The First Billion Years:
A Technical Development Program for Spectral Line Observations

Technical Progress Report March 2016

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1. Introduction

The goal of this project is technological development for a CO intensity mapping program whose ultimate target is the Epoch of Reionization. The specific areas funded by KISS include

- *Simulations:* Simulations of the CO signal and analysis pipeline
- *Ka-Band MMIC Development:* Assist JPL with MMIC design and testing
- *Ka-band Module Development:* Test front-end modules
- *Telescope Commissioning:* Commission telescope for Pathfinder receiver
- *Feeds & OMTs:* Design and fabricate feeds and OMTs for receiver
- *Cryostat:* Design and fabricate receiver cryostat

In addition, Stanford has provided matching funds which have allowed development in areas not covered by KISS funding. These include:

- *Signal Routing:* Exploration of efficient routing of signals to/from cryostat
- *Bias Electronics:* Fabrication of electronics for bias and control of modules
- *Digital Backend:* Design of digital backend for the receiver

In this report, we describe progress in these areas. We also describe very positive developments for the project: the NSF AAG proposal which was submitted in November 2014 has been successful. We have also successfully argued that a NSF MRI award to CARMA should be re-scoped to include digital backend development for COMAP, since CARMA is no longer functioning. Together, these two awards have brought an additional $2.5M to the project, demonstrating the leverage made possible by the original KISS awards.

Phase I is now fully funded through awards from KISS, NSF and JPL R&TD as well as contributions from Stanford and Miami. As described in the previous report, this phase involves building a 19-pixel receiver (the CO Mapping Array, or COMAP) and commissioning it on a 10m telescope at OVRO before observing for two years using a broadband digital backend in order to detect CO emission from galaxies at the peak of cosmic star formation around redshifts of z=3.

2. Simulations

Four groups are performing simulations for the project.

Risa Wechsler at Stanford and her student Tony Li are working on models for the strength of the CO signal. Undergraduate Dongwoo Chung has also joined this effort. The models by Li et al. (2015)[1] improve upon existing work by using an empirically-constrained connection between dark-matter halo mass and star formation rate, and by incorporating recent observational constraints on CO in high-z galaxies. Their predictions have informed the instrument and survey parameters of COMAP, such as field size, bandwidth and integration time; the adopted values of these parameters are shown in Table 1.

[1] ApJ, 2016, 817, 169

The predicted level of the CO (1-0) spherically-averaged power spectrum from around z~3 is shown in Figure 1 for a variety of models, including the fiducial model from Li et al (2015). The receiver bandwidth has been doubled compared to that previously reported, from 4 GHz to 8 GHz (made possible by the NSF MRI award). Li has produced simulations for the COMAP sensitivity in each of these two 4 GHz bands.

For the parameters in Table 1, the figure also indicates the expected sensitivity of the Pathfinder after 2 years of observing. The model predictions span two orders of magnitude, highlighting our current lack of knowledge about this crucial period in the assembly of galaxies. The fiducial model indicates that the signal in a single 4-GHz bandwidth should be detectable by the Pathfinder after 2 years with a total detection significance of 8σ and much of the parameter space can be ruled out or confirmed by COMAP. In the past year, a tentative detection[2] of the CO power spectrum at similar redshifts probed by COMAP has been made using the CARMA array. If this is indeed the CO signal then it would his place the level of the power spectrum in the region predicted by the fiducial model in which case we could detect the signal within 2 years of observing.

Li has also begun to investigate the impact of cross correlating with galaxy surveys and the effect of redshift errors. Chung has been working with Li to investigate the extent to which spectral interlopers will provide a confusing signal in our band. These are lines at other frequencies that are redshifted in our band. A preliminary estimate for HCN, the next brightest line with a rest frequency close to CO (1-0), indicates that the signal from this line will be subdominant to that from CO. This is an encouraging result, although further work is needed. In particular, a way to model other lines along with CO in a consistent manner would be useful. In particular, a way to do this by connecting to physical models of small regions while being able to describe the average properties of whole galaxies would be of benefit to many experiments and this is an area of active research for Li and Chung.

