Coherent Arrays for Astronomy and Remote Sensing

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Team Leads:

Prof. Tony Readhead
California Institute of Technology
acr@astro.caltech.edu

Dr. Kieran Cleary
California Institute of Technology
kcleary@astro.caltech.edu

Dr. Charles Lawrence
Jet Propulsion Laboratory
Charles.Lawrence@jpl.nasa.gov

Coherent Arrays for Astronomy and Remote Sensing
Keck Institute for Space Studies

Final Report

A.C.S. Readhead and Kieran Cleary

Summary

The Coherent Arrays for Astronomy and Remote Sensing Program sponsored by the Keck Institute for Space Studies has had a profound impact on astronomy at Caltech – both at JPL and on campus – and worldwide. It provided funds for the establishment of a world-class coherent detector laboratory – the Cahill Radio Astronomy Laboratory (CRAL) that, in collaboration with JPL and Northrop Grumman, now sets the global standard in coherent detectors in the centimeter-millimeter wavelength range – as shown by three key highlights: (i) NRAO's recent selection of CRAL MMIC detectors over its own in house MIC detectors for the upgrade of the ALMA Band 2 receivers; (ii) NSF's funding of a 16-element 85 GHz – 115 GHz focal plane array (ARGUS) for the Green Bank Telescope ($1M); and (iii) NSF's funding of the 26 GHz – 34 GHz CO Mapping Array Pathfinder (COMAP $2.5M). The funding of COMAP was particularly important since it demonstrated in the wake of the NSF decline of the CARMA proposal (2014) that the US astronomy community and the NSF were prepared to fund large new projects at the Owens Valley Radio Observatory (OVRO), enabling the OVRO to re-establish itself as a world-class radio observatory and convincing Caltech to continue its funding of the OVRO. It is no exaggeration that the KISS coherent detector program played THE major role in saving the OVRO. The position of the CRAL and of the OVRO is now very strong and the staff, decimated by the CARMA decline, is being rebuilt and is once more at a robust strength. Two new multi-national partnerships – the Radio Astronomy Partnership (RAP) and the MMIC Partnership (MMICP) have been established at Caltech as a direct result of the KISS investment in creating the CRAL, and these are providing independent funding to OVRO and the CRAL. There are now eight agency-funded programs at the OVRO and we are optimistic about the prospects of having two more programs funded in the next year, in view of important science breakthroughs at OVRO over the last 6 months.

1. Introduction

This program has enabled a spectacular improvement in the performance of Indium Phosphide (InP) HEMT (high electron mobility transistor) MMIC (monolithic microwave integrated circuit) amplifiers at frequencies above 67 GHz. A new test and measurement capability, the cryogenic probe station (CPS), was funded through this program and has become a "game changer" in the development of new instruments based on coherent arrays for radio astronomy.

This report summarizes the progress made in these two crucial areas of this program: amplifier development and coherent arrays.

Instrument, Project or Telescope	Frequencies (GHz)
ALMA IF	Band 6 IF + 128 amps for Japanese bands
AMI (Cambridge)	12–18
AmiBA	90
Aura-MLS	118
CAPMAP	90
CBI2	30
Effelsberg RF	22, 30, 45, 90
EVLA	all bands 1–50
GBT	most bands, 22 GHz array
JPL Deep Space Network	8.4, 22, 32
Korean VLBI	45
LMT Redshift Search Receiver	73–111
Odin	90–120
OVRO 40m	15
Planck LFI	30, 45, 70
QUIET	45, 90
SEQUOIA	80–115
SZA (CARMA)	30, 90
VLBA RF	22

Table 1 *Major telescopes with HEMT amplifiers from JPL CHOP and UMass Programs*.

2. MMIC Amplifiers

Three decades ago Schottky diode mixers and GaAs MESFET amplifiers dominated receiver front-ends in radio astronomy instrumentation. These were supplanted by SIS mixers at wavelengths as short as 1 mm and GaAs HEMT amplifiers in the 1980s. The 1990s witnessed another technological revolution with the development of InP HEMT devices with 100nm gate length. Discrete transistors and MMIC amplifiers developed under the NASA-led CHOP program became nearly ubiquitous in radio astronomy receivers between 20 and 80 GHz. Among other instruments, the devices can be found in the EVLA, ALMA and GBT (see Table 1).

