National Radio Astronomy Observatory

Very Large Array

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To: Scientific Staff, Engineers, Etc.

From: Frazer Owen FNO

Subject: The Concept of a Millimeter Array

I. Introduction

The purpose of this report is to summarize the concept of a millimeter wave array which NRAO might build in the next 5 to 10 years. What is contained here within is just a concept and not a finished idea. I hope it can serve as a starting point for further definition studies possibly leading to a formal proposal for funds.

At the present epoch NRAO has completed construction of the VLA with a highest operating frequency of 22 GHz. Possible future improvements might allow operation at 44 GHz but this is uncertain. Around the world, a number of higher frequency dishes and arrays are in the late planning or the construction stages. The single dishes planned seem likely to supercede the capabilities of the NRAO 12 meter fairly quickly. The arrays of up to 5 dishes are just beginning to operate and seem to roughly parallel the centimeter interferometers of the 1960's.

It thus seems obvious that instrumentally the time has come to consider larger arrays for operation at millimeter wavelengths. This seems a natural direction for NRAO given its experience with the VLA. About eight years ago NRAO did briefly discuss the possibility of millimeter interferometry. At that time it was thought that we should let the university community do the ground work. This has been and is in the process of happening. Now seems the right time to raise the question again.

Scientifically a millimeter array seems quite attractive. In the next section I will outline some of the projects that I see as exciting. Generally the situation looks very promising.

An important part of my concept is the advantage NRAO would have in carrying out such a project if it used the VLA site and all that comes with it. As a millimeter site, the VLA site appears to be equal or better than any existing millimeter sites and only clearly inferior to sites such as Mauna Kea or White Mountain. Even without the VLA the logistical advantages to large flat plains over these latter sites for an array are obvious. Many parts of the VLA may also be used for a millimeter array e.g. the railroad track, the waveguide, buildings, computers, electronics labs etc.). Also, and maybe most important, the operating budget of a millimeter array on the VLA site should be much less than for any new site and quite possibly would not be any greater than the existing Tucson budget. Much of the operation would require the same types of people as the present VLA. While it is clear that additions to the VLA staff would be necessary these might be held to a minimum.

II. Science

A. General

Much of the science that a millimeter array would produce would come from spectral line observations. Since this is not my area of expertise I will ask Barry Turner and Harvey Liszt to speak to this question in more detail. However it is clear that many mapping projects of galactic and extragalactic molecules would be important. Also less obvious projects such as solar recombination lines would be likely targets.

Less obvious is that there are a great variety of exciting continuum projects which would be possible with such an instrument. As discussed below for point sources my working concept of an array would have 15 ten meter dishes. With 1 GHz bandwidths and 100 K system temperatures, an r.m.s of about 0.1 mJy could be reached in about 8 hours. One can scale from this number to one's favorite set of parameters. Resolution with 1 km arms could be as high as 0.15 arcsec at 230 GHz or about 0.35 arcsec at 100 GHz.

Before we go into particular continuum projects it is worth pointing out the possible superiority of the interferometer over the single dish. For a 25 meter antenna 1 Jy corresponds to about 0.1 K. Thus 0.1 mJy corresponds to 10^{-5}K or a $\Delta T/T$ system $\sim 10^{-7}$. This seems to be a very difficult measurement to make in the real world of fluctuating sky and ground pick up. With the 36 foot we seem to have trouble getting below $\Delta T/T$ of 10^{-6}. However with an interferometer much lower levels appear possible as we have gotten down to $\Delta T/T \sim 2 \times 10^{-8}$ in the deepest surveys with approximately theoretical noise. The improvement with the interferometer probably comes from the background rejection by spacial frequency filtering and the many independent signals which are summed in aperture synthesis.

Ignoring the difficulties mentioned above, a single dish with a bolometer would be more sensitive at the highest frequencies. However, John Payne tells me that at frequencies below 150 GHz, heterodyne techniques seem to give better sensitivities than bolometers. Thus an array of similar collecting area will be at least as sensitive as a single dish. Only at the shortest wavelengths at which an array might operate is there a possiblity that a single dish would be more sensitive and this is at the very frequencies where pick-up and atmospheric flucuations are likely to be largest.

