webcast; several others attended remotely. There are no radio interferometers currently operating in this band, although there has been a receiver at the Arizona Radio Observatory 12m antenna on Kitt Peak for many years. The Green Bank Telescope has recently been equipped with a very sensitive 4mm receiver. These receivers, and prospects for a similar design for ALMA were reviewed in a discussion leading into science drivers for ALMA operation in that band.

One focus of 4mm science concentrates on the fundamental transitions of a number of deuterated molecules which fall into this band. Deuterium becomes enhanced over its cosmic abundance in molecules at low temperatures owing to exchange reactions in ion-molecule chemistry. These lines are therefore good probes of specific cold regions in astrophysical environments. They may be particularly useful when coupled with ALMA's high spatial resolution for identifying cold regions in the mid planes of protoplanetary disks. Similarly, the cold regions probed by these lines provide insights into the conditions in starless cores, which may subsequently evolve to star-centered cores. Of particular interest are those molecules which persist at low temperatures in the gas phase, such as N2H+ and NH2D, which were discussed by several speakers. This *cold chemistry* was identified as the key science for Band 2 and is highlighted below in Sec. II-A.

Important probes of the nearby Universe also lie in the 4mm band, among which the formaldehyde resonance transition figures prominently. Other lines migrate into the window as a function of the redshifts of their host galaxies; the window gives a view into the important period of evolution of the Universe. CO emission shifted to z~.6 provides a window into galaxies during the last ~5Gyr of evolution, a period in which the tremendous bursts of star formation began to quiet down. At the extreme limit one arc second subtends about 6 kpc. ALMA's superior sensitivity and spatial resolution will be important to our understanding of galaxy evolution.

Presentations are available at the Workshop website (https://science.nrao.edu/facilities/alma/naasc-workshops/alma-band-2-science-workshop/program). The excellent local support enabled distant participants to appreciate the science to be done should ALMA be equipped with Band 2 receivers.

A. Key Band 2 Science: Cold Chemistry

1. Chemistry of Galactic Star and Planet Formation

Due to its relatively high abundance and low critical density, CO is one of the most commonly observed tracers of material in molecular clouds. In regions of even higher density than molecular clouds, such as in star-forming cores and protoplanetary disks, studies based on CO observations suffer from high optical depth and the variable abundance of CO relative to H_2, a result of freeze-out onto the surfaces of dust grains. Dense cores and protoplanetary disks are often better studied via the (J = 1→0) of molecules that are less abundant than CO, have a higher critical density, and are less susceptible to freeze-out. Such molecules include HCO^+, HCN, HNC, and N_2H^+ and their deuterated isotopologues (DCO^+, DCN, DNC, and N_2D^+). Although the cosmological D/H ratio is very low (~10^{-5}), at low temperatures there are no barriers to deuterium fractionation, driving up the D/H abundance of key molecules as high as ~0.1 and making the rotational lines of deuterated molecules easily observable (e.g., Millar et al. 1989; Chen et al. 2010). Studies of deuterated molecules provide observational probes of star-forming material, tests of ion-molecule chemistry, and tracers of Big Bang nucleosynthesis (Wilson 1999). The fundamental (J = 1→0) rotational lines of many key deuterated molecules are found in the 70-80 GHz range, below the frequency coverage of ALMA Band 3, but well within the atmospheric window covered by ALMA Band 2. We highlight some of the core and disk related science drivers for ALMA Band 2 development in the following two sections.

a) Dense Cores

For the reasons described above, deuterium fractionation is especially high in starless cores and the youngest protostellar cores. Recent studies have suggested that the extent of deuterium fractionation can be used as a probe of the evolutionary sequence in both low and high mass cloud cores, a sort of chemical "clock" (e.g., Battersby et al. 2010; Chen et al. 2011; Pagani et al. 2011). In the star formation process, the D/H ratio is expected to peak just before the formation of protostars, when cores are coldest. Once the core has formed one or more protostars, the temperature will rise, lowering the D/H ratio. In a study of starless cores, Crapsi et al. (2005) showed the $[N_2D^+]/[N_2H^+]$ ratio is largest in cores showing significant CO freeze-out and signs of contraction due to self gravity (evidence that these cores are on the brink of star formation).

In protostellar cores, the $[N_2D^+]/[N_2H^+]$ ratio has been observed to decrease as the protostars become more luminous and heat up the material around them (Emprechtinger et al. 2009; Tobin et al. 2013). Studies of deuterated species, paired with observations of their standard form, can be used to place cores and clumps in an age sequence.

Molecules such as DCO^+, N_2D^+, DCN, and DNC are extremely important tracers of fractionation in these cores. The (J = 1→0) transitions of these molecules are especially useful to observe, given the cold temperatures in these cores (~10 K), as the higher-J transitions are not efficiently excited. Even the (1→0) lines present challenging observations for any observatory other than ALMA given their inherent faintness (≤1K), narrow line widths (~0.3 km/s), and large variation as function of radius. The lack of 4mm observing capability has made studies of the deuterium fractionation of starless cores very difficult to carry out. Those studies that have been done so far (e.g., Bacmann et al. 2003; Crapsi et al. 2005; Daniel et al. 2007) have often used pointings (not maps) from single-dish telescopes, making it impossible to study variations of the D/H ratio *within* cores (see Figure 1 for two of the only spatially resolved studies of D/H in dense cores). The high angular resolution provided by ALMA will make possible, for the first time, to carry out statistically significant studies of the chemical ages of dense cores by providing high-sensitivity and high-angular resolution observations of the $[N_2D^+]/[N_2H^+]$ line pair.