In 2007, Northrop Grumman developed a new 35 nm gate length process which offered the prospect of further improvement in performance, especially at high frequency. The KISS program reported here funded the setting up and outfitting of the Cahill Radio Astronomy Lab[1] (CRAL) and the development of the CPS, both of which enabled a collaboration with JPL to exploit the 35 nm process for radio astronomy and paved the way for other proposals to NASA and NSF which allowed that work to be continued.

As a result, MMIC amplifiers now exceed SIS-based receivers in noise temperature performance at W-band and offer many practical advantages when it comes to the construction of focal plane arrays, making them attractive for this application even at frequencies above 100 GHz. At the same time, the 35 nm MMICs from this effort have demonstrated superior noise temperature performance over “chip-and-wire” (microwave

[1] http://cral.caltech.edu

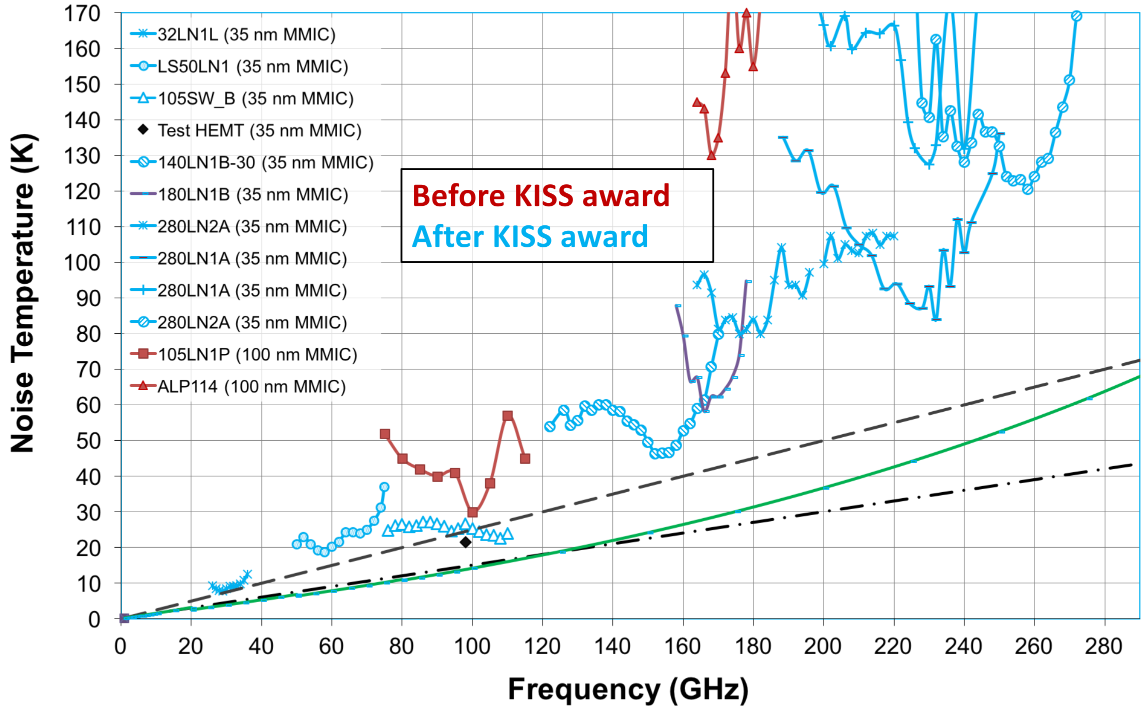

Figure 1 *This figure shows the performance of MMIC amplifiers in the 30-300 GHz range. State-of-the-art results, based on measurements of 30 nm designs are shown in blue. The best results obtained prior to the KISS* Coherent Arrays *award are shown in red. The dashed and dot-dashed curves indicate noise temperatures which are five times and three times the quantum limit, respectively. The green curve is the latest HEMT noise performance prediction based on measurements of 35 nm devices.*

integrated circuit, or MIC) amplifiers in the 67-90 GHz band. It is likely that this lead is maintained at higher frequencies owing to the difficulty in making stable MIC amplifiers with the 35 nm transistors.

