Development of an Enhanced MM-Wave Interferometric Array to Probe the High Redshift Universe

A Proposal to the National Science Foundation
Major Research Instrumentation Program
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Project Summary

We are proposing to build an interferometric array of 2.5 m diameter radio telescopes and a versatile wideband digital correlator to greatly enhance and expand the frequency and imaging capabilities available with mm-wave interferometry to the national radio astronomy community. Our immediate scientific goal is to increase the speed and quality of our Sunyaev Zel'dovich (SZ) effect imaging of galaxy clusters. By increasing both the speed and available time by more than an order of magnitude, we can fully exploit the enormous scientific potential offered by the SZ effect, providing invaluable information on the evolution of large scale structure and the cosmological parameters which describe our universe. As outlined below, we will 1) take a complete, redshift-independent inventory of galaxy clusters and provide critical constraints on large scale structure, 2) make detailed images of selected clusters to determine the expansion rate (Hubble constant H_o), the deceleration parameter q_o, and the cosmological matter density Ω_M; in combination, our measurements of q_o and Ω_M will constrain the total energy density Ω_o and the contribution to the energy density from a cosmological constant Ω_Λ.

The enhancements proposed here will lead to a dramatic increase in the size and completeness of galaxy cluster samples, as well as the quality of SZ effect imaging. The 1 yr cluster sample obtained with the proposed array, which should detect more than 300 clusters at $z > 0.5$ and more than 100 at $z > 1$, would be unparalleled, and would become the standard catalog of distant, massive clusters. We will be able to provide strong constraints on cosmological models and will, for example, provide an independent test of the type Ia supernovae results which favor an accelerating universe.

Furthermore, we will combine the 2.5 m telescope array with the existing six 10.4 m telescopes at OVRO, to build a powerful heterogeneous interferometric array operating at cm through mm wavelengths. The possibility to also add the ten 6.1 m telescopes from BIMA to this array at a new high altitude site would lead to an exceptionally powerful and unique capability for U.S. radio astronomy. The proposed enhanced heterogeneous array will be used to support first-rate scientific programs spanning studies of large scale structure in the universe, galaxy formation, the detailed kinematics and star formation properties of galaxies, the gravitational collapse of molecular material to form solar-like stars and protoplanetary disks, and the details of the circumstellar disks. The array of smaller telescopes allows much greater image quality at all wavelengths; it will provide a much more comprehensive view of star forming regions by allowing high sensitivity imaging on all scales from those of the parent molecular clouds to the compact protostellar/planetary systems themselves, yielding precise information on the gravitational collapse of molecular material and the evolution of the circumstellar disks. The large range of angular scales will allow detailed investigation of the physics, chemistry and evolution of molecular clouds in our galaxy, as well as the detailed kinematics and star formation properties of molecular clouds in external galaxies.

The heterogeneous array concept is orthogonal to the homogeneous array concept embraced by NRAO for the millimeter array (MMA). The heterogeneous array provides superior sensitivity to large angular scales by using interferometric techniques on very short baselines, data which a homogeneous array can only acquire with large single dishes. Our SZ imaging already demonstrates the strength of interferometry to achieve high sensitivity on these scales; indeed the VSA, CBI and DASI CMB imaging telescopes have also embraced interferometric techniques for precisely this reason. Secondly, the large range of telescope sizes ($\times 4$) provides considerable overlap between the range of angular scales covered by using interferometric techniques with the smallest baselines, and the scales probed by single dish techniques with the largest telescopes. This overlap ensures excellent calibration in the rare case when single dish data is required, which we note will be much less frequent than for the homogeneous array, where estimates indicate it will be required nearly half of the time. The heterogeneous array is an attractive solution to the large angular scale imaging problem inherent to interferometry. The array will offer the entire U.S. radio astronomy community unique and complementary capabilities to those of the proposed MMA to be located in the southern hemisphere.

The array will be built at the University of Chicago. Graduate and undergraduate education and research will be integrated together in the construction and use of the sub-array. Students will play a major role in the project, exposing them to all aspects of scientific and engineering research. They will learn valuable skills which will aid them in pursuit their careers, whether in industry or academia.

Outreach and education related to the project will be disseminated and implementated through established structures and mechanisms of CARA and of the Adler Planetarium and Astronomy Museum. These programs, which reach out to local high schools teachers and students, will use the excitement of exploring our universe to help attract women and minorities to science.

Project Description

A. Results from Prior NSF Support

The PI received an NSF Young Investigator Award which was directed at new instrumentation. Specifically, he used these funds to develop the first astronomical submm-wave interferometer (with R. Hills, Cambridge) and, along with additional funds from a NASA/MSFC DDF grant and a Packard Foundation Fellowship, the Sunyaev Zel'dovich Effect imaging system (with M. Joy, NASA/MSFC and W. Holzapfel, U. C. Berkeley). The PI also led an effort to add polarimetric capabilities to the OVRO mm-wave array. Although funded by a NASA OSS grant, it was used to enhance the NSF funded OVRO mm-wave array. Lastly, the PI, with Mark Dragovan, is now leading the effort to build the Degree Angular Scale Interferometer (DASI) with NSF OPP funding via the Center for Astrophysics Research in Antarctica (CARA). The results and state of these programs are discussed below. The Sunyaev Zel'dovich Effect (SZE) imaging system is discussed in some detail (Section A4) as it is the starting point for the enhancements proposed here.

A1. *CSO–JCMT Submm-wave Interferometry*

The CSO-JCMT submillimeter interferometer is the first astronomical submm-wave interferometer. We used it to make the first measurements of the sizes of accretion disks around nearby young solar-like stars (Lay *et al.* 1994, Carlstrom *et al.* 1995). The interferometer has been used successfully at frequencies as high as 662 GHz achieving an angular resolution $0.2''$. Observing sessions roughly 12 days long have been scheduled about twice a year with most of the observing dedicated to proposals submitted by the community. The interferometer has been used to investigate the dependence of accretion disk properties on the stellar type and evolution (e.g., Pudritz *et al.* 1996), to investigate disk emissivities and temperature as a function of radius (e.g., Lay, Carlstrom, and Hills 1997), to determine the submm spectrum of the SgrA* complex (Serabyn *et al.* 1997), and to probe the molecular component in the central regions of active galaxies (e.g., Wiedner 1998). The CSO-JCMT project was the focus of Ph.D. dissertations by Oliver Lay and Martina Wiedner.

A2. *Millimeter Interferometric Polarization at OVRO*

The PI has also successfully developed millimeter interferometric polarization capabilities for the OVRO mm-array using novel, tunable reflecting polarizers. This project was the focus of Rachel Akeson's Ph.D. research (Akeson 1996). The instrument has been used to image the magnetic field morphologies toward several protostellar accretion disk systems (see Akeson and Carlstrom 1997). The instrument is now fully installed and calibrated; use of the polarimetric capabilities is open to outside proposals.

A3. *The Degree Angular Scale Interferometer (DASI)*

The PI is now co-PI with Mark Dragovan to build the Degree Angular Scale Interferometer (DASI). DASI is a thirteen element, extremely compact (20-cm feed horns), interferometric array designed to image intrinsic anisotropy in the cosmic microwave background (CMB) at angular scales of 0.25 to 1.5 degrees. DASI uses $26-36$ GHz HEMT receivers modeled after Sunyaev Zel'dovich project receivers. The instrument should be completed and tested in Chicago in 1999 Spring and Summer and will then be shipped to the NSF base at the South Pole. It is expected to produce data starting in 2000 February and continuing until at least February 2002. Currently, two students are working toward their Ph.D.s on this project.

A4. *Sunyaev Zel'dovich Effect (SZE) Imaging*

The work proposed here is an extension of our existing SZE interferometric imaging experiment. In this experiment we have made observations of the CMB temperature decrement toward galaxy clusters; these decrements result from Compton scattering of CMB photons by the hot intracluster medium (Sunyaev and Zel'dovich 1972). Our approach, described in more detail below, has been to image clusters using low-noise, cm-wave receivers mounted on the OVRO and BIMA mm-arrays during the summer months when atmospheric conditions are unfavorable to mm-wave astronomy. The SZE experiment and the desired enhancements to the project were the focus of the PI's successful application for the McDonnell Centennial Fellowship Award ($1M), which is now being used as partial matching funds here.