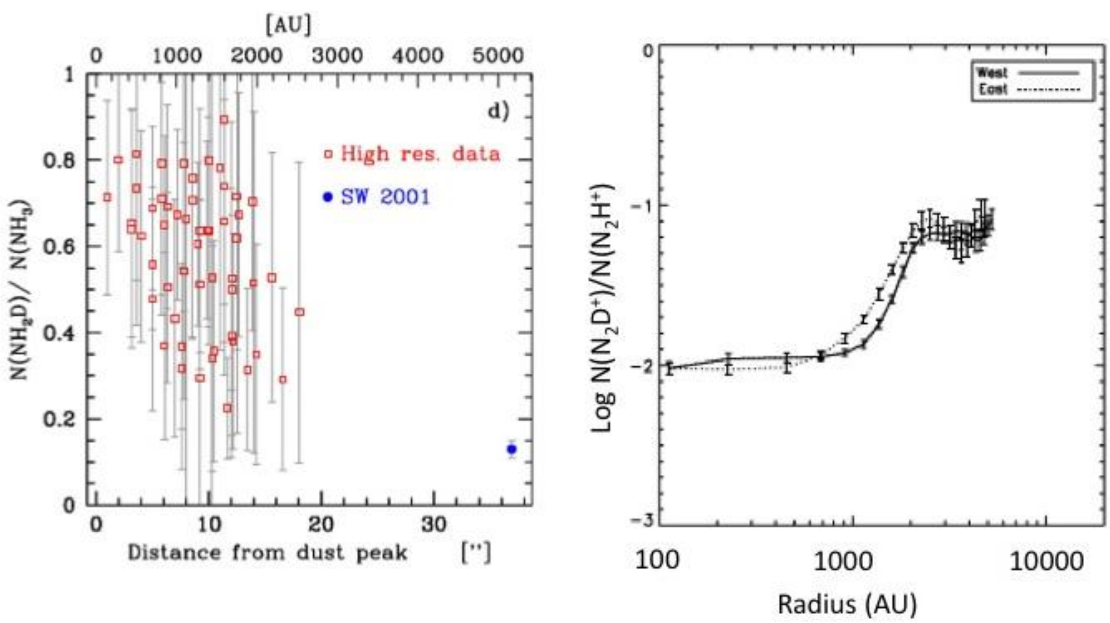

Figure 1: (left) The D/H ratio decreases as a function of radius in the starless core L1544 (Crapsi et al. 2007). (right) The D/H ratio increases as a function of radius in the protostellar core L1157 (Tobin et al. 2013). In both cores the D/H ratio cores the D/H ratio is highest in regions of high density and low temperature, with heating from the protostar in L1157 altering the deuterium fractionation in its vicinity. Thus, D/H is an excellent tracer of the chemical age of both starless and protostellar cores.

b) Protoplanetary Disks

Protoplanetary disks are made of multiple zones, including a warm outer disk irradiated by the protostar and a cold, dense midplane exposed only to an attenuated radiation field. The midplane is an important region because it is the site of planet formation, it is the main reservoir of mass in

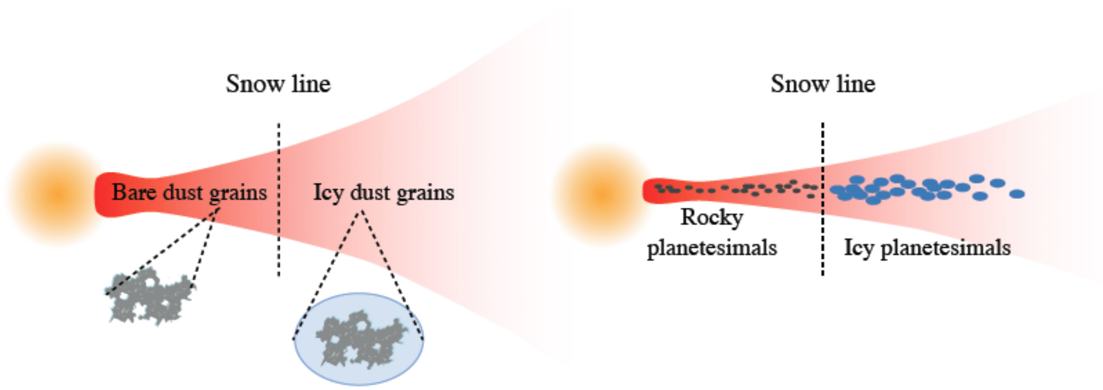

Figure 2: Close to the protostar, dust grains have no ice mantles. At larger radii, however, gas phase molecules freeze out onto the surfaces of dust grains, creating ice mantles. As a result of this process, icy planetisimals form at large radii, while rocky planetisimals form close to the protostar.

the disk, and it is the probable source of complex organics. Some molecules (notably CO) in the midplane freeze-out onto the surfaces of dust grains, so it is probed best by the lower-energy rotational lines (e.g., J = 1→0) of molecules that resist freeze-out. In addition, deuterium fractionation in the midplane increases the ratio of deuterated species compared to their standard form, making these molecules ideal probes of the midplane. In particular, species like DCO^+ and N_2D^+ trace regions with temperatures below 20K, while species like H_3^+ and its deuterated isotopologues trace regions below 16K. ALMA Band 2 will provide the only access in the world to resolved observations of key J = 1→0 transitions of deuterated molecular tracers of disk midplanes.