In this section, we describe the development of the CPS and discuss the game-changing impact this has had on the development of coherent arrays. We also describe the advances in MMIC amplifier performance which have been made possible through the use of the CPS and the funding provided by this program. Figure 1 summarizes the performance in MMIC noise temperature over the 30-300 GHz range, showing the situation before and after the efforts kick-started by our KISS funding.

2.1 Caltech Cryogenic Probe Station

The process of evaluating new device technologies has historically been tedious. Devices were modeled, installed in packages and tested at room and cryogenic temperatures. Based on this performance, the models are updated and additional amplifiers can be designed around the device. The slowest part of this process is the cryogenic testing of devices, particularly where device uniformity is important (e.g., in array applications) and statistics must be established. In order to address this measurement bottleneck, and using

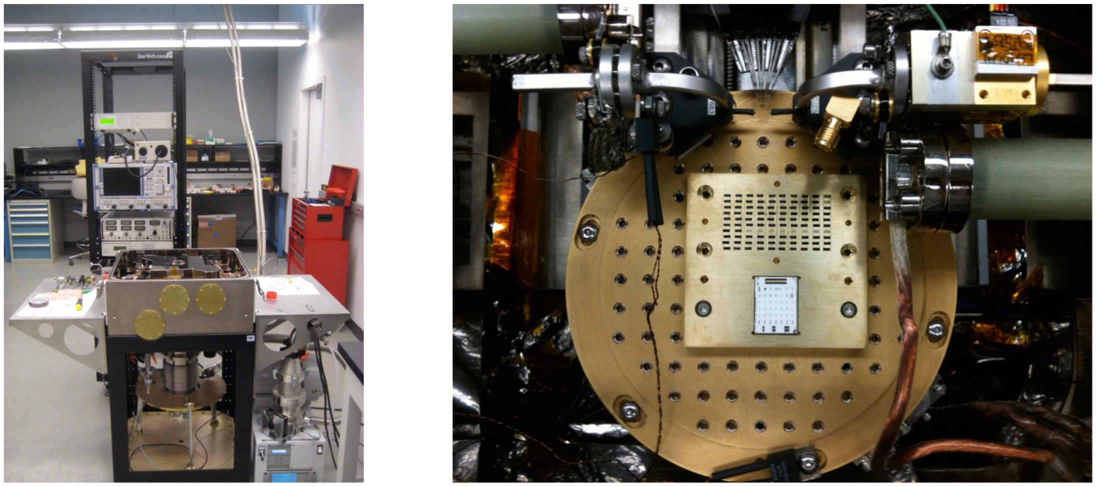

Figure 2 *Caltech Cryogenic probe station with rack of associated control and measurement equipment (left). Probe station interior, showing the RF probes and the chip.* carrier with inset calibration substrate (right).

seed funds from the Keck Institute for Space Science (KISS), Caltech-JPL has developed a cryogenic probe station (CPS; see Fig.2) capable of measuring MMIC amplifiers for S-parameters and noise temperature (currently in two separate cool-downs) at 18 K. The CPS has been used to characterize the 90 GHz amplifiers from a number of wafer runs, allowing rapid characterization of these devices in far greater numbers than before possible. Most recently, the CPS has been used to measure the relative noise performance of 600 amplifiers from 35 nm wafers carrying new designs for ALMA Band 2 (see Section 2.4). This was achieved in around 200 hours, with each measurement taking about 20 minutes. Neglecting the time needed to package these devices, testing them by traditional means would take around 150 days, assuming two devices were tested per cool down.

Packaging 600 chips would cost over $50,000 for assembly alone, so the CPS also offers significant economies. These cost-savings, along with the factor ~20 reduction in measurement time, allows chips to be characterized in numbers that would have previously been prohibitive, opening up large-number statistics for the cryogenic performance of these devices.

The CPS allows screening for cryogenic noise and gain, but also the careful selection of chip combinations to produce the desired performance in cascade. *This non-destructive, cryogenic screening capability has not previously been possible at these frequencies*.