Instrumental/survey parameter	
System Temperature[a]	40 K
Number of dual-polarization feeds	19
Beam full-width half-maximum	4 arcmin
Frequency band	26-34 GHz
Frequency channel width	40 MHz
Square survey area/patch	2.5 sq. deg.
Observing time/patch[b]	1500 hr
Sensitivity per channel	1026 μK s$^{1/2}$
CO (1-0) redshift range	2.4-3.4

Table 1: Instrumental and survey parameters for COMA

[a]We Based on 16 K amplifier noise temperature, 11 K window + telescope, 10 K atmosphere and 2.7 K CMB.

[b]We assume observing time is divided equally over 4 patches with ~35% observing efficiency. So, 750 hr per patch is equivalent to ~1 year of operation.

[2] As yet unpublished, but presented at AAS January 2016 by Karto Keating.

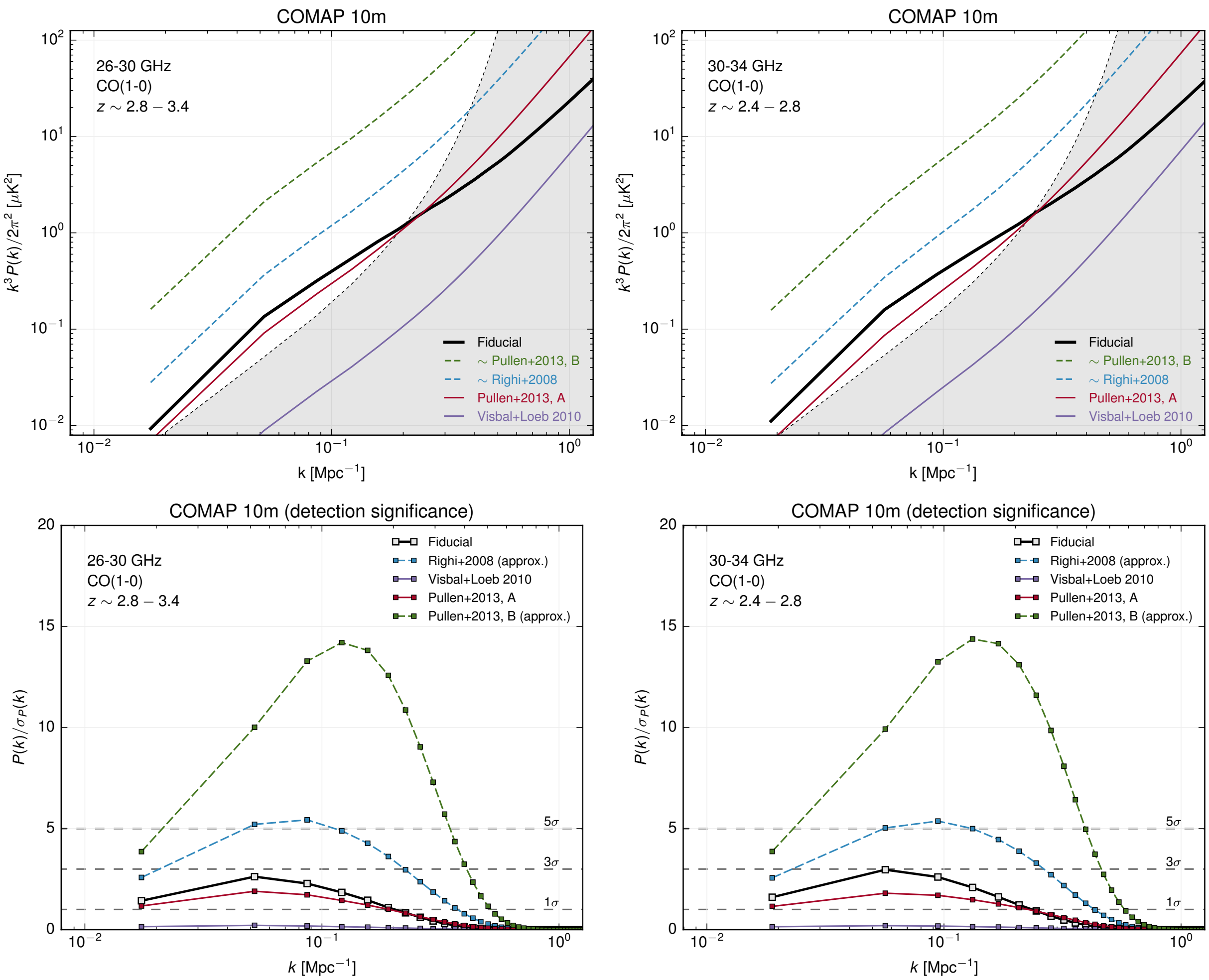


Figure 1: CO intensity power spectra forecasts (top) and detection significance (bottom) for COMAP for our fiducial model and other models in the literature for the 26-34 GHz (left) and 30-34 GHz (right) bands.

At JPL, Brandon Hensley is starting to work on simulations and will also participate in the modeling of foreground lines.