ALMA Band 2 would give access to the J = 1→0 transitions of key molecules, such as:

- Deuterated Ions: DCO^+, N_2D^+
- Deuterated Neutrals: C_2D, DCN
- Other isotopologues: $H_2{}^{13}CO$, $^{13}C_2H$, $H^{13}CO^+$, $HC^{18}O$, $H^{13}CN$, $HC^{15}N$
- Small organics: H_2CO, C_2H

In the next two subsections we highlight two important cases for ALMA Band 2 observations of protoplanetary disks.

(1) The locations of snow lines and their sharpness

A snow line in a protoplanetary disk is the boundary region where a molecule (e.g., CO) freezes out onto dust grains and leaves the gas phase. Beyond the snow line, dust grains have thicker ice mantles, greatly affecting planet formation efficiencies. Icy grains are stickier than bare grains, creating larger dust grains, pressure traps, and generally promoting the growth of planetary bodies, especially the gas and ice giant planets (see Figure 2). Dust grains without icy mantles lead to conditions that form the rocky planets (e.g., Ciesla & Cuzzi 2006; Ros & Johansen 2013).

Snow lines in protoplanetary disks are revealed by their chemical signatures. The CO snow line, for example, has recently been revealed by ALMA Cycle 0 observations of N_2H^+ in the disk around TW Hya (Qi et al. 2013) and of DCO^+ in the disk around HD 163296 (Matthews et al. 2013). Since N_2H^+ is quickly destroyed by CO (to make HCO^+ and N_2) the CO snow line is revealed by N_2H^+ observations – N_2H^+ is only found in regions where CO has frozen out. ALMA Band 2 will open up the possibility of observing additional snow lines, beyond CO, and will also enable more detailed characterization of the CO snow line.

(2) Tracing deuterium fractionation throughout disks

The D/H ratio in the Earth's ocean ($\sim 1.6\times10^{-4}$) is almost an order of magnitude higher than that of the gas giant planets and a factor of a few higher than that in the ice giant planets (see Figure 3; Hartogh et al. 2011). This ratio is similar to that in comets found in the Oort cloud and Kuiper belt, suggesting that these bodies may represent the origin of the Earth's oceans. ALMA Band 2 observations of deuterated species in protoplanetary disks opens up the possibility of studying deuterium fractionation as a function of radius and scale height, thereby helping to explain the origin of the wide range of D/H in planets in our solar system.

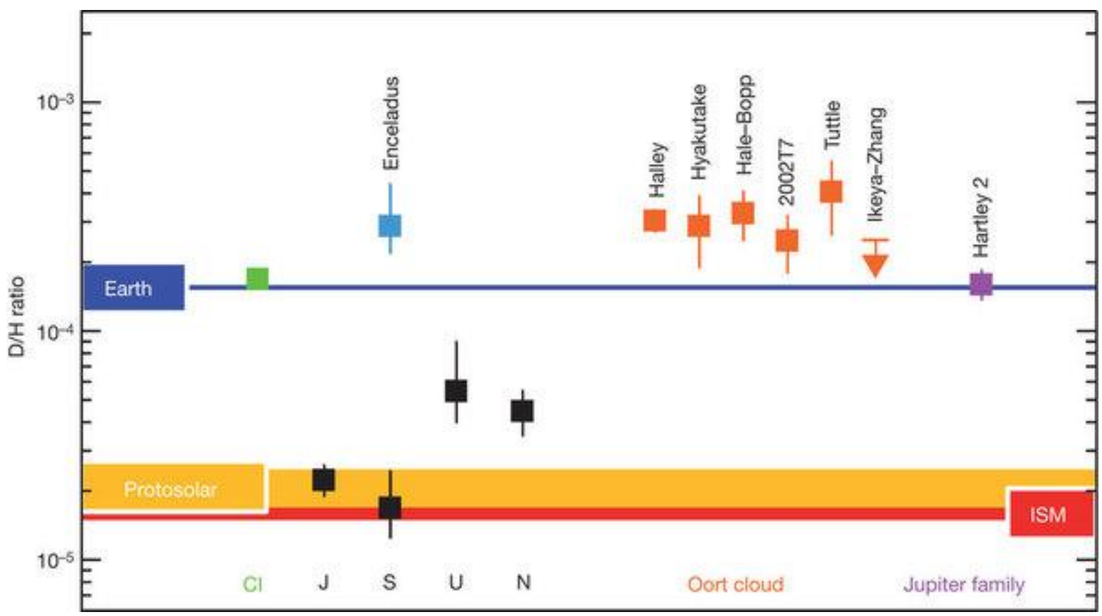

Figure 3: The D/H ratio on Earth is similar to that of Oort cloud and Jupiter family (with Kuiper Belt origins) objects, suggesting these as the origin of Earth's water. The gas giant (Jupiter and Saturn) D/H ratio is almost an order of magnitude lower than that of Earth's, with the ice giant planets (Uranus and Neptune) having an intermediate D/H ratio. ALMA Band 2 observations will enable the study of deuterium fractionation as a function of disk radius and scale height, shedding new light on the origins of Earth's D/H ratio.

III. Draft Specifications and ICDs

The receiver noise specification for ALMA band 2 is 30 K SSB over 80% of the RF band and 47 K SSB at any RF frequency in the band [Cunningham 2007], where the RF band is defined as 67-90 GHz. This noise performance is to include all contributions from warm optics, cryostat windows, and IR filters. Table 1 shows the preliminary gain and noise budget for the Band 2 cartridge. It assumes a combined room temperature lens and window. This makes clear the penalty paid by the baseline refractive optics design and motivates the effort to investigate a reflective optics solution. As indicated by Table 1, the optics and the cryogenic LNA dominate the receiver noise. To achieve the specifications will require reflective optics and a LNA with less than 25K noise temperature over 80% of the band. Section IV describes the progress for the low-noise amplifier. Unfortunately, the progress toward a reflective optics design was hampered by the extra resources needed to complete the Band 2 OMT prototype, as described in Section VII. The optics design, and therefore also the draft specifications and ICDs, are proposed to be addressed in a follow-on ALMA Band 2 development project, submitted in August 2013.