Since the first results were obtained in 1994 August (Carlstrom, Joy, and Grego 1996), we have continued to increase the instrument sensitivity and imaging speed. We have now imaged the SZE toward 27 clusters;

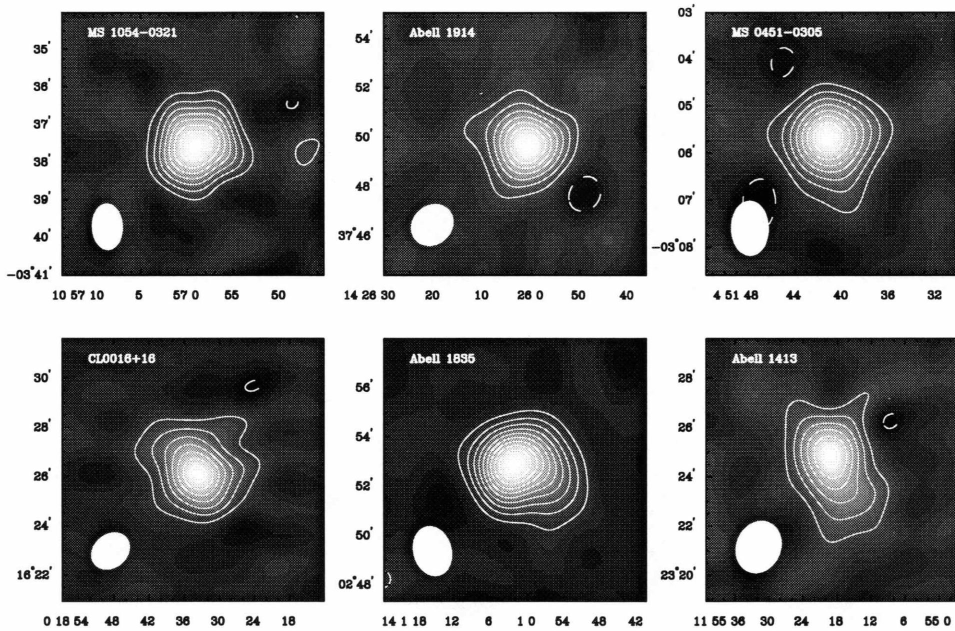


Figure 1: A sample of the Sunyaev Zel'dovich Effect images obtained to date with our receivers mounted on the OVRO and BIMA mm-arrays during the summer months. With the proposed instrument enhancements, we can survey 1 deg^2 in a month to a sensitivity comparable to our deepest single cluster images. The synthesized beam is represented by the white patch in the lower left of each panel, and contours are offset by 2σ.

a sample of these are shown in Figure 1. The SZE project and the resulting limit on the mass density of the universe were the focus of Laura Grego's Ph.D. dissertation (Grego 1999). Currently, four Ph.D students (three at U. Chicago and one at U. Alabama) are working toward their degrees on the project.

It is well known that a distance-ladder independent estimate of the Hubble constant H_o can be determined by analysis of the SZE and X-ray emission observed toward a cluster of galaxies (see the recent review by Birkinshaw 1999). The ability to measure the direct distance to the cluster relies on the fact that the SZE is dependent only on the density of hot electrons integrated along the line of sight, while the X-ray emission depends on density squared integrated along the line of sight, i.e., on the emission measure. Under the assumption of hydrostatic equilibrium, the two measurements thus allow a direct measure of the physical size of the cluster and hence its distance based on the well understood physics of ionized plasmas. There are, of course, several possible sources of systematic errors; these include gas clumping, non-spherical gas distributions and gas temperature gradients.

Our SZE interferometric data allow us to constrain the gas density profiles and lead to improved estimates of the Hubble constant. In particular, we use our observations to constrain parameters of a β model distribution of cluster gas $n_e(r)$ (Cavaliere and Fusco-Femiano 1978):

$$n_e(r) = n_e(0)\left(1+\frac{r^2}{R_c^2}\right)^{-3\beta/2} \tag{1}$$

where R_c is the core radius and 3β is the power law index of the gas distribution at large radius. The SZE temperature decrement, under the additional assumption of an isothermal gas, is then given by

$$\Delta T\,(\theta) = \Delta T(0)\left(1+\left(\frac{\theta}{\theta_c}\right)^2\right)^{\frac{1}{2}-\frac{3}{2}\beta} \tag{2}$$

where $\Delta T(0)$ is the decrement at zero projected radius, θ_c is the projected core radius, and $R_c = D_A\theta_c$, where D_A is the angular diameter distance. In Figure 2, we show the constraints from joint analysis of our SZE data with ROSAT x-ray data on the shape parameters for the electron distribution in the cluster MS0451 with the contours of constant H_o overlaid (Reese *et al.* 1999). Note the correlation between parameters β and R_C, but also note that lines of constant H_o lie roughly parallel to this correlation, indicating that H_o is nevertheless well constrained by the interferometric data. We find a similar alignment for lines of constant gas mass fraction, as discussed below (see Grego 1999, Grego *et al.* 1999a, Grego *et al.* 1999b).

Using the analysis techniques described in Grego 1999, we have determined the gas fraction for 18 clusters. Because clusters collapse from such large volumes (of order 1000 Mpc^3), their matter content provides a fair

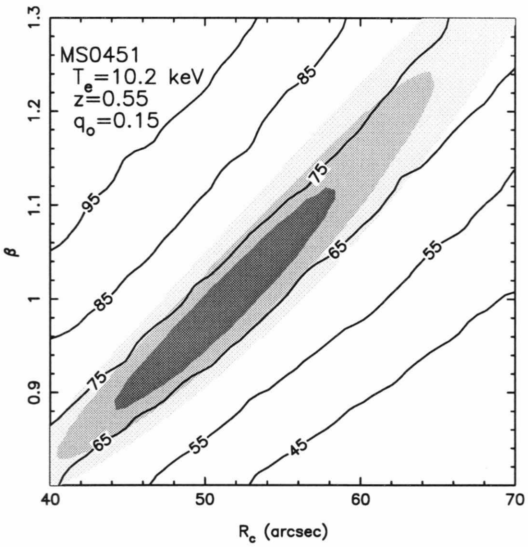


Figure 2: The results of a joint analysis of our Sunyaev Zeldovich Effect data and ROSAT X-ray data for the cluster MS0451-03 at $z = 0.54$ (Reese *et al. 1999*). The axes are the shape parameters from a standard β model for the cluster electron density (see Eq. 1). One, two and three σ allowed parameter regions are denoted by gray scale; note that although the parameters β and R_C are strongly correlated, this has little impact on the derived Hubble constant, because lines of constant $H_\circ$ run parallel to the correlation. Lines of constant gas mass, binding mass and, therefore, gas mass fraction also lie parallel to this β-R_C correlation (see Grego 1999, Grego *et al.* 1999a, Grego *et al.* 1999b).

sample of the universal mix of baryons and dark matter; this supposition is consistent with N-body and gas dynamical simulations of cluster formation (e.g. Evrard 1997), and is supported to some extent by the uniformity of the gas fractions we and others measure. The gas mass fraction we derive thus leads to an estimate of Ω_B/Ω_M (White *et al.* 1993), where Ω is the matter density of the universe relative to the critical value ($\Omega \equiv \rho/\rho_{crit}$), Ω_B refers to the density ratio for baryons, and Ω_M refers to the density ratio for the total mass, including dark matter.

We find a mean gas fraction of $0.11h_{65}^{-1} \pm 0.015$, where we take $H_\circ = 65h_{65}^{-1}$ km/s/Mpc. Using the value of $\Omega_B h_{100}^2 = 0.019 \pm 0.0014$ derived from big bang nucleosynthesis calculations and the measured Deuterium abundances toward high-z L_α absorption systems (Burles and Tytler 1998), our SZE data lead to an estimate for the matter density of the universe, $\Omega_M = 0.30h_{65}^{-1} \pm 0.08$, after accounting for the the galaxy contribution to the baryon content and the small fraction of baryons lost during infall to the cluster potential. This result is consistent with values derived by inverting cluster X-ray emission measures (e.g. David, Jones, and Forman 1995, Mohr and Evrard 1999) and with values estimated by fitting models of cluster formation and evolution (e.g. Bahcall 1999). In addition, the consistency of independent gas fraction measurements from SZE and X-ray observations provides constraints on clumping in the cluster gas.

The enhancements proposed here will lead to an amazing increase in the size and completeness of the cluster sample as well as the quality of the SZE imaging; as detailed in Section B3, these changes in the available data are so extraordinary that they may well result in revolutionary new science results. With the proposed instrument we will be able to determine both $H_\circ$ and the gas mass fraction as a function of redshift and most significantly, at redshifts beyond $z = 1$ where cosmological differences are most pronounced (see Figure 3); we will provide strong constraints on cosmological models and will, for example, provide an independent test of the type Ia supernovae results which favor an accelerating universe (Perlmutter *et al.* 1999, Riess *et al.* 1998). We have also been awarded a NASA LTSA 5-year grant for research directed at obtaining the best estimates of the Hubble constant and gas mass fraction from combined SZE and X-ray data, and for thoroughly investigating cluster atmospheres and possible systematic effects. Please note that no funds are requested for the analyses in this proposal.