B. Continuum projects

1) Microwave decrement

The class of experiment I consider most important that could be done in the continuum is mapping of the microwave decrement in the directions of rich clusters of galaxies and possibly other objects. This effect, also known as the Sunyaev - Zeldovich effect, is caused by scattering of the 3K background radiation by hot gas usually in rich clusters. The effect produces a "cold spot" longward of 1 mm (the peak in the 3K spectrum) and a "hot spot" shortward of 1 mm. At 1 mm the effect is zero. On the long wavelength side 3 mm is probably the best place to observe the S-Z effect. Typical sizes of the region containing hot gas in a distant cluster based on current x-ray data is about 1 arcmin although the cluster would probably look bigger in the microwave decrement due to the different dependence on n_e. Clusters at z~ 0.1 would be a few arcminutes in extent. Typical signals should be ~1 mK and some marginal detections have been made. The strength of the decrement is proportional to

$$\int n_e \, T \, d\ell$$

through the source. This is interesting in its own right but the most powerful use of the S-Z effect comes when it is combined with x-ray observations which measure

$$\int T^{-\frac{1}{2}} n_e{}^2 d\ell$$

as well as providing an estimate of T from the shape of the spectrum and various emission lines. When dependence of cosmology is considered it turns out that by combining these two observations it is possible to obtain a distance directly to each cluster. From this data and a cluster redshift one can estimate q_o and H_o independently of any of the standard problems of using standard candles as distance indicators. This technique was considered the best possibility for measuring q_o of all known techniques by the extragalactic subgroup of the Field committee. The only problem is that one must know the distribution of n_e and T along the line of sight. This is best done by mapping the cluster both in x-rays and in the microwave decrement. The first priority of the Field report is the AXAF x-ray observatory which will do the necessary job in the x-rays. A ground based millimeter interferometer seems the best way to accomplish the rest of the project from the ground.

In my opinion measuring q_o, and thus determining if the universe is open or closed, is the single most important result that could come from astronomy in the near future and thus demands considerable effort.

An instrument capable of mapping the "cold spots" in clusters would also be capable of reaching new sensitivity levels and the right angular scales for study of anisotropies in the 3K background. Such data are among the few ways we have of getting at galaxy formation and properties of the early universe.

2) Radio Galaxies and Quasars

One can think of a variety of important problems with radio galaxies and quasars with which a millimeter array with the sensitivity suggested above could deal with. With an r.m.s. sensitivity of 0.1 mJy more than 10^4 extragalactic sources exist which could be mapped. Important goals would include the determination of the frequencies at which the extended emission in such sources steepens. This information will constrain particle acceleration models.

The spectra of compact nuclei in extended radio sources as well as for sources dominated by their nuclear components at lower frequencies will be interesting. Typically the limit for the old 36 foot was about 100 mJy at 90 GHz. We should improve more than two orders of magnitude on this limit. For similar reasons the problem of radio quiet quasars can be explored at new levels. The array could also be used for millimeter VLBI since it should have more collecting area than any other millimeter telescope planned in U.S.

3) Thermal Emission

Many of the most important problems would relate to detection of thermal emission. The millimeter array should actually be more sensitive than the VLA for optically thick thermal emission especially at 1.2 mm. In normal galaxies it should be possible to clearly separate thermal and non-thermal emission as well as to detect the long wavelength end of the dust emission spectrum (at 1.2 mm). In external galaxies regions of interest would extend up to a few arcminutes. Dust emission from proto-stellar nebulae may also allow us to study forming solar systems. These systems would be ≤ 1 arcsecond in extent. Mapping of proto stellar nebulae was considered one of the most important projects considered for the LDR space infrared telescope but clearly out of its reach because of the resolution required.