2.1.1 Chip Screening

In the past, individual MMIC amplifier chips could be packaged and tested individually and the lowest noise blocks were then selected to become part of the receiver. For focal-plane array applications, the individual array elements typically incorporate multiple receiver functions in a single integrated package. Since the amplifier chips cannot be packaged, tested and then removed non-destructively from the package to be re-used in the integrated module, this means that the cryogenic noise and gain properties of the chips used in these integrated packages could not be known beforehand. Instead, chip selection was made on the basis of measurements on other devices from the same wafer or on room-temperature on-wafer DC characteristics. Depending on the size of the sample of packaged devices, one could predict the average properties of the devices from a particular wafer but this did not take into account the sometimes significant intra-wafer variability in chip performance.

With the cryogenic probe station, we can non-destructively measure the cryogenic S-parameters and noise of the MMIC amplifier chips. This enables cryogenic screening of amplifiers for integrated MMIC modules. Even for applications where individually-packaged amplifiers are needed, such screening saves time and expense, which might be wasted in screening the packaged devices.

To date, the CPS has been used to perform chip selection for the CARMA 3-mm upgrade, the *Argus* 100 GHz spectrometer array and ALMA Band 2 receivers.

3. *Developments Resulting from the KISS Award*

Here we describe the programs which have allowed us to continue the work of MMIC development kick-started by the KISS award.

*2.2.1 NASA APRA Wafer Run*s

In 2009, JPL successfully won funding through NASA's Astronomy and Physics Research and Analysis (APRA) program for wafer runs on the 35 nm process in order to further reduce the noise temperature of cryogenic amplifiers in the 40–200 GHz range. Three wafer runs were carried out and many new designs in this frequency range were tested. At the CRAL, measurements using the CPS were focused on the main science band of interest: the 75-116 GHz range, and new world records were established at this band and higher frequencies (Fig. 1). The designs funded by this program formed the basis for successful amplifiers used in CARMA, *Argus* and NRAO's ALMA Band 2 prototype receiver.

2.2.2 CARMA 3 mm upgrade

Prior to the demise of the Combined Array for Research in Millimeter-wave Astronomy (CARMA), the NSF funded an upgrade of its 3mm receivers (through the CARMA grant). Because of the low-noise achieved with the APRA-funded designs, InP MMICs were selected for these receivers and the NSF award included funds for a wafer run to produce a sufficient number of amplifiers for CARMA. These amplifiers were cryogenically probed at Caltech in order to select the best devices.

