LMSA: JAPANESE PLANS FOR A LARGE MILLIMETER AND SUBMILLIMETER ARRAY

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1. Introduction

The LMSA was originally planned as a Large Millimeter Array (LMA) where an array of thirty 10 m telescopes would be realized by adding 25 more telescopes to the Nobeyama Millimeter Array (NMA). However, because the recent discoveries of rotating protoplanetary disks around young stars and CO gas from very distant galaxies, sub-arcsec imaging with the highest achievable sensitivity at millimeter and submillimeter wavelengths is now considered very important as a capability of the proposed array (Ishiguro et al. 1994).

Sub-arcsec imaging is essential, for example, in order to resolve the protoplanetary disks in nearby star forming regions such as the Taurus region where $0.1''$ at a distance of 140 pc corresponds to 14 AU, a scale comparable to our solar system. To achieve an angular resolution of $0.1''$ at 1 mm, an array of 2 km maximum baseline located at a very high and dry site is required. Since submillimeter observations at the Nobeyama site are very difficult, we decided to find a site for the LMSA outside Japan. Mauna Kea and northern Chile are being considered as potential sites for the LMSA.

In the current design concept, the LMSA will consist of 50 telescopes of 8–10 m diameter, the total collecting area of which is equivalent to a single dish of 70 m diameter. The LMSA will cover observing frequencies from 80 GHz through the 800 GHz band. Since 1994, site testing has been conducted extensively in northern Chile using a 220 GHz tipping radiometer and an 11 GHz site-testing interferometer.

Scientific directions, the planned system, and site testing activities in Northern Chile are reported in this paper.

2. Scientific Program for the LMSA

The LMSA will be used to study all types of radio emission at millimeter and submillimeter wavelenghts, especially molecular line emission from low temperature gas and dust continuum emission. Observations at submillimeter wavelengths provide higher sensitivity to thermal dust emission than at millimeter wavelengths (by a factor of 10^2–10^3). Important astronomical problems, such as the formation and evolution of stars and of protoplanetary systems, could be studied by making use of this advantage. Recently, rotating protoplanetary gas disks around young stars were revealed with the NMA (Kawabe et al. 1992; Saito et al. 1995). However, the resolution (2-3″) was insufficient to resolve the structure. Sub-arcsecond imaging is essential in order to resolve protoplanetary disks in nearby star-forming regions such as the Taurus region. With multi-line imaging of protoplanetary disks in high-excitation molecular lines, it will be possible to measure the radial variations of the physical conditions. Continuum observations at multi-frequency bands will provide information on the growth of dust toward planetesimals. Although detection of individual planets will be very difficult, high resolution imaging of face-on protoplanetary disks might show radial gaps due to mass contraction into planets. Polarization observations with the LMSA at 300 GHz–500 GHz will show the magnetic field structure in protoplanetary disks, providing very important information on the role of magnetic fields in the evolution of disks.

The formation and evolution of galaxies and QSOs, in terms of star formation and AGN activities, are also very important topics for the LMSA. The power of spectral lines is approximately proportional to ν^3. Strong dust emission at high z is redshifted to millimeter and submillimeter regions, the strength of which is proportional to ν^{2-4}. Accordingly, observations at higher frequencies are much more productive in detecting this emission. Recent millimeter-wave observations of CO from IRAS F10214+4724 using single dishes and interferometers indicate that the huge amounts of molecular gas are associated with this high-z galaxy, which has an extremely high infrared luminosity (Brown and Vanden Bout 1992; Kawabe et al. 1992; Tsuboi and Nakai 1995). Searching for high-z "proto-quasars" might also be possible by observations of highly redshifted emission of a strong [C II] 158 μm line (Loeb 1993), which is an important coolant in photon-dominated regions in galaxies. The [C I] 610 μm line traces photo-dissociation regions in the interstellar medium and can be observed together with high level transitions of the CO molecule (CO[J = 7–6] or CO[J = 4–3]) at submillimeter wavelengths. In these kinds of observations of distant objects, high sensitivity and sub-arcsecond resolution will play very important roles.