To fully appreciate the impact of the SZE project to date— especially its impact on the radio astronomy community— and its relevance to the proposed instrumentation development, it is important to point out that our low-noise cm-wave receivers remain on the BIMA array for about a month per year after our observing session and are used by the BIMA scientific community. The time allocation committee selects among internal proposals (internal to U. Berkeley, U. Illinois, U. Maryland, and Academia Sinica, Taiwan) to schedule the array during this period. The time is oversubscribed with a wide range of projects, including investigations of the dust properties in local molecular clouds, both star forming and quiescent, investigations of the anomalous dust emission from rapidly spinning dust grains, searches for CO emission from high-z galaxies, and searches for protoclusters. There is clearly interest from a large community in adding this frequency band to the mm-arrays, as well as adding imaging capabilities for extended, low-brightness emission.

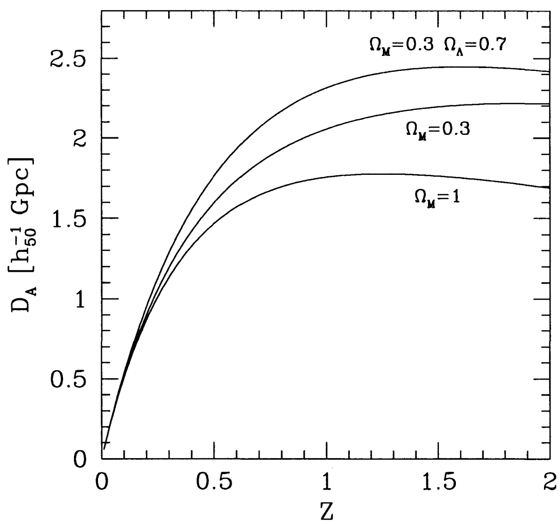


Figure 3: The angular diameter distance, D_A, as a function of redshift z for three different cosmologies. Note the greater cosmological discriminatory power afforded by high redshift distance measurements. We expect to find of order 100 clusters with $z > 1$ by conducting a SZE survey for one year. Followup studies of these clusters with optical and X-ray telescopes combined with deeper Sunyaev Zel'dovich Effect imaging with the proposed array would enable direct distance measurements to many of these clusters.

A5. *Timing and Resources*

The timing of the instrumentation development proposed here meshes well with the DASI schedule. Unlike most ground-based instrument deployments, DASI will be not be directly accessible for 9 months of the year. Meanwhile, the excellent crew and laboratory support that has been put in place at Chicago must begin work on another project or risk being destroyed. The project proposed here is ideal as it builds directly on the expertise already assembled, both technical and scientific.

B. Research Activities

We are proposing to build a powerful new sub-array of small, 2.5-m, radio telescopes to greatly enhance the mm-wave imaging capabilities available to the radio astronomy community. The sub-array is described in detail in Section C below. In this section we first indicate how the addition of the sub-array will dramatically improve the performance of the existing mm-array by providing high sensitivity interferometric data on large angular scales. We also point out that this method of obtaining large angular scale data will not be possible with the planned NRAO Millimeter Array (MMA) project which will consist of a homogeneous array of 12-m telescopes; the MMA plans to use total power techniques to recover the short baseline data. The heterogeneous array being proposed here will therefore provide a unique capability and will help ensure the vitality of the university groups and the continued training of new students in state-of-the-art mm-wave techniques and astronomy. We next describe our primary science goals with the sub-array. We feel that the initial observations with the new sub-array will lead to rapid advances in the state of our knowledge of galaxy clusters, galaxy cluster evolution, and large scale structure; these advances— perhaps even revolutionary advances— are driven by the unprecedented imaging speed and quality of the SZE observations with the proposed sub-array. This alone provides strong justification for NSF funding, especially considering the large fraction of matching funds. However, because the proposed array will become part of the OVRO mm-array, it will be used to do much more than SZE science. Eventually outfitted for all the mm-wave bands, this facility will serve the entire radio astronomical community as a unique and powerful facility for years to come.

B1. *Benefits of a Heterogeneous Array*

Interferometry is usually thought of as a technique for obtaining high angular resolution. However, for our SZE imaging experiment (described in section A4), we used interferometry to obtain extremely high sensitivity; that is, our technique exploits the extremely high stability of interferometry. And, in fact, by installing our low-noise, cm-wave receivers on the mm-arrays we effectively downgrade the angular resolution to match the angular scales of galaxy clusters.

There are several factors that lead to high stability of interferometry. For example: 1) The beam of a pair of telescopes within an array is essentially a two-slit interference pattern which *simultaneously differences* the sky emission, naturally rejecting atmospheric emission; each pair of telescopes of the interferometer is only sensitive to a limited range of Fourier components of the sky brightness. 2) Any source of emission that does not track at the celestial rate (the natural fringe rate) is strongly suppressed. Thus, while atmospheric emission adds noise to an interferometer, this noise does not contribute to artifacts in the map that can be mistaken as signal; the noise received by the individual elements of the interferometer does not correlate. 3) It is possible to add several layers of fast (1 to 100 kHz) phase-switching to remove instrumental offsets, from the correlator for example, or to reject other sources of noise introduced to the system downstream from the receivers. 4) The absolute pointing of an interferometer is set by the stability of the Earth's rotation and not the telescope's encoders and pointing model (if the array elements are mounted on individual mounts).

The SZE observations made with our low-noise, cm-wave receivers mounted on the the OVRO and BIMA mm-arrays demonstrate the ability of interferometric systems to achieve very high sensitivity for extended, low surface brightness emission: we have obtained noise levels of 10 to 30 μK for our cluster fields. We have also observed a few "blank" fields both as a check of our system and also to set an upper limit on the level of intrinsic CMB anisotropy on arcminute scales ($\ell \sim 4000-5000$); we achieved an upper limit of $\Delta T < 10$ μK at 68% confidence (Holzapfel *et al.* 1999). The results of the Cambridge Anisotropy Telescope (CAT) which detected CMB anisotropy at intermediate scales also attest to the robustness of the interferometric technique for obtaining extremely high sensitivity (Scott *et al.* 1996).

On the contrary, it is very difficult to achieve high sensitivity on large angular scales with a conventional single dish telescope, particularly for continuum emission. To be successful, the single dish SZE experiments have had to take great care to control sources of systematic error, using careful beam switching strategies and complex receivers, or AC coupled bolometers and drift scans (see review in Birkinshaw 1999, also Myers *et al.* 1996 and Holzapfel *et al.* 1997). We note that the ability of interferometry to reject atmospheric noise contamination is being exploited by several ground based CMB anisotropy experiments, the VSA, DASI, and CBI.

While the single dish experiments mentioned above have been successful, they are not appropriate for filling in the missing short spacing data for an interferometer. In the total-power mosaicing method proposed for the MMA, the same array elements will be used to obtain the total power data, i.e., the short baseline data (Cornwell, Holdaway, and Uson 1993). This is sure to work well for bright emission, but without enormous expense and care beyond that planned for the MMA, it will not provide enough sensitivity to measure the low continuum levels we wish to consider here. A telescope designed and implemented for the very best total power sensitivity is not consistent with one designed optimally for interferometry. Furthermore, the single dish observing strategies which give the best sensitivity to extended emission (e.g., azimuth scans) are not sufficient to provide all the desired short baseline information for the interferometer. In short, the optimum way to recover the short baseline information is with an interferometer.

The heterogeneous array we are advocating here will be able to achieve higher sensitivity to extended emission— i.e., emission for Fourier modes sampled by baselines shorter than 12-m— than will be obtainable with the MMA. The addition of the sub-array to OVRO will provide a unique and powerful capability into the foreseeable future.

B2. *Overview of Proposed Enhancements to the Sunyaev Zel'dovich Effect Imaging System*

As discussed in Section A4, we have built low-noise, HEMT-amplifier receivers and have used them on the OVRO and BIMA mm-wave arrays for extended periods during the summer months, when the weather is not optimum for mm-wave observing, but is still quite reasonable for our cm-wave (28.5 GHz) observations. Our equivalent input noise temperatures for the receivers now range between 12 to 20 K; we are building our own amplifiers in our laboratory at U. Chicago, and we expect to have the noise temperatures of all ten receivers around 10 - 14 K for the 26 - 36 GHz band. These noise temperatures are impressive, especially considering that the atmosphere contributes about 10 K at zenith on a good day, and the telescope spill-over contributes between 8 and 15 K at the two observatories. Clearly, we cannot improve the system performance much by further lowering the receiver noise temperatures.