At Manchester, a new postdoctoral scholar, Stuart Harper has taken over work on the pipeline, incorporating the CO signal predicted by Li et al. and also working on incorporating models of systematic effects such as receiver gain and atmospheric fluctuations.

At Oslo, Ingunn Wehus has successfully obtained funding from the Norwegian government for a graduate student who will focus on pipeline simulations for COMAP. The student is currently being recruited.

3. Ka-Band MMIC Development

In the last progress report, we described efforts to design new MMIC amplifiers optimized for the COMAP band. These efforts have gained urgency since we have been able to double the size of the digital backend through the NSF MRI award. The front end amplifier modules already built using JPL R&TD funds used MMIC amplifiers optimized for the original 30-34 GHz band (Figure 2). Preliminary measurements on the new MMIC amplifiers indicate that the noise temperature has successfully been optimized for the full 26-34 GHz range (Figure 2, right).

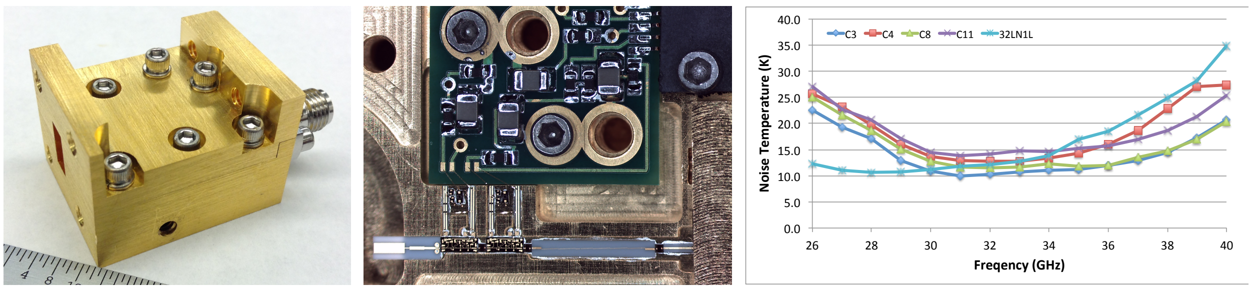
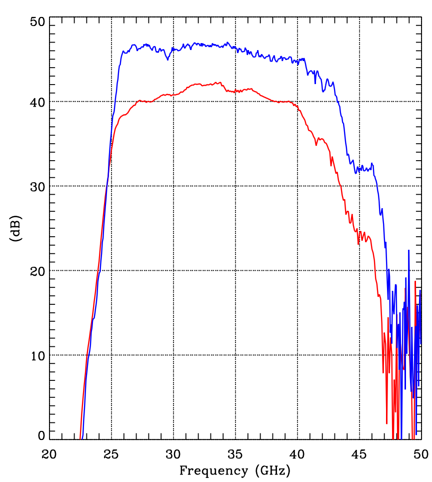