Table 1: Preliminary gain and noise budget for the ALMA band 2 receiver.

Component/Stage	Gain (dB)	Noise Temperature (K)	T_{EQ} (K) referenced to the input
Lens/Window (297K)	-0.16	11.1	11.1
IR Filters (15K, 110K)	-0.1	2.5	2.6
Feedhorn (15K)	-0.1	0.35	0.4
OMT (15K)	-0.1	0.35	0.4
Cryogenic LNA (15K)	30	30	33.4
Cryogenic Isolator (15K)	-1	3.9	insignificant
Cryogenic Postamp (15K)	25	80	0.1
Waveguide Feedthru (297K)	-1	77	insignificant
Donwnconverter (297K)	-15	5000	insignificant
Warm IF Amplifier (297K)	20	175	insignificant
Total	**57.5**		**48.0**

IV. Prototype Low-Noise Amplifiers

Along with the receiver optics, the cryogenic LNA is the most important contributor to the overall receiver noise. There are two options for the Band 2 cryogenic LNA. For the potentially lowest noise performance, the baseline option is to use 35nm gate length InP HEMT MMIC LNAs. Preliminary results of small samples from a few wafer runs show lower noise in both ALMA Bands 2 and 3 than can be obtained using the current state-of-the-art hybrid “chip-and-wire” LNAs using the best 80nm gate length InP HEMTs [Bryerton 2009 and Varonen 2013].

Fig. 4 shows the measured performance to date of the best 35nm MMICs in the Band 2 frequency range compared to hybrid MIC LNAs built using CRYO3 transistors. While the MMICs do here show the potential for lower noise, it is not yet clear that this performance can be obtained in large quantity. This issue is addressed in the follow-on ALMA Band 2 development project proposal.

There have been two MMIC designs targeted for ALMA Band 2--these are shown in Fig. 4 as MMIC-A (“EBLNA81”) and MMIC-B (“EBLNA81B”). The EBLNA81B was designed in response to EBLNA81 appearing to be tuned slightly high in frequency for Band 2. The redesign appears to be successful as the performance below 80 GHz is significantly improved. However, more data is clearly needed before a final achievable specification can be determined.

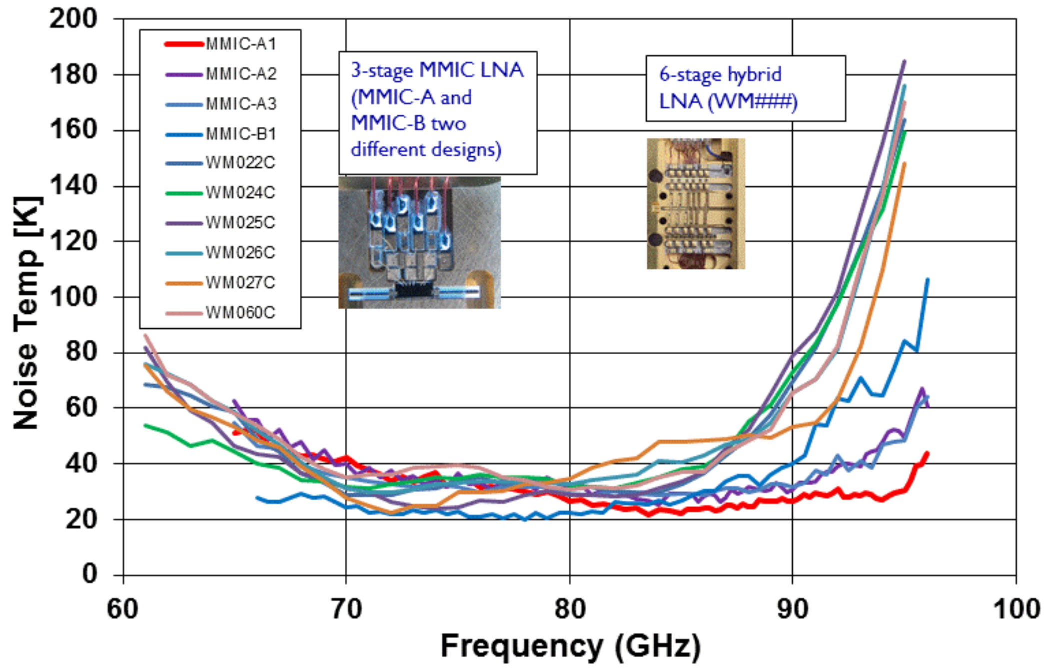

Figure 4: Measured receiver noise of 35nm MMIC LNAs and 80nm MIC LNAs (labelled as "WM###C") designed for ALMA Band 2

V. Prototype 2SB Downconverter

The Band 2 cartridge will be implemented as a cryogenic HFET front-end followed by a conventional room-temperature mixer that is compatible with the existing ALMA local oscillator frequency plan and IF subsystem. In other words, we require a 67-90 (or 67-94) GHz fundamental-frequency, image-rejecting mixer with at least 4-12 GHz IF bandwidth. Although single-sideband operation could be achieved with individual component mixers and hybrids as described later, a single-chip implementation would further facilitate uniformity of performance. This integration would minimize cabling and/or manual wire bonds in the RF circuit, leading to improved reliability, stability, and gain flatness.