There are three obvious ways to improve the sensitivity and productivity of our Sunyaev Zel'dovich Effect imaging system: 1) increase the correlation bandwidth, 2) match the array elements to the angular size scales of interest, and 3) observe throughout the year to take advantage of the best weather as well as the large amount of integration time.

First, we consider the correlation bandwidth. Currently the electronics at the mm-arrays allow of order 1 GHz of correlation bandwidth; our receivers output 10 GHz. A wideband correlator would instantly increase our imaging speed by a factor of ten, and the new correlator would also greatly increase our imaging

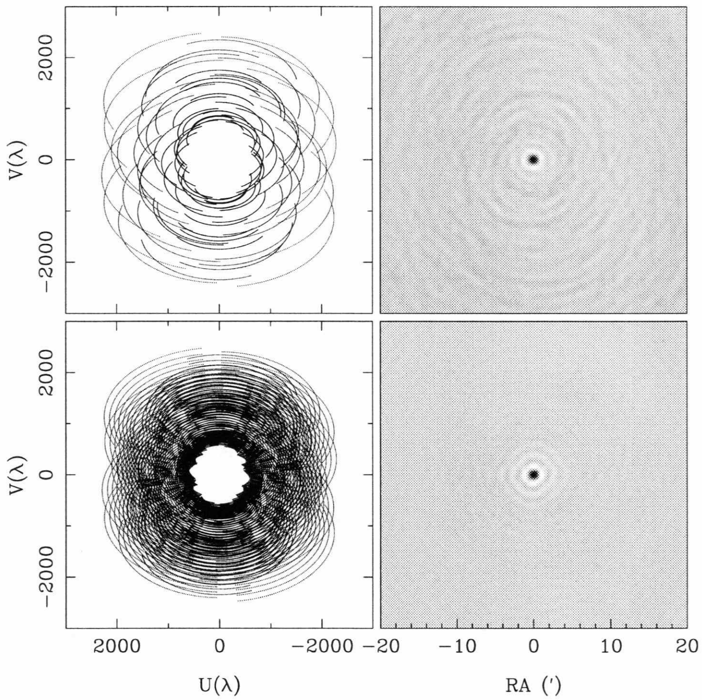


Figure 4: The top panels show the $u - v$ coverage and resulting beam (uniform weighting) for a single 1 GHz wide channel. The lower panels show the increase in $u - v$ coverage and the resulting beam when eight 1 GHz channels are correlated. Observation times are 7 hrs in each case. Note that the proposed wide-band correlator allows more uniform $u - v$ coverage, dramatically reducing the amplitude of the beam sidelobes.

quality by densely filling in the $u - v$ plane. In Figure 4 we show the effect of increasing the correlation bandwidth from 1 GHz to 8 GHz on both the $u - v$ coverage and the resulting beam. The $u - v$ sampling corresponds to 7 hrs observing with the proposed 2.5 m array in a close-packed configuration.

Second, we consider matching the angular scales of interest. Consider first that the cluster gas distribution is reasonably well approximated by the β model (Eq. 1) which has three parameters: a core radius R_C, a normalization and an asymptotic falloff of $n_e \propto r^{-3\beta}$. If $\beta = 2/3$, the resulting temperature decrement profile (Eq. 2) has an analytical Fourier transform given by

$$F(u) = \Delta T(0)\theta_c \frac{e^{-2\pi\theta_c u}}{u} \tag{3}$$

where $(2\pi\theta_c)^{-1} = 550\,(1\ \mathrm{arcmin}/\theta_c)$. Note that at short baselines the visibility varies as a power law, while at longer baselines the visibility falls off exponentially. The SZE is therefore somewhat unusual in that the visibility flux received is larger when smaller telescopes are used (that is, when used near their shadowing limit).

The optimum telescope diameter and $u - v$ coverage depends on the scientific goals. Clearly, for detailed imaging of targeted clusters, one desires to maximize the $u - v$ range sampled. In Figure 5, we show the results of "observing" a massive galaxy cluster with the proposed 2.5 m sub-array, with BIMA, and with OVRO, all outfitted with our cm-wave receivers. We show the visibility for a cluster produced in an N-body and gas dynamical simulation. Such simulated clusters are evolved within different cosmological models, experience merging consistent with hierarchical structure formation, and exhibit X-ray morphologies consistent with observed clusters (Mohr and Evrard 1999); therefore, these simulated clusters provide more realistic templates than isothermal β models. Nevertheless, one can see that in this case the best fit β model (solid line) provides a reasonable description of the true cluster visibility (points). Regardless of the fine details of the cluster visibility, it is clear that the new sub-array provides crucial information inaccessible to arrays with larger diameter telescopes.

We emphasize that although the noise of an interferometer in flux is independent of baseline length for a given telescope size, this is not the case for brightness sensitivity. The brightness sensitivity, i.e., rms flux per beam, is related to the beam dilution, which is given roughly by $(D/B)^2$ where D is the diameter of the telescope and B is the separation of the telescope pair (the baseline). The brightness sensitivity is therefore highest for baselines near the shadowing limit and decreases rapidly as the telescope separation increases. The heterogeneous array concept allows one to maintain high brightness sensitivity over a large range of

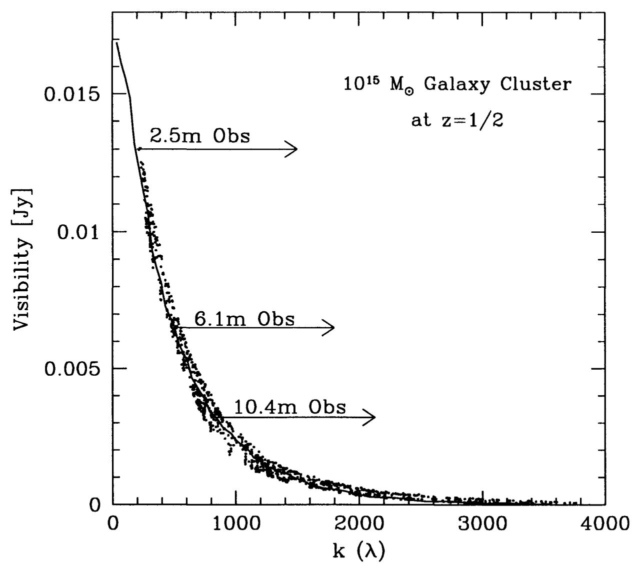


Figure 5: The left panel is the visibility for a simulated, high mass cluster "observed" with the proposed sub-array, BIMA, and OVRO. Points correspond to actual visibilities, the heavy line corresponds to the best fit circular β model, and the arrows denote regions accessible to each array. The right panel shows the 2σ confidence limit on the morphological parameters of the cluster gas distribution. The dashed line corresponds to an 84 hr observation with the current setup on BIMA, and the solid line corresponds to an 84 hr observation with an 8 GHz correlator on the heterogeneous, university array.

baselines.

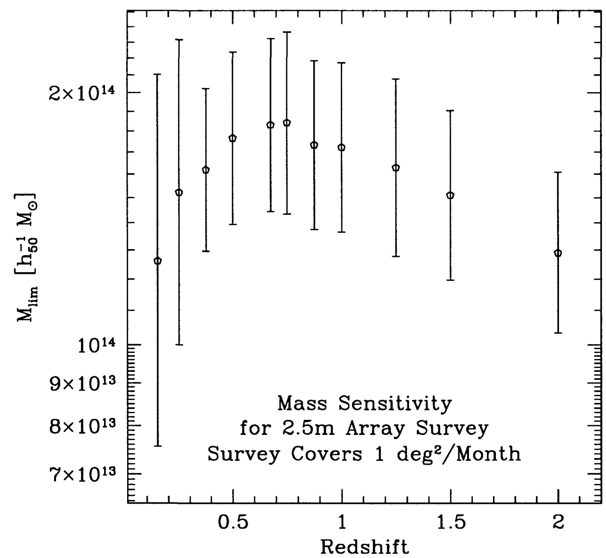
One of our main scientific goals is to use the SZE to survey large regions of the sky ($\sim$1 deg^2 per month); this survey provides a redshift independent search for galaxy clusters and filamentary, large scale structures. The optimum diameter of the array elements for this experiment is determined by the size which gives the fastest detection rate. In addition to the cluster visibility curve discussed above (see Figure 5), we must consider the visibility noise, which is proportional to $1/(D^2\sqrt{t_{int}})$, where t_{int} is the integration time per field, and the instantaneous field of view, which is proportional to $1/D^2$.