Figure 2: (Left) Exterior of a COMAP amplifier module. (Center) Interior of the amplifier module, showing RF and DC-bias components. (Right) Noise measured on four such modules, showing noise temperatures of 10-15 K in the main COMAP band of 30-34 GHz. Also shown is the noise temperature of a single 32LN1L amplifier, which has been optimized for the new COMAP band of 26-34 GHz.

4. Ka-Band Module Development

As described in the previous progress report, design, fabrication and assembly of 40 amplifier modules for the receiver is complete. Figure 2 shows one module (exterior and interior) as well as the noise temperature of four such modules. Each module contains two amplifiers and a band-defining filter. The module has a waveguide input and coaxial output. The assembly of the modules took place at JPL, under an R&TD award.



Debugging of the modules is now complete. A drop in gain of a few dB around 29 GHz was exhibited by some modules when cooled, however this was traced to a problem with the measurement setup.

If the measurement of the 32LN1L described in Section 2 is verified in more measurements of this amplifier, then we will begin a process of replacing the first amplifier in each of the modules with a 32LN1L over the coming months.

Figure 3: Measured room temperature (red) and cryogenic (blue) gain of a typical amplifier module.

5. Mixers

Connectorized mixers have been selected for COMAP in order to minimize the risk of leakage and cross-talk problems which might have occurred using printer circuit board and surface-mount components. Baseline mixers have been purchased and will be tested at OVRO in the coming months.

6. Telescope

The optical design for the 10m telescope is nearing completion. The feeds will be corrugated, of diameter ~56mm and length ~250mm. The feeds will be placed at the Cassegrain focus and a new, larger, secondary reflector is required. The optics are designed such that the variation of the beam shape with frequency is minimized (Figure 4).

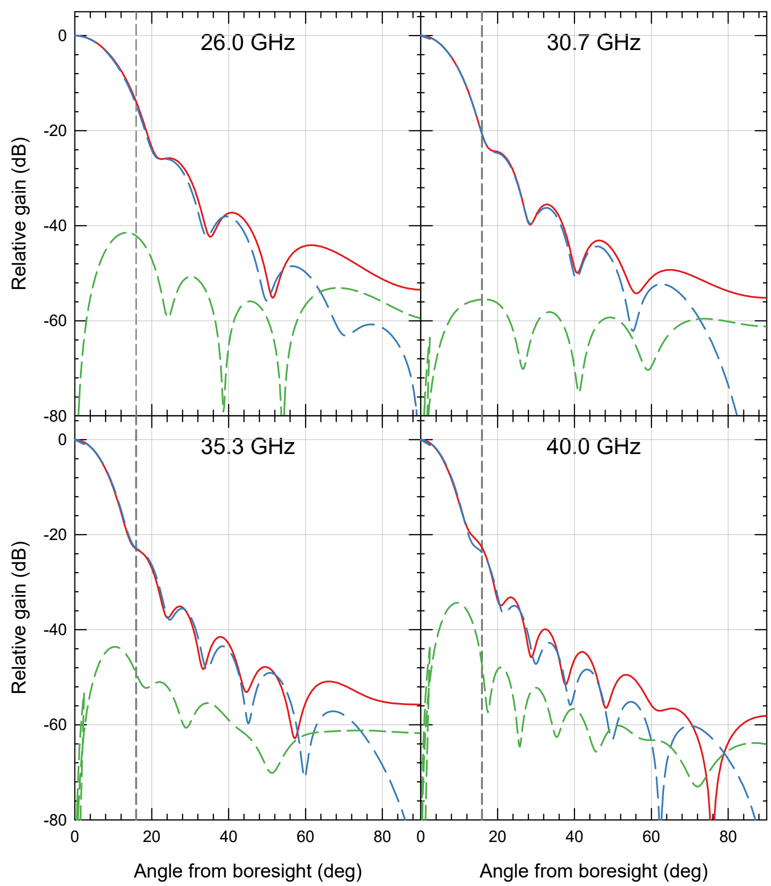


Figure 4: Beam simulations for the 10m optical design (blue: E-plane, red: H-plane, green: polarization in 45-degree plane) at four frequencies in the 26-40 GHz range.