Although it is very difficult to summarize all the scientific targets in this paper, the LMSA will open new directions in studying interstellar chemistry, molecular clouds in our galaxy and in nearby galaxies, disks, inflow/outflow around young stellar objects, mass loss from evolved stars, circumstellar shells, etc.

3. Description of the Planned System

The scientific requirements described previously define the following capabilities of the LMSA:

1. Wide frequency coverage at millimeter and submillimeter wavelengths (80–800 GHz);
2. Sub-arcsecond imaging;
3. Very high sensitivity at millimeter and submillimeter wavelengths;
4. Quick imaging with high dynamic range.

To achieve an angular resolution of $0.1''$ at λ 1 mm, the maximum baseline must be longer than 2 km. In a preliminary design of the array, fifty 10 m antennas are connected to achieve a total collecting area of 4000 m^2, equivalent to that of a 70 m diameter single dish. With this collecting area and $T_{\rm SYS}$ = 300 K, 100 μJy (5σ) sensitivity will be achieved at 350 GHz. An example of the proposed array configurations is shown in Figure 1, where four different configurations are overlayed. The array sizes under consideration are 100 m, 300 m, 700 m, and 2 km. All antennas should be transportable to realize each of these configurations. The 100m configuration will be used for high-sensitivity surveying of distant galaxies and wide field mosaicking observations. The array configuration has a good instantaneous (u, v) coverage. This will allow us to collect data sets in periods of good radio seeing, so that we can obtain high quality and high resolution images using an ensemble of good snap-shots.

The antennas must be designed for efficient operation at frequencies as high as 850 GHz, requiring a surface accuracy $\sim$15 μm rms and a pointing accuracy of $\sim 1.0''$. A preliminary design of the antenna structure is shown in Figure 2. The mechanical structure is designed based on conventional Nasmyth optics in order to have enough space for installing a large receiver system. The quadrupod is supported directly from the central hub in order to minimize the gravitational deformation and the radio blockage. The main reflector of the new NMA 10 m antenna has similar design whose mechanical and thermal performances are under test at Nobeyama. Another important aspect of antenna design is mass production and construction at a very high site. The antenna structures should be assembled at lower altitude and brought to the site in sections.

Receivers in the atmospheric windows between 80(40) GHz and 850 GHz are planned for each antenna (see Table 1). HEMT amplifiers will be

Figure 1. An example of the proposed array configurations. Four different configurations for 100 m, 300 m, 700 m, and 2 km maximum baselines are overlayed. In actual design, the north-south size will be elongated to improve the (u,v) coverage over a wide range of declinations.

Figure 2. A preliminary design of the mechanical structure of the LMSA antenna based on conventional Nasmyth optics.

TABLE 1. Summary of Instrumental Parameters

Array		
	Number of Antennas	50
	Total Collecting Area	$\simeq$4000 m^2
	Maximum Baseline	2 km
	Max. Angular Resolution	$0.1''$ ($\lambda = 1$ mm)
Antennas		
	Diameter	8 m - 10 m
	Surface Accuracy	$\sim$ 15 μm rms
	Pointing Accuracy	$\sim 1.0''$ rms
Frequency bands		
		(35 - 50 GHz)
		80 - 140 GHz
		130 - 200 GHz
		200 - 310 GHz
		330 - 420 GHz
		390 - 500 GHz
		630 - 710 GHz
		800 - 900 GHz
Correlator	FX-type	1225 cross-correlations
		50 auto-correlations
	Bandwidth	> 4 GHz
	Frequency Channel	> 10000 ch / baseline
	Max. Freq. Resolution	40 kHz
		(0.1 km/s at 115 GHz)

used for 40 GHz and 100 GHz and SIS mixers will be used for the higher frequency bands. In each band a wide tuning range is desirable so that one can observe anywhere within the entire frequency band. A new type of SIS junction called "PCTJ" (Parallel Connected Twin Junction) has been developed at Nobeyama. Experiment with a PCTJ SIS mixer at 100 GHz showed that a very low noise performance was obtained over a wide frequency range without any mechanical tuning elements (Noguchi et al. 1995). This type of SIS mixer is being tested at 500 GHz at Nobeyama. These receivers will have an instantaneous bandwidth of >4 GHz. Dual frequency or dual polarization modes will be included for limited frequency bands.