For the case of point source sensitivity, as is usually discussed, one readily finds that the parameter to optimize for conducting a survey is nD, where n is the number of telescopes. However, for the SZE, where the visibility function at short baselines increases more steeply than $1/B$, we find that smaller telescopes are actually better. We have selected a diameter of 2.5-m as a compromise between detection rate and imaging quality when combined with the existing telescopes of the OVRO array. The bottom line is that the 2.5 m sub-array will provide better cluster sensitivity than a similarly equipped array of 6-m or 10-m telescopes.

B3. *Sunyaev Zel'dovich Effect Science With the Sub-array*

As discussed above and in Section A4, using our low-noise cm-wave receivers on the university mm-wave arrays has allowed us to obtain high signal to noise images of the SZE toward 27 clusters spanning redshifts from 0.14 to 0.83. Typically each measurement has required 6 to 12 transits of source. These measurements represent an enormous increase in the quality of SZE data; with them we are now beginning to tap the tremendous scientific potential of the SZE that was first realized in the early 1970's. These observations have been used to set constraints on the Hubble constant H_0 and the cosmological density parameter Ω_M. Our cluster database can, in principle, also allow one to begin constraining models of structure evolution, which in turn are sensitive to underlying cosmology (e.g. Bahcall and Fan 1998, Blanchard and Bartlett 1998, Viana and Liddle 1998). Nevertheless, to obtain tighter constraints on the cluster gas morphology (see Figure 5) and improved distance estimates, we require much better data. Moreover, our cluster sample is selected primarily from known X-ray clusters and therefore suffers from selection effects typical of X-ray samples.

With the proposed sub-array, we will be able to conduct a survey which will detect all clusters more massive than $\sim 2 \times 10^{14}$ $M_\odot$ over a large region of the sky *no matter what the cluster redshift.* In essence,



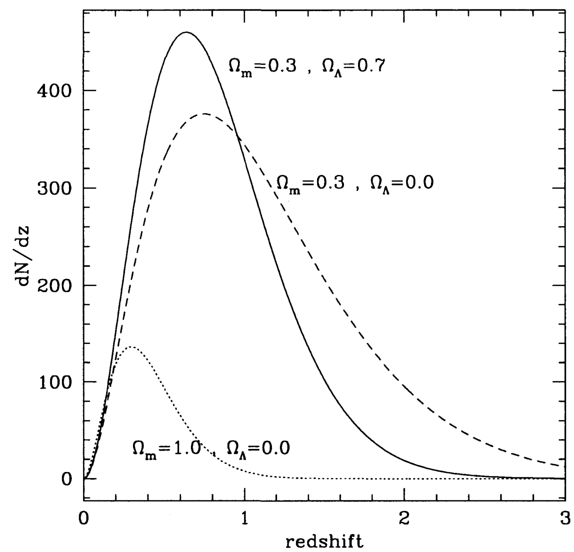


Figure 6: We show M_{lim} versus z (left) and the predicted detected cluster z distribution for several cosmologies (right). We determine M_{lim} at each z by "observing" numerically simulated clusters (see Section B3.1). Clusters with $M = M_{lim}$ are detected with 5σ significance with the 2.5 m array in survey mode; M_{lim} uncertainties reflect morphological variation in the cluster population.

we desire to exploit the amazing fact that *the observed temperature decrement of the SZE is independent of the distance to the cluster.* As detailed in Section B3.1, such a survey would produce a large, high z cluster sample with a simple selection function; this sample would be an ideal starting point for further Hubble constant and deceleration parameter measurements (providing a much needed, independent check of the type Ia SNe results), as well as for testing models of cluster formation and evolution. In addition, the proposed sub-array could image large scale structures such as the filaments that bridge clusters; these images would provide direct detections of the low density, warm baryonic gas which may constitute the largest component of baryonic matter in the present day universe (Cen and Ostriker 1998).

We already have in place an exceptional team for analyzing our SZE and X-ray data, funded in part by the NASA Long Term Space Astrophysics program. We are currently working on the careful extraction of cluster distances from the combined SZE and X-ray data already in hand. We are using existing N-body and gas dynamical cluster simulations to understand the effects of temperature and density structure on our analysis and are just beginning a 5000 hr supercomputer program to produce a large ensemble of state of the art, hydrodynamical cluster simulations which will be an important resource for future SZE analyses. In addition, we are working with the Chandra (AXAF) Hubble constant key project team to provide SZE data, and as PI's or co-I's, we are expecting to obtain deep Chandra observations toward a number of clusters to compare with both our SZE observations and the simulations.

In this proposal, we are seeking funds to greatly enhance our SZE imaging system by first increasing the correlation bandwidth from 1 GHz to 8 GHz and then building a sub-array of ten 2.5-m telescopes. With over an order of magnitude faster imaging, denser $u-v$ coverage, and approximately an order of magnitude more integration time available, the proposed sub-array and wideband correlator will allow the full potential of SZE science to be realized. Our determination of the Hubble constant, deceleration parameter and the baryonic mass fraction will benefit enormously from the better imaging and larger cluster samples at higher redshift. Below we discuss several of our scientific goals in greater detail; these include: an SZE survey (Section B3.1), the imaging of filaments and large scale structures (Section B3.2), studies of intrinsic and secondary CMB anisotropies (Section B4), and other science (Section B5).

B3.1. *The Sunyaev Zel'dovich Effect Survey*

Below we detail the year-long survey with the proposed 2.5 m sub-array and new wideband correlator. The first step in estimating the number of clusters we expect to detect is to determine the limiting cluster virial mass $M_{lim}(z)$ that we can detect with high confidence, given the properties of the array and our goal of surveying 1 $\deg^2$ per month. Because the cluster detection limit depends on mass and morphology, we determine the mass limit using "observations" of simulated clusters output at the appropriate redshift. Specifically, at each redshift of interest we "observe" an ensemble of 48 clusters simulated within 4 different cosmological models (Mohr and Evrard 1997); these simulated clusters vary in mass by an order of magnitude at the present epoch. By "observing" clusters output from simulations at different redshifts, we naturally account for the morphological changes which occur as clusters evolve with redshift. We then analyze these observations, determining the $\Delta\chi^2$ between the best fit β model and the null model. M_{lim} is the mass corresponding to a 5σ detection, and the uncertainty on M_{lim} reflects the variation in cluster morphology at that redshift. As shown in Figure 6, we can conservatively expect to detect $2 \times 10^{14} h_{50}^{-1} M_\odot$ clusters at any redshift with high confidence. (We note in passing that with the full, heterogeneous array in survey mode M_{lim} falls to well below $10^{14} h_{50}^{-1} M_\odot$.)

Coupling the limiting mass with the Press-Schechter formalism and an assumed cosmological model, we calculate the expected number of detected clusters (Holder, Carlstrom, and Mohr 1999). We examine three different cosmological models: the currently favored $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.65$ as well as an open model and the standard CDM model. All models are normalized to produce the observed number density of clusters at $z = 0$. Note the cosmological sensitivity of the observed surface density of clusters detected in an SZE survey (Figure 6).

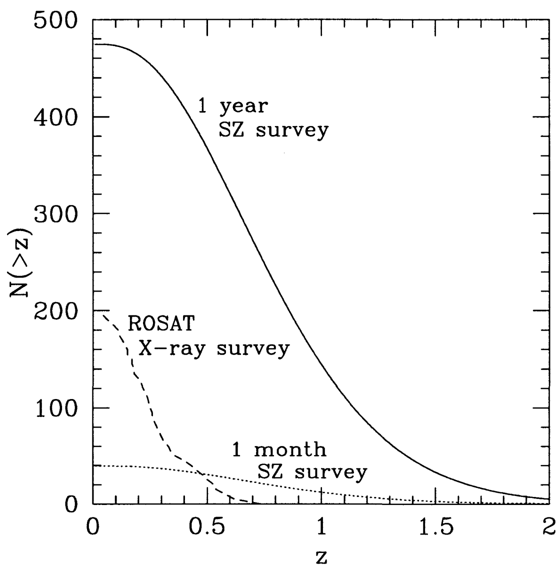


Figure 7: The expected number of clusters detected with the proposed sub-array in survey mode for one month– 1 $\deg^2$– (dotted) and one year– 10 $\deg^2$– (solid). The predictions are based on the currently favored $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ flat CDM cosmology; the predicted numbers are higher for an open CDM model. The resulting sample of clusters, with more than 300 clusters with $z > 0.5$ and more than 100 with $z > 1$, would be unparalleled both in size and in the simplicity of the selection function; it would become the standard catalog of distant, massive clusters. For comparison, we show the cluster sample from a deep, serendipitous, X-ray survey of $\sim$160 $\deg^2$ carried out using archival ROSAT PSPC images (Vikhlinin et al. 1998).