One of the CARMA 10m telescopes has been selected to be used as the 'testbed telescope'. The CARMA 1cm receiver on this telescope will be used to test the second-stage downconverters and digital backend, as well as to gain experience with systematics such as the standing wave between the secondary and feedhorn. This telescope has been connected to power and the antenna computer connected to Ethernet via optical fiber. By the summer, the 1cm receiver will be activated and a prototype downconverter and digital backend will be in place. An intensive set of tests will be performed in order to inform the design of the COMAP receiver.

Work has begun on scoping the control system for the 10m telescope. There is an existing CARMA control system but this is far more complex than needed for COMAP, since it was designed to operate the CARMA interferometric array. Depending on the outcome of the scoping exercise, the COMAP control system may use elements of the CARMA system or it may implement a different system based on that used by other single dishes at OVRO (40m, C-BASS). A basic control system is aimed to be in place for control of the testbed telescope by the summer.

7. Signal (RF and LO) distribution (Stanford subaward)

In order to reduce a potential systematic error from standing waves between the feedhorn and the secondary reflector, we have decided to adopt single circular polarization, so that the reflected signal will have the orthogonal polarization and be rejected. This simplifies the RF routing out of the Dewar, since there will now be just 19 RF lines to route. Stanford are working with Miami to design an internal mounting and RF routing structure for inside the cryostat.

Sine the RF bandwidth has been doubled, the LO scheme is being revised and we will prototype the new LO chain in the coming months.

8. Polarizers and Feeds (was Stanford subaward, now OVRO)

OVRO has taken over this task (Stanford have taken on a new ‘Calibration Hardware’ task instead, which is more aligned with the current expertise in the Church group). With the adoption of single polarization, we require polarizers with excellent cross-polar rejection. One option is to use the achromatic polarizers from the CBI2/DASI experiments. These are available and have the ability to switch polarization states, although this will not be required for COMAP. We are currently investigating whether these will fit within the available space. The other option is to design new polarizers and James Lamb at OVRO is working on a new polarizer design which incorporates the vacuum window and circular to rectangular transition.

As mentioned in Section 6, the feed horn design is nearing completion. A prototype horn based on this design will be machined at OVRO in the coming months.

9. Cryostat (Miami subaward)

With the optical design nearing completion, the feedhorn interface with the cryostat will soon be frozen. In the meantime, Miami have been working on a preliminary cryostat design (Figure 5). This design incorporates an offset cold head, which allows access to the amplifier modules from the rear, for easier routing of RF cables. The first stage mixers are mounted in chassis on the exterior of the cryostat. The feeds are warm since the loss is expected to be very low and this removes the need for a relatively large window. Cryostat manufacture is expected to begin in 1-2 months.