Due to synergies between the ALMA requirements as stated above and that of a potential 3mm focal plane array on the Green Bank Telescope (GBT), the design and fabrication of a broadband, I/Q, balanced mixer was also completed during the period of performance of this design study. The chip dimensions are 1.3 x 1.0 x 0.1 mm, and it was fabricated by United Monolithic Semiconductors (UMS) in their GaAs Schottky diode MMIC process. The fabrication of these MMICs was not part of the original proposed design study, but was the outcome of a shared-run opportunity. These MMICs were only recently delivered as of writing of this report and will be tested in the next year. A chip photograph and simulated performance is shown in Fig. 5.

As a backup solution, proposed as part of this design study, a commercial multi-chip MMIC solution was investigated. The HMC-MDB277 MMIC mixer from Hittite Microwave Corporation was used as the fundamental DSB mixer. With no image-rejecting capability, two such chips are required along with external RF/LO hybrids and splitters to complete the image-rejecting mixer configuration for each polarization. Preliminary measurements indicate that this

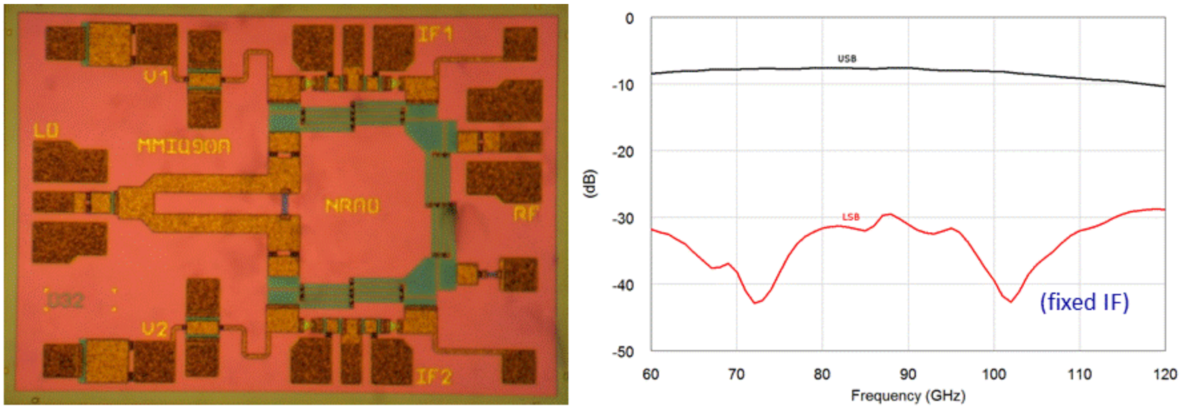

Figure 5: Photograph and simulated performance of a sideband-separating balanced mixer operating from 60-120 GHz. The plot on the right shows simulated upper sideband (USB) and lower sideband (LSB) conversion gain at the USB IF output versus LO frequency at a fixed IF. It indicates a predicted sideband rejection ratio greater than 20dB for LO frequencies from 60-110 GHz.

approach will meet the ALMA sideband rejection requirements, though the LO power requirement is relatively high and will increase the total cost of the LO components. With no image-rejecting capability, two such chips are required along with external RF/LO hybrids and splitters to complete the image-rejecting mixer configuration for each polarization. A photograph of the prototype 2SB module built using these MMICs as part of the design study is shown in Fig. 6. Fig. 6 also shows the USB and LSB measured data at LO frequencies of 75 GHz and 80 GHz. It appears to meet the ALMA sideband rejection requirements, though the LO power requirement are relatively high and will increase the cost of the LO components. This module was tested using an external IF hybrid.

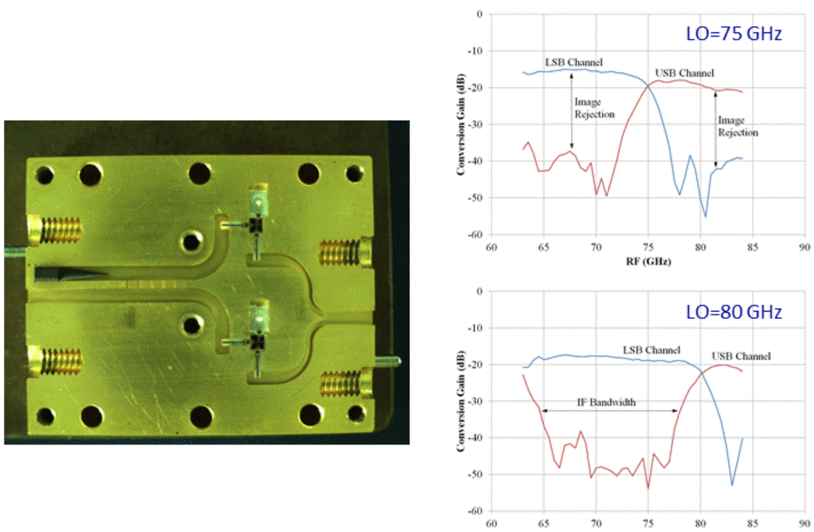

Figure 6: Photograph (left) and measurements (right) of packaged 2SB MMIC downconverter module

VI. Prototype LNA Testing at the ARO 12m Telescope

As discussed earlier, two different LNA technologies (80nm MIC and 35nm MMIC) are possible candidates for use in the ALMA band 2 receiver. It was proposed in this design study to evaluate these technologies with actual test observations on a radio telescope. The Arizona Radio Observatory (ARO) completed such tests by observing on the former 12m telescope (see

Fig. 7) of the ARO at Kitt Peak. The Kitt Peak site (elevation ~ 6500 ft.) is excellent for measurements at Band 2, as supported by observations in this frequency region by the ARO 60 - 90 GHz receiver. The baseline user instrument was a dual-polarization, SIS mixer system. The ARO compared the performance of the current SIS receiver with the two prototype LNA systems on the telescope with on-sky measurements, both in spectral-line and continuum modes, including long integrations on astronomical sources. In order to conduct such tests, the two amplifier types were incorporated into separate receiver cartridges (Fig. 8). These cartridges were then installed into the same Dewar that houses the current ARO Band 2 SIS receiver. This Dewar contains a 4 K refrigerator system with 1.5 watts of cooling capacity such that all receiver cartridges can be evaluated at 4 K. (The ALMA band 2 LNAs will be on the 12 K plate, but their performance at 4 K is indicative and, in fact, very interesting for other applications.)