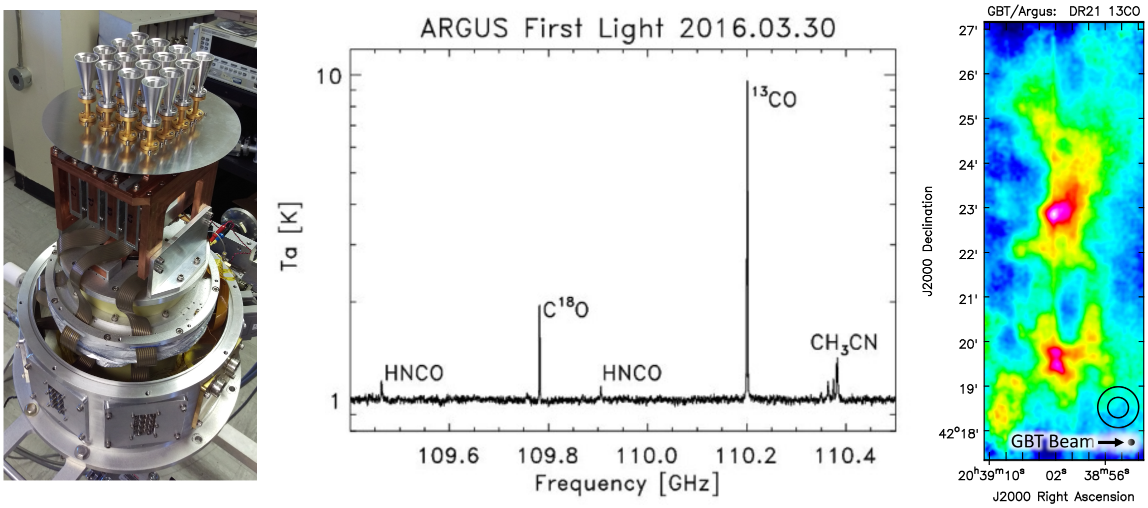

Figure 3 *(Left):* Argus *receiver cryostat interior, showing feedhorns, front-end modules and cryogenic IF/LO boards; (Center): Argus first-light spectrum taken towards Orion; (Right): Argus commissioning image of the high-mass star formation region DR21 in* ^{13}CO $J = 1 - 0$.

2.2.3 Argus

Argus (NSF AST 1207825; PI Sarah Church, Stanford University) is a 16-pixel, 85-115 GHz spectrometer array currently being commissioned on the Green Bank Telescope (GBT). The amplifier designs used in this array were also based on earlier prototypes developed using APRA funding. The amplifier chips were cryogenically probed for selection based on the lowest noise. This was particularly important given the very high level of integration in the miniaturized front –end modules (which were also designed at Caltech).

Figure 3 shows the receiver interior during lab testing as well as a commissioning spectrum taken towards Orion and an image of star-formation region DR21. The future availability of GBT to the US community is now is doubt, as this facility is divested from NRAO. This use of the *Argus* receiver forms a key part of the science case for continued operation of GBT at high frequency as it provides a much-needed complement to the Atacama Large Millimeter Array (ALMA) for US astronomers.

2.2.4 NRAO/ALMA Band 2 Amplifiers

NRAO won finding from the ALMA Development Upgrades program, with Caltech/JPL as a subcontractor, to build a prototype Band 2 receiver covering 67-90 GHz. For its part, Caltech/JPL undertook to design new MMIC amplifiers for this frequency range and provide sufficient amplifiers for a full roll-out of NRAO's Band 2 receiver. Funding was provided for a full wafer run on NGC's 35 nm process, which was spread over two half-runs: the first to test new designs and the second to obtain a production quantity of the best designs. At the same time, NRAO would design an amplifier based on microwave integrated circuit (MIC) technology, using individual transistors. Selection of the amplifier for the production of all receivers would be based on a straight competition between the MIC and MMIC designs.

To date, the first wafer run has been completed and MMIC designs from this run have been tested and incorporated into prototype amplifier modules. The Caltech/JPL MMIC performance is significantly better compared to that of the MIC designs from NRAO and so the MMIC designs have been formally selected by NRAO for their Band 2 production proposal to ALMA. In fact, the MMIC designs have set a new record in performance at this frequency, achieving sub-20K noise temperatures at frequencies over 70 GHz for the first time.

3. Management Aspects of the Program

3.1 Funding Resulting from this Program

(i) This overall program has been matched at JPL with ~$1.2M in R&TD funds
(ii) We believe that it is a direct result of this program that we received ~$1.2M in NASA APRA funding (after being declined every year for the preceding 8 years)
(iii) A direct result was our Stanford-Caltech-JPL NSF ATI funding of ~$1.0M
(iv) $200k in private funding to build a new receiver in the CRAL
(v) $1M in NSF funds (CARMA grant) to build the CARMA 3mm receivers
(vi) $680k for the development of ALMA Band 2 amplifiers

3.2 Papers/Technical Reports to date

Papers published based on work done at the KISS-funded CRAL or using KISS-funded facilities (such as the CPS) are listed below.

Varonen, M., Reeves, R.,Kangaslahti, P., Samoska, L., Kooi, J., Cleary, K., Gawande, R., Akgiray, A., Fung, A., Gaier, T., Weinreb, S., Readhead, A., Lawrence, C., Sarkozy, S., Lai, R., An MMIC Low-Noise Amplifier Design Technique, IEEE Transactions on Microwave Theory and Techniques, vol. 64, no. 3, pp. 826-835, March 2016