As can be seen in Figure 7, one year of observing with the new sub-array will deliver more clusters with redshifts higher than $z \sim 0.8$ than are found in the deepest, large area X-ray cluster catalogs (Vikhlinin *et al.* 1998). This assumes that the currently favored $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ cosmological model is appropriate; if $\Omega_\Lambda = 0$ the numbers increase (see also Figure 6). Note that the proposed array will deliver more $z > 0.5$ clusters in a month– 1 $\deg^2$– than are found in the entire 160 $\deg^2$ Vikhlinin catalog. This is the true power of SZE cosmology, because it is exactly these high-redshift clusters which provide the most stringent cosmological constraints; as an added bonus, the SZE survey selection function would be simple (see Figure 6). *Our 1 yr cluster sample, with more than 300 clusters at $z > 0.5$ and more than 100 at $z > 1$, would be unparalleled, and would become the standard catalog of distant, massive clusters.*

B3.2. *Filaments and Large Scale Structure*

A survey with the proposed sub-array will directly detect, with high confidence, objects with characteristic scales of 1-10 arcmin producing SZE decrements as small as $\sim 50\ \mu$K (see simulated survey of supercluster in Figure 8). Therefore, depending on the details of structure formation, we expect that the survey will deliver the first images of the low density gas in the filaments that bridge galaxy clusters. These large scale structures— apparent in the galaxy distribution of the first CfA redshift survey (De Lapparent, Geller, and Huchra 1986)— are the most striking features in structure formation simulations and may well be the largest reservoirs of baryons in the local universe (Cen and Ostriker 1998). The proposed sub-array provides a unique way to directly image these structures through their effect on the CMB. Coupling direct filament detection via weak lensing (sensitive to total mass) with our SZE survey would provide measurements of baryon fractions on very large scales and place constraints on mechanisms— like hot, galactic winds expected during bursts of star formation— which redistribute baryons more efficiently than dark matter. Detections of this hot, low density gas would enable a far more complete accounting of the baryons in the low redshift universe.

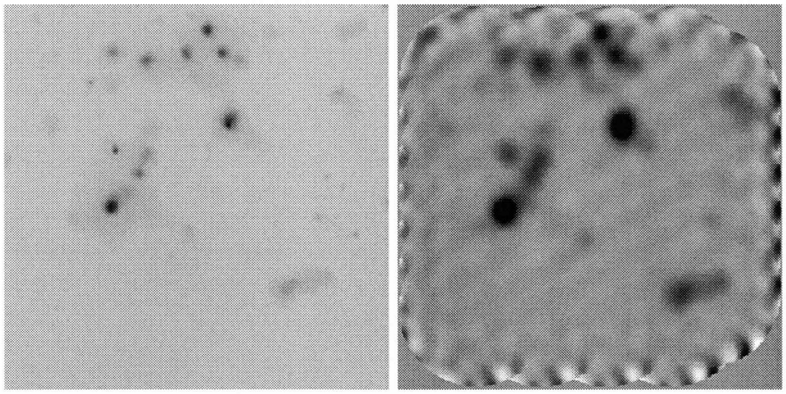


Figure 8: The left panel shows the SZE signal from a supercluster produced in an N-body and gas dynamical simulation (D. Bond, private comm.). The right panel shows the reconstruction of this field from a mosaic of "observations" with the proposed 2.5 m sub-array in survey mode. The rms background variations in the reconstructed image are ~7 μK.

B4. *Intrinsic and Secondary Anisotropy in the Cosmic Microwave Background (CMB)*

In presently favored cosmological models, structure in the CMB is exponentially damped at arcminute scales, due both to photon diffusion and smearing of intrinsic fluctuations resulting from the finite thickness of the 'surface' of last scattering. If the universe is subsequently reionized, the intrinsic fluctuations can be further eroded as the CMB photons are rescattered on all scales up to the size of the new horizon. Moreover, motion of the scatterers on the new last scattering surface can lead to second order anisotropies which are larger than the primary anisotropies on comparable scales (Ostriker and Vishniac 1986, Hu and White 1997). The details of the recombination process and the epoch of reionization are thus encoded in the CMB on scales to which the proposed sub-array will be sensitive. Simulated observations of the CMB for a universe reionized at $z = 20$ with optical depth $\tau = 0.13$ show that the proposed sub-array will detect the damping tail with S/N $\sim$ 100 on $4'$ to $6'$ scales; on smaller angular scales we should be able to detect the secondary anisotropy with S/N $\sim$ 10. With our receivers and the proposed correlator on the BIMA array (see Section E), we should be able to detect the secondary CMB anisotropy on $1'$ to $2'$ angular scales with a S/N > 10.

B5. *Other Science*

The proposed array is well suited to a large range of scientific investigation beyond studies of the SZE and CMB anisotropy. As mentioned in Section A4, the BIMA community already uses our 26 – 36 GHz receivers to conduct a large range of observational projects including detailed imaging of CCS emission of nearby molecular clouds to probe the kinematic and density structure of clouds, investigations of the spectral index of the emission from dusty regions at long wavelengths to search for the signature of rapidly spinning grains or an anomalously hot free-free component (see Leitch *et al.* 1997 and Draine and Lazarian 1998), investigations of the large scale emission and spectral index of supernovae remnants as well as the lobes of radio galaxies, searches for high-z CO emission from dusty protogalaxies and searches for hyperfine emission from highly ionized carbon and nitrogen.

In addition to enhancing the 26-36 GHz capabilities for the radio astronomy community, the eventual out-fitting of the proposed sub-array at higher frequencies (to match those of OVRO) and combining it with the OVRO array will provide a powerful and unique heterogeneous array for conducting mm-wave science.

The array will be used to support first-rate scientific programs spanning studies of large scale structure in the universe, galaxy formation, the detailed kinematics and star formation properties of galaxies, the gravitational collapse of molecular material to form solar-like stars and protoplanetary disks, and the details of the circumstellar disks. The heterogeneous array provide a much more comprehensive view of star forming regions by allowing high sensitivity imaging on all scales from those of the parent molecular cloud to the compact protostellar/planetary systems themselves, yielding precise information on the gravitational collapse of molecular material and the evolution of the circumstellar disks. The large range of angular scales will allow detailed investigation of the physics, chemistry and evolution of molecular clouds in our galaxy, as well as the detailed kinematics and star formation properties of molecular clouds in external galaxies. This combined array will offer unique and complementary capabilities to those of the proposed NRAO millimeter array to be sited in the southern hemisphere.

B6. *Personnel*

Here we list the number and type of all personnel using the instrumentation for research and research training on a regular basis. Excluding people at OVRO and BIMA, our personnel is made up of a minimum of 3 faculty or equivalent, 2 engineers, 5 postdocs, and 7 graduate students. Undergraduate students will play a role in the project through internships and summer programs. There are also several other research groups at Chicago that are interested in using the proposed array. If we include OVRO and BIMA, we are then including the radio astronomy departments of Caltech, U. C. Berkeley, U. Illinois and U. Maryland. As outlined in Section E, the array will become available for use by the entire radio astronomy community.

C. Description of Research Instrumentation and Needs

An interferometer is a complex, precision instrument. Although, we are essentially proposing to build all the components for a new array, it is important to recognize that we are actually building additional telescopes and correlator power for an existing array. This greatly minimizes the amount of new design and development, which in turn minimizes the cost as well as the uncertainty in the cost and timescale of the project. In the following sections we discuss the major components of the array.