The ARO 12m telescope had a suite of spectrometer back ends that were used during the test observations. All back ends required a 1.5 GHz input. A frequency down-converter was built to convert the 60 – 90 GHz output from the amplifiers to the 1.5 GHz IF required by the back ends. This down-converter also enabled single-sideband operation for the LNA receivers, thus maximizing their performance. A block diagram of the test receiver is shown in Fig. 9. As shown in the block diagram, an extra room temperature postamp was required for the MMIC LNA receiver due to the lower gain of the MMIC versus the MIC. This added extra noise to the MMIC receiver. This is easily remedied in future by designing the cryogenic MMIC LNA to have more gain and ensuring that the warm portion of the receiver chain will have negligible impact on the overall receiver noise.

In addition to measurements of receiver noise, long integrations on the sky were performed with each receiver. The integrated spectra from these observations are shown in Figs. 10-11. Overall, these measurements showed little difference between the two types of LNAs when used in an astronomical receiver setting.

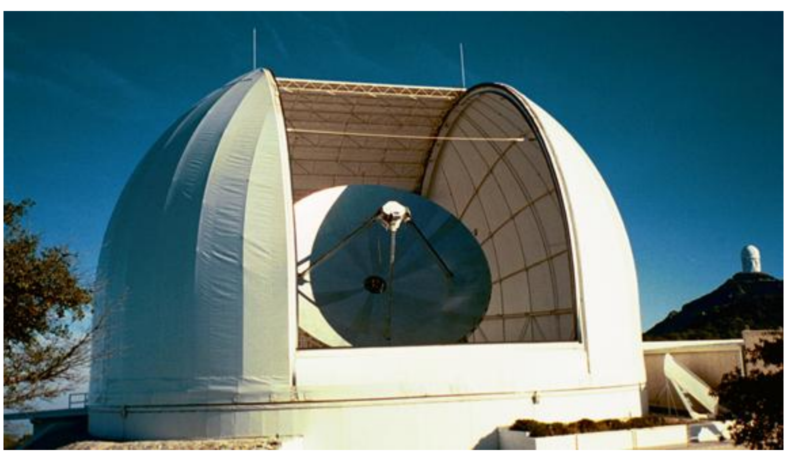

Figure 7: Photograph of ARO's former 12m telescope on Kitt Peak, site of the Band 2 SIS-LNA comparisons described in this report.

Figure 8: ARO receiver cartridges with 80nm MIC LNA (left) and 35nm MMIC LNA (right).

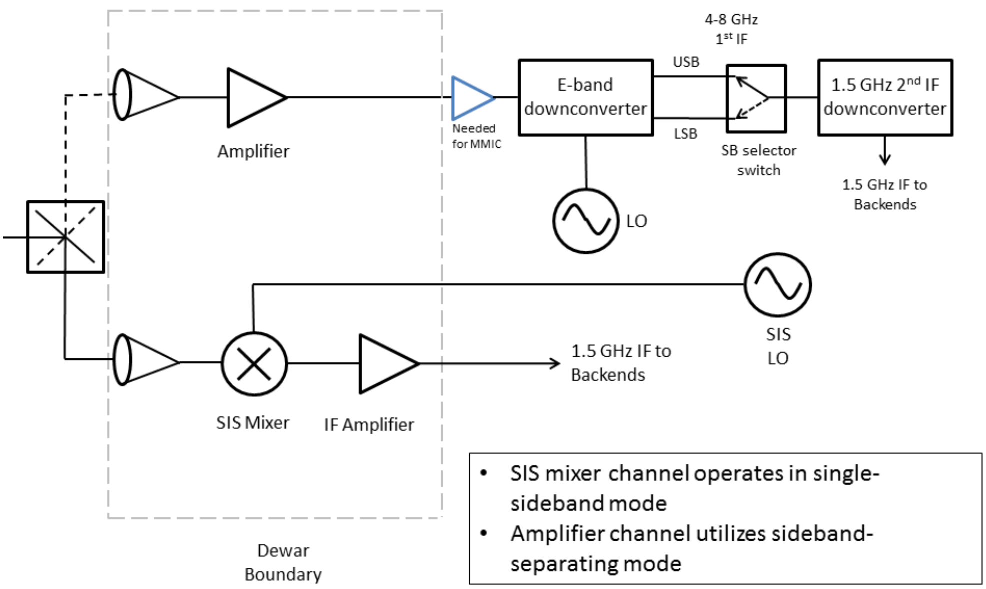

Figure 9: Block diagram of ARO 12m receiver system used to compare the performance of the Band 2 SIS and LNA systems.