Gawande, R., Reeves, R., Cleary, K., Kooi, J., Readhead, A.C., Gaier, T., Kangaslahti, P., Samoska, L., Varonen, M., Church, S., Deveraj, K., Sieth, M., Voll, P., Harris, A., Lai, R., Sarkozy, S., A W-band heterodyne receiver module prototype for focal plane arrays, Microwave Symposium (IMS), 2014 IEEE MTT-S International, 2014

Reeves, R., Cleary, K., Gawande, R., Kooi, J., Lamb, J., Readhead, A., Weinreb, S., Gaier, T., Kangaslahti, P., Russell, D., Samoska, L., Varonen, M., Lai, R., Sarkozy, S., Cryogenic probing of mm-Wave MMIC LNAs for large focal-plane arrays in radio-astronomy,, 2014, 9th European Microwave Integrated Circuit Conference (EuMIC), pp.580-583

Varonen, M., Reeves, R., Kangaslahti, P., Samoska, L., Akgiray, A., Cleary, K., Gawande, R., Fung, A., Gaier, T., Weinreb, S., Readhead, A.C.S., Lawrence, C., Sarkozy, S., Lai, R., A 75–116-GHz LNA with 23-K noise temperature at 108 GHz, 2013, Microwave Symposium Digest (IMS), IEEE MTT-S International , pp.1-3

Samoska, L., Varonen, M., Reeves, R., Cleary, K., Gawande, R., Kangaslahti, P., Gaier, T., Lai, R., Sarkozy, S., W-Band cryogenic InP MMIC LNAs with noise below 30K, Microwave Symposium Digest (MTT), 2012 IEEE MTT-S International, 2012

Gawande, R., Reeves, R., Cleary, K., Readhead, A.C., Gaier, T., Kangaslahti, P., Samoska, L., Church, S., Sieth, M., Voll, P., Harris, A., Lai, R., Sarkozy, S., W-band heterodyne receiver module with 27 K noise temperature, Microwave Symposium Digest (MTT), 2012 IEEE MTT-S International, 2012

Russell, D., Cleary, K., Reeves, R., Cryogenic probe station for on-wafer characterization of electrical devices, 2012, Rev. Sci. Instrum., 83, 044703

4.3 Presentations/Conferences to date

Lamb, J., Cleary, K., Gawande, R., Kooi, J., Laxen, M., Plambeck, R., Reeves, R., Kangaslahti, P., Varonen, M., Sideband-separating MMIC receivers for observation in the 3-mm band, Proc. SPIE 9914, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII, 99140H (July 19, 2016)

Sieth, M., Deveraj, K., Voll, P., Church, S., Gawande, R., Cleary, K., Readhead, A.C., Kangaslahti, P., Samoska, L., Gaier, T., Goldsmith, P., Harris, A., Gundersen, J., Frayer, D., White, S., Egan, D., Reeves, R., Argus: a 16-pixel millimeter-wave spectrometer for the Green Bank Telescope, 2014, Proc. SPIE, 9153

Gawande, R., Reeves, R., Samoska, L., Cleary, K., Readhead, A.C., Gaier, T., Kangaslahti, P., Varonen, M., Church, S., Devaraj, K., Sieth, M., Morgan, M., W-band IQ sub-harmonic mixers with low LO power for cryogenic operation in large arrays, 2014, 9th European Microwave Integrated Circuit Conference (EuMIC), pp.301-304

Sieth, M., Church, S., Lau, J.M., Voll, P., Gaier, T., Kangaslahti, P., Samoska, L., Soria, M., Cleary, K., Gawande, R., Readhead, A.C.S., Reeves, R., Harris, A., Neilson, J., Tantawi, S., Van Winkle, D., Technology developments for a scalable heterodyne MMIC array at W-band, Microwave Conference (EuMC), 2011 41st European, 2011

4.4 Students working on these projects

One Caltech SURF student, Nathanial Baskin, worked on these projects.

4.5 Coordination of efforts

Coordination of efforts between JPL and campus has primarily been through a weekly meeting which has provided a very useful forum for campus/Lab interaction. (This meeting is on hiatus while we attempt to recruit new staff to the CRAL after a dip in funding has resulted in existing staff moving to positions elsewhere).

We also maintain a close connection with Maryland and Stanford with Harris and Church visiting Pasadena often and reciprocal visits to Stanford.