C1. *Telescopes*

The 2.5-m telescopes are the only completely new component of the proposed sub-array in that none currently exist at the mm-arrays. Although our first science goals will be pursued using the 26 to 36 GHz band, the plan is to eventually use the array at all frequencies available to the mm-array, which may be as high as 350 GHz if the OVRO array is moved to a higher site. This requires that the telescope surface be accurate to $25 \mu m$ RMS and the pointing be at least a 1/20 of the beam at 350 GHz, i.e., about $4''$. We contacted Vertex Communication Corp. (*a.k.a.* TIW) and Composite Optics. TIW believes the specifications could be met using a precision machined cast reflector. Composite Optics also believes the specification could be met easily with a monolithic reflector. We also have experience building precision optics and telescope mounts, e.g., the optics and truss structure shown in Figure 9 and the DASI telescope. More directly relevant to this proposal, co-I M. Joy was responsible for the casting and precision machining (at NASA/MSFC) of the 13 primary reflectors for the CBI telescopes (Padin *et al.* 1999). He has achieved a 25 μm RMS surface accuracy for a 0.9-m parabolic reflector. We are certain that we could machine panels for a reflector design using panels similar to the BIMA 6.1-m design, although with many fewer panels. This option would be considerably less expensive than the TIW or Composite Optics alternatives. We have decided to investigate these options and to be our own prime contractor to take full advantage of the facilities available to us. We also will investigate modern lightweight mount designs being developed by D. Woody and others for the MMA telescopes[1].

C2. *Receivers and Local Oscillators (LO)*

We already have ten low-noise HEMT based 26-36 GHz receivers, LO's, optics, and mounts which we use for our SZE imaging program at OVRO and BIMA. A photo of one of our receivers, optics, and truss structure mounted at the Cassegrain focus of an OVRO 10.4-m telescope is shown in Figure 9. Note, that our receivers and tertiary do not interfere with the mm-wave optics. We simply remove the mm-wave tertiary which is an optical flat located near the Cassegrain focus to direct the mm-wave beam to the Nasmyth focus in the sidecab. In the future, we plan to motorize the mm-wave tertiary so that mm- or cm-wave bands can be selected automatically.

Our existing first LO's are electronically tunable YIG oscillators that cover 26 to 40 GHz. Our phaselock modules are compatible with the OVRO/BIMA LO chains and electronics.

We have continued to improve the sensitivity of our receivers which are based on InP HEMT amplifiers developed by M. Pospieszalski at NRAO (Pospieszalski *et al.* 1995). We are now building the amplifiers in

[1] See http://www.ovro.caltech.edu/ lamb/mma/page2.html.

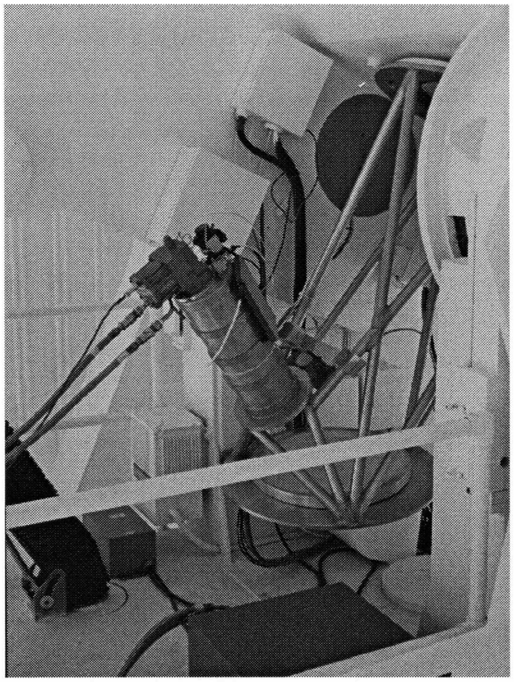


Figure 9: One of our ten low noise 26 - 36 GHz HEMT based receivers mounted on an OVRO mm-array telescope. The space frame holds the receiver and large tertiary mirror which allows an image of the secondary to be placed on the mouth of our cooled feed horn. We have outfitted all six of the OVRO 10.4-m telescopes with space frames and tertiaries. The measured aperture efficiency of this optical system is 75% at 30 GHz. The mm-wave receivers are selected by inserting a optical flat mirror near the Cassegrain focus to redirect the beam through the elevation bearing to the Nasmyth focus in the sidecab.

our laboratory at the University of Chicago and expect to have the noise temperatures of all receivers in the range of 10 - 15 K across the band. We are not requesting any funds in this proposal for receivers or the first LO's and phaselocks.

C3. *LO Chain and Reference System*

Our existing first LO and phaselocks are compatible with the OVRO and BIMA local oscillator reference systems. We intend simply to duplicate the existing LO distribution and the LO chain. This will require duplicating the intermediate component of the LO chain, an X-band YIG oscillator and its phaselock loop. This will also allow the system to be completely compatible when mm-wave receivers are installed at a later date, as well as when cm-wave receivers are installed on the larger telescopes.

C4. *Telescope Stations and Array Considerations*

The array configurations will always be fairly compact, with long baseline data being provided by the larger existing 10.4-m telescopes. The array being proposed here will require a region spanning ~30-m. We plan to have 30 telescope stations to provide array configurations optimized for observing at all declination ranges above $-30°$. We also want to accommodate different science driven imaging requirements. For example, the CMB primary anisotropy observations will require the most compact configuration, while the detailed imaging of the SZE will require the best angular dynamic range. Due to the compactness of the arrays, we will need only one IF/LO/power/signal connection point per telescope.

C5. *Signal Transmission*

The signals for everything but the receiver IF can be transmitted via conventional cables. The broadband IF will be transmitted using broad bandwidth, analog modulation fiber optic technology (available from Ortel Corp). To maintain the low noise temperature of our system, we must consider the limited dynamic range of these systems. We will achieve system temperatures of ~30 K, which corresponds to a 'Y - factor' [2] of 10. We plan to use a precision and calibrated 10 dB attenuator so that we can always transmit at the optimum level through the fiber optic system. We note that the arrays are currently using Ortel fiber optic systems, but they do not require such high dynamic range since their Y–factors are much lower and they transmit much less bandwidth.

[2] The Y-factor is the ratio of the power received from the sky to that received when an ambient load is placed in the beam. Such measurements are used at the mm-arrays currently to determine the system temperature.

C6. *Baseband Downconversion and Correlator*

The downconversion to baseband will use standard analog splitters and channelizers to define the separate IF channels. The channelizers are then followed by the modules to downconvert to baseband. This system is nearly identical to the system used in DASI.

We plan to work with OVRO engineers to build a flexible Mark II generation of their digital correlator design. Dave Hawkins who is a co-I on this proposal is the leader of the OVRO correlator effort. The correlator would be completely compatible and flexible; it can be reconfigured to handle more telescopes at the cost of total bandwidth. For example, the 10 telescope (45 baseline) 8 GHz system proposed here could also be used to correlate 16 telescopes (120 baselines) with 3 GHz bandwidth.

OVRO is currently developing the Caltech-OVRO Broadband Reprogrammable Array (COBRA) Correlator. The initial OVRO specifications are for eight 500 MHz bands for a total of 4 GHz of bandwidth for the six antenna and 15 baselines. The 500 MHz bands are digitized to two bits and demultiplexed to give a 32-bit wide by 62.5 MHz data stream feeding a digital delay. Each 6U height (a standard size for compact PCI or VME crates) digitizer card will process two 500 MHz bands. The basic correlator module is a 6U height card that takes the digitized signals from four antennas on four cables and produces five baselines of cross-correlation. There are ten Field Programmable Gate Arrays (FPGAs) on each card. Currently available FPGAs will provide 50 lags per baseline for a spectral resolution of 20 MHz across the 500 MHz bandwidth. The whole system including computer and power supplies for two 500 MHz bands for the OVRO array fits in a single commercial compact-PCI crate. The architecture is very flexible and can be used for a wide variety of projects.

COBRA is also designed to work with the next generation of chips from Altera without any re-engineering of the boards or crates. The boards are being designed to operate at clock rates as high as 125 MHz. This will allow full utilization of the next generation of FPGAs that will operate at this higher clock rate with the same power as the current chips. This anticipated speed up will be used to improve the spectral resolution of the OVRO version of COBRA.

The increased speed can also be applied to the correlator being proposed here. The digitizer card will be replaced with ones that have four samplers to handle 500 MHz analog bandwidth from four telescopes. The same cabling that routed four telescopes to each correlator card will now route eight telescopes (two per cable) to each card. Each correlator card will process 16 baselines at coarser resolution. It is possible that we might not immediately achieve the full 125 MHz speed. In this case we would have to decrease our bandwidth accordingly.

C7. *Control System, Data Acquisition, Reduction and Analysis*

The control and data acquisition system will again be duplicated from the OVRO design. Beyond ensuring compatibility, this guarantees an excellent system. This system is the result of several man-years of work. While it exists already, we expect to contribute considerable effort to duplicating it into our system. OVRO has agreed to let us work with their engineers to bring our system online.