Many stellar problems will also be within the capability of the array. These range from detection of the photosphere/chromospheres in nearby stars to stellar mass loss from a variety of objects.

The solar system will also offer many interesting targets including mapping of planets and possible detection of thermal emission from comets.

This brief list of just a few of the possible continuum projects should emphasize the wide range of problems a millimeter array can tackle. Such a range should improve our chances greatly of acceptance and support of the astronomical community.

III. A Working Concept

A. General Concepts

To deal with the science discussed above a fairly flexible instrument would be necessary. Ideally the array should have 1) high sensitivity both to point sources and extended emission, 2) as wide a field of view as possible,

3) frequency coverage from 30 to 230 GHz, 4) a capability for rapid map making (snapshots), and 5) as high resolution as possible.

My concept has started with a Wye shaped array with at least 15 antennas. Antennas of 10 meter diameter seem to be the largest practical size. Arm lengths would be ≤ 1 km, consistent with sub arc second resolution and the likely limits of the atmosphere. The antennas should be capable of operating at 100 GHz most of the time and at 230 GHz under the best conditions. Wide bandwidths (1 to 5 GHz) and low system temperatures would be necessary for the desired sensitivity.

Many of the problems in spectral line and also in the continuum, such as the S-Z effect, probably require wider fields of view than a 10 meter antenna would allow. Thus a second array of 3 meter antennas (15) would be desirable and would involve only a modest increase in the project's budget. Thus two arrays are envisioned, only one of which would operate at a given time due to correlator limitations.

The VLA site would be the site of the array for reasons discussed in the first section.

B. Details

1) Telescopes

Bill Horne thinks a ten meter antenna good to 230 GHz should be straightforward. After all we just got through building a new 12m. Obviously a three meter would be easier. Costs of the ten meter telescopes have not yet been estimated in detail but seem likely to be ≤500 K a piece.

2) Receivers

Receivers seem likely to be SIS mixers. 80-120 GHz would be the most important band, then 230 GHz, followed by 30-50 GHz. Let's guess 250K/system based on discussion with Sandy Weinreb.

3) IF Transmission System

The IF bandwidth should be as wide as possible. Could we use 15 GHz as an IF frequency? I get the impression that the IF will limit the bandwidth in any case.

Peter Napier has suggested using the existing waveguide for the IF. Since the baselines are so short higher frequencies could thus be used. Others do not like this idea.

4) LO

The LO performance needs to be a good deal better than with the VLA. 0.1 degree/GHz seems as a likely spec. With the VLA we seem to be getting about 0.5 degrees/GHz.

5) Correlator

The correlator seems to be one of the most challenging parts of the array. If we use the current VLA correlator as a model we can estimate costs and use these to compare with other solutions. Ray Escoffier tells me that it would cost about a million dollars today to reproduce the VLA correlator. Three VLA correlators ($3M) could handle any of the following.

	bandwidth	channels	telescopes
1)	4 GHz	2	15
2)	2 GHz	4	15
3)	2 GHz	2	21

While these parameters are acceptable the correlator clearly does limit certain parts of the design. This area needs a lot of looking into.

6) Computers

Almost all the computing should look like the existing VLA system and thus allow alot of copying both in the estimates in this memo and the actual programming.

a) On-line
The control system should be no more complex than the VLA and thus should cost ~500K

b) Calibration
Hopefully we can use the pipeline system of the VLA for spectral line observations and not need a large, new investment here.

c) Post - processing and other calibration
The Dec-10/AIPS systems should handle all problems. All that should be needed are clones. (1 M)

7) Lay-out of the array

The biggest problem here would be avoiding shadowing by the VLA while using as much of the track as possible.

Obviously all is more complicated than the remarks given above; however, none of it seems impossible.

IV. Cost Estimate for Millimeter Array

Telescopes	$11.0 M
Receivers	7.5 M
Correlator, IF, LO	4.0 M
Computers	1.5 M
Site	3 M
Transporters	1 M
Management	2 M
Contingency & Etc.	6 M
TOTAL	$36. M

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