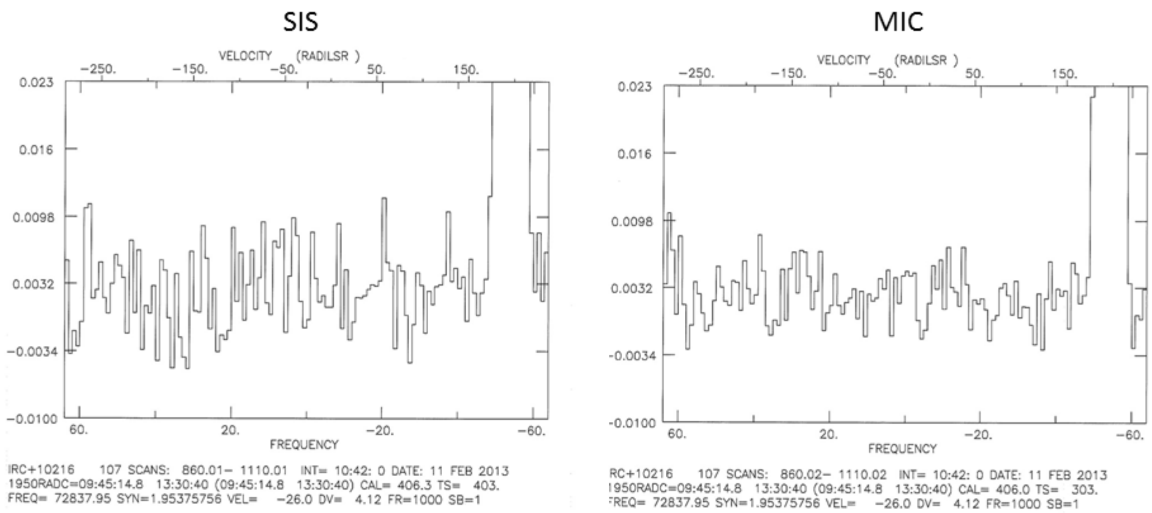

Figure 10: Measured spectra at 72.8 GHz from 10hr 42min integration on source IRC+10216 using the ARO 12m telescope for both the SIS (left) and MIC LNA (right) receiver channels. System temperature was 403K for the SIS channel and 303K for the MIC LNA channel.

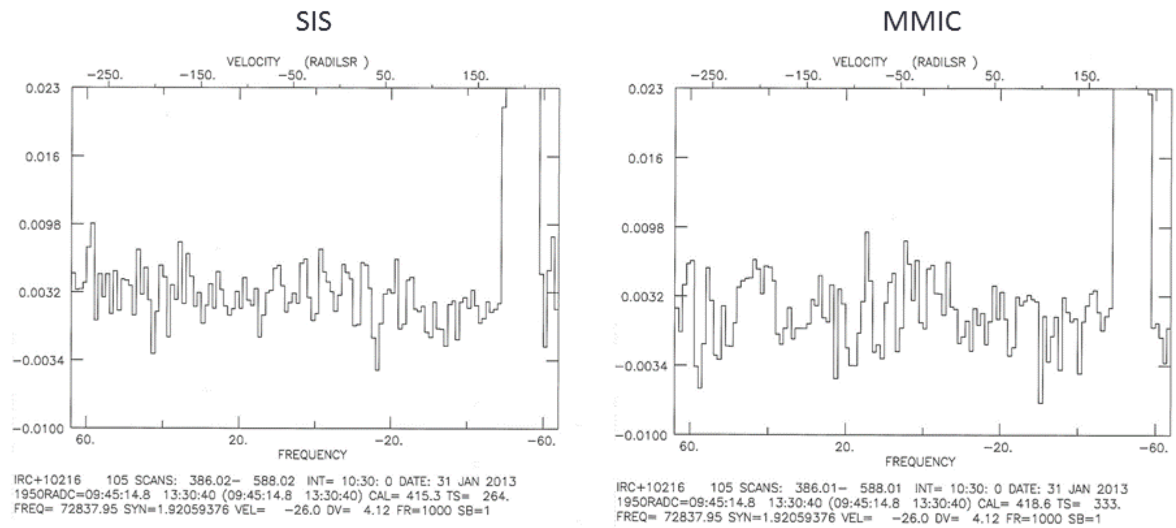

Figure 11: Measured spectra at 72.8 GHz from 10hr 42min integration on source IRC+10216 using the ARO 12m telescope for both the SIS (left) and MMIC LNA (right) receiver channels. System temperature was 264K for the SIS channel and 333K for the MIC LNA channel.

VII. Optics

The optics for bands 1 and 2 are the most demanding in terms of size. The optical elements are too large to be accommodated inside the cryostat, so as per the original ALMA receiver optics design [Lamb 2001] only the feed horns can be cooled. Reflective optics were originally considered but the folded geometry resulted in optics that were too large to fit in the space above the cryostat without obscuring other bands. Use of a single lens to couple into the corrugated horn resulted in a much more compact design and is therefore the current baseline optics plan.

In this baseline optics plan, the Band 2 receiver window location on the cryostat plate warrants a beam tilt of 2.48° to the telescope axis. In order to provide an illumination taper of about -12 dB at the edge of the subreflector, a horn of reasonable length with a focusing lens to transform the waist of the horn to the telescope waist is proposed. The horn will be cooled to 15K. The lens is at a distance of 102mm from the aperture of the horn. The lens is at 300 K and also serves as the vacuum window. The telescope waist is located at a distance of 261mm above the lens. By proper choice of the feed parameters and the focal length of the lens, the feed waist can be matched to the telescope waist at all frequencies within the band. The dissipation loss, truncation effects and reflection in the lens is estimated to contribute about 11 K to the receiver temperature, as shown in Table 1. The infrared (IR) filters at the 15-K and 110-K stages contribute another 2-3 K.