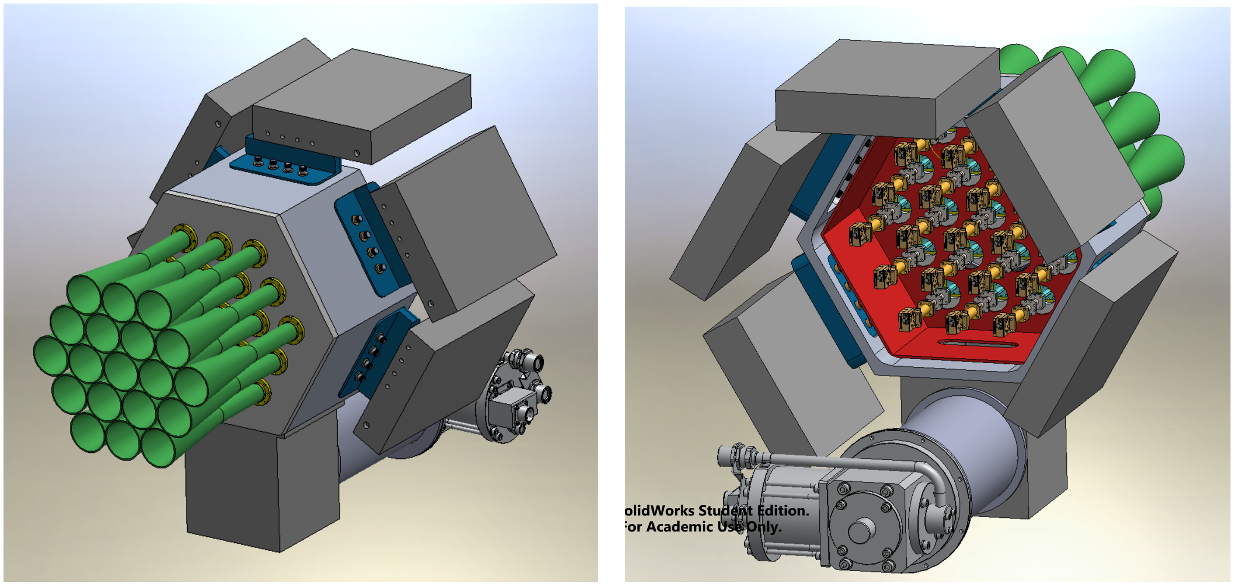


Figure 5 Renderings of preliminary design for COMAP receiver cryostat. The 19 warm feeds of the array can bee seen on the left. Arrayed around the outside are the 5 first-stage mixer chassis. The cold head is offset to allow easy access to the amplifier modules from behind (right).

10. Bias/control Electronics (Maryland Subaward)

The prototype electronics have been demonstrated to work well in the lab and a second design iteration is now underway.

11. Digital Backend

The original KISS award did not include funds for a digital backend but matching funds were supplied by Stanford for the construction of a 1-GHz digital backend. Our NSF AAG proposal requested funds for a backend which could process 4 GHz from 19 pixels (dual polarization). Figure 6 shows the baseline design for one unit of the digital backend and the NSF AAG request was for 38 such units. Although we were granted the NSF AAG award, the requested funds were cut by about 8%. However, the rescoping of the CARMA MRI award has allowed us to maintain the size of the digital backend. Now that we have switched to single polarization (to reduce the effect of the standing wave systematic error), we can double the RF bandwidth for the same size digital backend.

A single spectrometer consisting of a ROACH2 and two 5 Gsps ADCs has been set up in the lab at Caltech. Graduate student Ryan Monroe has developed FPGA code for a spectrometer that is currently being tested at OVRO as part of the Starburst project. This code has also been installed on the COMAP prototype backend at Caltech. Based on experience with Starburst over the coming weeks, revisions may be made to the spectrometer. The prototype backend will then be installed at OVRO as part of the testbed system during the summer, in order to digitize signals from the CARMA single-pixel 1cm receiver on the testbed telescope.

Following this field testing, the full backend will be assembled and tested in the lab at Caltech.