The reduction and analyses software is already in place as it is identical to the software we use now. We are continually improving this system, particularly the analyses software. This work is funded through other grants.

D. Impact of Infrastructure Projects

The proposed sub-array will have an immediate and major impact on U. Chicago's and the nation's scientific goals; it will lead to a major increase in our understanding of the evolution of large scale structure, the mass density of the universe, the history of the expansion of the universe, and the ultimate fate of the universe. Observational pursuits of these fundamental issues were identified as the *top recommendations within the area of Cosmology and Fundamental Physics by the report of the Task Group on Space Astronomy and Astrophysics (TGSAA) Committee on Astronomy and Astrophysics* (TGSAA 1997). These fundamental issues also echo those raised in the Science Opportunities section of the last decadal survey report on Astronomy and Astrophysics, where the potential of using the SZE to determine distances to a large number of galaxy clusters was specifically noted (Bahcall *et al.* 1991).

The high angular dynamic range of the proposed sub-array combined with the OVRO array will lead to a much better understanding of star formation by enabling us to, quoting from the list of recommended priorties by the TGSAA report within the area of Planets, Star Formation, and the Interstellar Medium, *"characterize the very earliest stages of star formation by observing the structure and dynamics of protostellar regions."*

The proposed heterogeneous array will have a major impact on academic research infrastructure in radio astronomy. This is particularly true in the field of mm-wave interferometry, which the university research groups pioneered and where they continue to lead innovation in the field. By its promise of fundamental scientific results in the near term and its major role in fulfilling the need for a sensitive hetergeneous mm-wave array in the long term, the proposed array will help ensure the health and vitality of radio astronomy in the universities. The need not just to maintain but to improve both the technical level and commitment to university mm-wave interferometry is vital to the nation's plan to go forward with the NRAO millimeter array project (MMA). The array proposed here offers a direction forward that keeps the university research groups at the leading edge of technology (increasing the number of committed universities) and provides unique capabilities complementary to those of the MMA.

The best students are attracted to fields that they believe are challenging and that will yield new exciting and fundamental scientific results. Students are attracted to pursuing research in the fields discussed in Section B. The public also has a fascination and appetite for knowledge about the fundamental questions of the universe and about the manner in which scientists attempt to answer such questions. Students are also attracted to the experimental challenge offered by new instruments and techniques. We strongly believe the proposed array would do more than maintain the high quality of students being trained currently — it will increase their number.

As an example, consider the instrumentation projects listed in Section A. These have so far led to Ph.D. theses for three women (Rachel L. Akeson, Martina Wiedner, and Laura Grego) and one man (Oliver P. Lay). The postdocs and students involved in these new instrumentation projects receive valuable skills in all of the scientific and engineering aspects of research and instrument development. Clearly it is important to our nation's science goals to ensure that students are given a perspective of the entire research process. With this experience and perspective, they can gain the confidence to become leaders in the field.

D1. *Education and Outreach*

The University of Chicago is committed to the highest standards of undergraduate and graduate education. The PI, J. Carlstrom, intends to incorporate his research and related technology in both formal and informal science education efforts. In his role of associate director of the Center for Astrophysical Research in Antarctica (CARA), and owing to U. Chicago's close relationship with the Adler Planetarium and Astronomy Museum, the PI has access to a well-established and vibrant educational network committed to strengthening the general science literacy of the nation. CARA organizes a wide variety of educational programming coordinated by Randall Landsberg, director of education and outreach, and Adler is one of the leading public education and outreach centers for astronomy in the Midwest. This network provides a vital regional and national infrastructure with many participants, including the Illinois State Board of Education, the Chicago Public Schools (85% low income, 90% minority), Fermi and Argonne National Laboratories, and many universities, colleges, and community colleges. Outreach through this network reaches a diverse audience at all levels of the educational continuum and includes hands-on laboratories, teacher workshops, education technology programs, curriculum development, internet technology, physically and virtually traveling exhibits, remote observing, and residential science camps at Yerkes Observatory. Adler, CARA and other partners will provide "in kind" contributions arising from this infrastructure and aid in the dissemination of the ideas behind and the results arising from the proposed research. Outreach and Education related to the research proposed here will thus be assured successful dissemination and implementation through established structures and mechanisms.

The components for the proposed sub-array will be built at U. Chicago. The project will have a high visibility to undergraduate students from all disciplines, and several will be directly involved. We also plan to use the project to expose local high school students and associate degree students to scientific and engineering research through participation with the existing education and outreach programs at CARA and the Adler Planetarium.

The PI is developing a hands-on course, *Exploring the Universe with Radio Telescopes*, which will cover topics closely related to the research program proposed here. The course is a hands-on undergraduate freshman level course using a 4.5-m radio telescope located on the roof of the physics teaching center at U. Chicago. The course will also incorporate results from other radio telescopes including the research proposed here. The new course will use the excitement of scientific discovery to teach an appreciation for scientific research as well as basic science principles. We plan to make the telescope remotely operable and to develop a web-based course. At that time, the PI will use the extended network already developed by CARA, CUIP[3], and the Adler Planetarium to reach a much larger range of students and educators who will access the telescope remotely.

The new radio telescope course will be first offered in 2000 Spring. Workshops to train high school and undergraduate teachers will be held soon after. The PI is enthused about this project and has arranged to make this his primary teaching responsibility. The development of the proposed array and the data from it will be used to enrich the course. No funds to be used explicitly for education and outreach are requested in this proposal.

E. Project and Management Plans

The project will be managed by the PI at the University of Chicago. Much of the work will be done in parallel. The planned timeline is given here.

1) The downconverter and correlator will be developed and built in collaboration with OVRO engineers. After these are completed (in second year of funding), we will install the correlator and our receivers on the BIMA array to conduct a survey of the SZE and of CMB anisotropy for a period of roughly two to three months. The receivers will remain on the BIMA array as long as requested (we expect 1 to 2 months) and the correlator will remain with the BIMA array to be used with their mm-wave system for a longer period of time while we build the rest of the system (~1 year).

2) While the correlator is being built, we will work on the telescope design. The telescopes will be built after the BIMA survey is conducted. During the third year of funding we will install the telescopes at OVRO[4]. After the telescopes are installed we will bring the correlator from BIMA to the new array.

3) We will then begin our SZE survey. We also expect to use the earlier time with our receivers on BIMA, as well as some additional time with our receivers on OVRO to survey our fields for point sources. We expect the SZE survey to last about 1 year.

4) We will then work toward combining the 2.5-m telescopes with the OVRO 10.4-m telescopes. The allocation of observing time for the separate arrays and for the combined array will be determined by peer review with the rough split between Caltech and Chicago's time negotiated ahead of time. The fraction of time allocated to outside users (i.e., the entire astronomical community) will approach ~50% as it currently is for the OVRO mm-array. Advertisements for the observing time will be published in the AAS newsletter. There will be no user fees.

Maintenance and operation costs for the proposed array are expected to be modest at ~\$250k per year which includes funds to cover a postdoc, student, and repairs. The PI plans to propose for these funds to the NSF on the same schedule as for the OVRO and BIMA review/funding cycle. We suggest the project also be reviewed by the same NSF panel assembled for the OVRO and BIMA grants.

E1. *Impact of Merging the OVRO and BIMA mm-wave Arrays*

Plans are being discussed for combining the OVRO and BIMA mm-wave arrays at a new high altitute site. Our proposal is not contingent on whether such a merger proceeds. We stress, however, that such a merger would further strengthen our proposal. In particular, it would greatly strengthen these important university radio astronomy research groups. In the event of a merger, our plan is to participate fully by making our proposed array part of the merged array. The University of Chicago would then negotiate for a fraction of the observing time that would reflect its contribution. We note that the merger would benefit all participants greatly, as the power of the combined array would be much greater than the sum of its parts. We strongly endorse the merging of the OVRO and BIMA mm-arrays.

[3] CUIP (Chicago public schools and University of Chicago Internet Project) is a group of faculty, administrators and students at U. Chicago who work with local schools to obtain T1 lines (27 schools have been linked so far), set up a system administration system, upgrade the system as the principal desires, and provide curriculum support to department heads. CUIP and Science Partners work closely together with two other groups: teacher trainers from the Chicago Public Schools assigned to each region for the explicit purpose of training classroom teachers to use technology in the classroom, and an intern program from Governor's State University that provides half-time computer savvy graduating seniors to work in the schools specifically on technology issues. See the web page at http://astro.uchicago.edu/outreach/cuip/ for more details.

[4] If a new high site is being developed then we plan to install the telescopes there.

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