Phase stabilized optical fibers will be used for transmission of reference signals for phase-locking and IF return signal (Ishiguro, 1994). A wide-band (>4 GHz) FX-type correlator system will be used which can offer flexible operations. A 4 GHz A/D converter is undergoing a test which was developed for the Ultrawide Band Correlator (1 GHz bandwidth) in NMA (Morita, 1994). For spectral-line observations, it can function as several separate spectrometers, all of which may be tuned to different central frequencies from the same or different receivers. The auto-correlation mode is important when using the array as 50 independent single dishes. The instrumental parameters of the LMSA are summarized in Table 1.

One of the key technologies needed to achieve $0.1''$ resolution is active phase correction. New techniques of phase correction are proposed and under test at various millimeter interferometers. We are currently investigating differential radiometry and paired antenna methods. In the former method, the difference between atmospheric emission measured by two independent radiometers located at each telescope is used to correct atmospheric phase errors (Welch, 1994). In the latter method, continuous phase correction is made possible by using two closely located antennas as an element of the interferometer, one of which is pointed to a calibrator source continuously.

4. The Potential LMSA Sites and Site Testing Activities

The criteria for the potential LMSA site are: 1) atmospheric transparency at millimeter and submillimeter wavelenghts, 2) radio seeing to achieve subarcsec resolution, 3) low wind velocity for good pointing accuracy, 4) a flat and wide ($\sim$ 3 km $\times$ 3 km) area to locate the array, 5) accessibility to the site, 6) infrastructure, etc. Under these criteria, the potential LMSA site should be a very dry site at very high altitude.

Mauna Kea (Hawaii) and the Atacama desert in northern Chile are considered as the potential sites for the LMSA in the northern and southern hemisphere, respectively. As site testing has already been conducted on Mauna Kea by other groups (Masson, 1994), we decided to focus our site testing activities in northern Chile. Northern Chile has one of the driest deserts on Earth, with a mean annual precipitation is less than 10 mm. There are very flat areas at high altitude suitable for locating the LMSA.

In 1992 and 1993, we visited about twenty of the possible sites in Northern Chile. These sites are distributed $-22.5°$ to $-25.5°$ in latitude and 2500 m to 5000 m in altitude. Four meteorological stations were set up on selected sites in these regions (see Figure 3). In 1995, we installed a 220 GHz

Figure 3. Map of northern Chile. The hatched area shows regions higher than 4000 m.

radiometer and an 11 GHz radio seeing monitor at Rio Frio (4100 m) (one of the potential LMSA sites) and started measurements. NRAO installed similar equipment at Chajnantor (5000 m) for MMA site testing. The site testing activities in northern Chile have been conducted in collaboration with SEST/ESO, the University of Chile, and NRAO.

So far, site testing has been based on opacity measurements where atmospheric phase stability has been evaluated indirectly. Recently, it has proven very useful to assess site quality with direct measurements of the atmospheric phase fluctuations by using a small interferometer to receive a signal from a geostationary satellite (Ishiguro et al. 1990). The advantage is that it is possible to monitor the phase fluctuations continuously at a constant elevation angle. This kind of interferometer is called a Radio Seeing Monitor(RSM). The RSM at Rio Frio consists of a pair of 1.8 m antennas, separated by about 300 m, which receive a beacon signal at 11.2 GHz from an INTELSAT satellite. From a zero-baseline test, the RSM has proved to have an accuracy of 0.3° rms, corresponding to 20 μm rms in pathlength. Thus, although the measuring frequency is relatively low, we can measure the radio seeing at millimeter and submillimeter wavelenghts.

We will choose the LMSA site after collecting data for at least one year and comparing them with those for other sites including Mauna Kea.

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