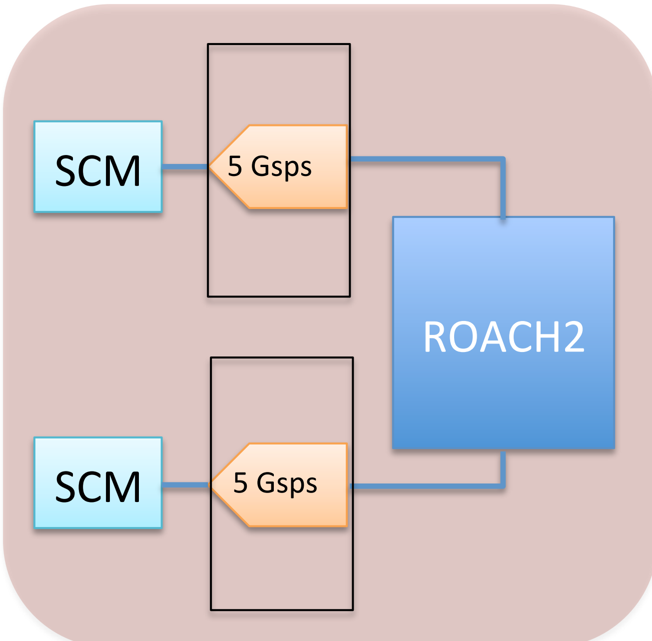


Figure 6: Digital backend design based on CASPER hardware. A signal conditioning module (SCM) conditions the signals from the receiver for input to a 5 Gsps digitizer. Two such digitizers are controlled by a single 'ROACH2' FPGA board. This backed unit will process 4 GHz from a single polarization – the full digital backend will require 38 such units to process 8 GHz from each of 19 pixels.

12. *V-band MMICs and Mixers*

At JPL, a related effort continues to develop components for measuring the CO power spectrum from space, funded by R&TD. Eight 40-80 GHz MMIC LNA designs revised and submitted for fabrication later in 2015. New mixers have been designed and were fabricated in May 2015. The LNAs and mixers were cryogenically tested in waveguide housings and the best were found to have a receiver noise temperature of 22K at 48 GHz, and low noise from 40-60 GHz. The cryogenic results were obtained at 30K ambient, and further cooling of the MMICs to 20K is expected to reduce the noise by a few Kelvin more. The results set a new world record for U-band MMIC LNA noise (40-60 GHz) and are the subject of a recently accepted European Microwave Conference paper. New MMICs based on these results are currently being studied for the North America Array.

13. Campus Technical Progress (and Milestones)

The following milestones have been achieved (including Stanford, Maryland and Miami subawards):

i) 38 amplifier modules have been tested and are functioning cryogenically;
ii) A new MMIC design optimized for broader bandwidth has been tested;
iii) A 10m telescope, previously part of the CARMA array at Cedar Flat, has been connected to power and Ethernet at OVRO. This will operate as a testbed telescope using a CARMA 1cm receiver to test backend prototypes and investigate systematic

errors;

iv) Preliminary optical and cryostat designs have been completed;

v) Prototype bias electronics have been tested;

vi) A prototype digital backend running functioning FPGA spectrometer code has been installed in the lab at Caltech;

Remaining milestones for the KISS-funded component include:

i) Completion of telescope control system;

ii) Fabrication of feeds and polarizers;

iii) Fabrication of cryostat.

14. JPL Technical Progress (and Milestones)

JPL assisted with troubleshooting of the COMAP receiver modules.

Milestones: 38 amplifier modules have been tested and are functioning cryogenically.

15. List of all Relevant Presentations and Publications

A paper on the simulations by the Stanford group (Li et al. 2015) has been accepted by ApJ. Cleary gave presentations on the project at AAS in Janurary 2016 and at an Intensity Mapping Workshop at Stanford in March 2016. Li also presented at the Stanford workshop.
A paper by Samoska (JPL) on "Cryogenic Low Noise MMIC Amplifiers for U-Band (40-60 GHz)," has been accepted for presentation at European Microwave conference for October, 2016 in London, UK.

16. List of Postdoctoral Scholars and Graduate Students

At Caltech, graduate student Ryan Monroe is providing his spectrometer FPGA code and advises on CASPER hardware.
At Stanford, graduate student Matt Sieth has worked on COMAP and an undergraduate student, Kelley Stifter, is joining the Church group to work on the RF signal routing;
At JPL, postdoc, Brandon Hensley, has started to work on foregrounds for COMAP.