Improvements to the baseline optics design were proposed to be investigated during this design study. These improvements included an alternative optics design with a meniscus lens that mounts at the aperture of the horn. The lens would be coolable to 15 K, resulting in a potential 7K reduction in receiver temperature. Antireflection coating or grooving of the lens for broadband matching would also be explored. The lowest noise option of using reflective optics to match the waist of the horn to that of the telescope was also proposed to be explored.

In all scenarios, a single feed horn is employed and the two polarizations are separated using an othomode transducer (OMT). As part of this design study, a 67-90 GHz OMT based on turnstile junction was developed and three numbers of the OMT were fabricated in the CDL machine shop. CDL has successfully developed OMTs of this design for X-, Ku- and Q-bands. In spite of the experience gained in machining of this type of OMT during the development process, the machining of the E-band OMT was slower than anticipated, mainly due to the smallness of the various component parts. It also points to the fact that we may have hit the upper limit of manufacturability of this design. Preliminary measurements have been completed using a WR-10 calibration. Fig. 12 shows the assembled OMT and measured reflection coefficient from 69-96 GHz. More refined measurements will be done with WR-12 calibration using the Anritsu VNA in Green Bank. We will investigate further the manufacturability, including cost, of this OMT in quantities need for full production of Band 2 cartridges. Due to the increased resources needed for OMT design and fabrication, we were unable to complete the optics analysis and improvement studies described in the previous paragraph. These are addressed in the follow-on Band 2 development project proposed in August 2013.

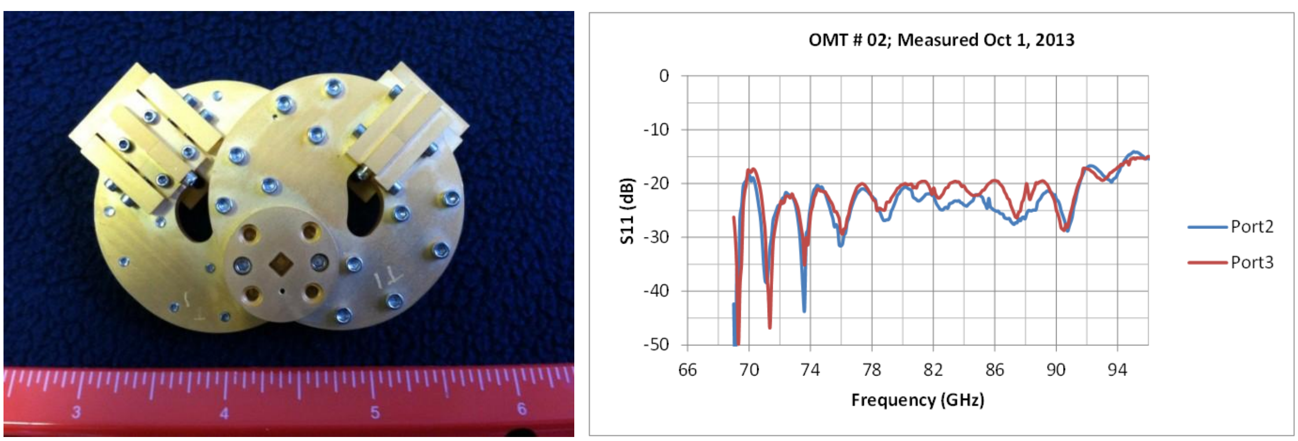

Figure 12: Photograph of the OMT (left) and measured reflection coefficient for the two polarizations

VIII. Conclusions and Future Work

During this one-year design study, several important advances were made toward the realization of a production-ready Band 2 receiver cartridge for ALMA. These include characterization of two types of cryogenic low-noise amplifiers, including use in an astronomical setting for long integrations; design and testing of downconverter module solutions, and design and fabrication of a orthomode transducer. In addition, a Band 2 science workshop was held, identifying and expanding on the key science areas to be explored with a Band 2 receiver on ALMA. More work remains to be done before a Band 2 cartridge is ready for full production and outfitting on ALMA. This remaining work, predominantly in optics design and in amplifier manufacturability, is the subject of a two-year project proposed in August 2013 to the ALMA development program

IX. References

Bacmann et al. 2003, ApJL, 585, 55

Battersby et al. 2010, ApJ, 721, 222

Bryerton, E. et. al. 2009 IEEE MTT-S Int. Microwave Symp. Dig.

Chen et al. 2010, ApJ, 743, 196

Chen et al. 2011, ApJL, 713, L50, 196

Ciesla & Cuzzi 2006, Icarus, 191, 178

Crapsi et al. 2005, ApJ, 619, 379

Cunningham, C. T., Tan, G. H., Rudolf, H. and Saini, K. 2007, "Front-End Sub-System for the 12 m-Antenna Array Technical Specifications", ALMA-40.00.00.00-001-A-SPE

Daniel et al. 2007, ApJ, 667, 980

Emprechtinger et al. 2009, A&A, 493, 89

J. W. Lamb, J. W., Baryshev, A., Carter, M. C., D' Addario, L., Ellison, B. N., Grammer, W., Lazareff, B., Sekimoto, Y., Tham, C. Y. 2001, ALMA Memo 362.

Matthews et al. 2013, A&A, in press

Millar, Bennet, & Herbst 1989, ApJ, 340, 906

Pagani, Roueff, & Lasaffre 2011, ApJL, 739, 35

Qi, Oberg, & Wilner et al., 2013, arXiv:1307.7439

Ros & Johansen 2013, A&A, 552, 137

Tobin et al. 2013, ApJ, 765, 18

Varonen, M. et al. 2013 IEEE MTT-S Int. Microwave Symp. Dig.

Wilson 1999, Rep. Prog. Phys., 62, 143