Current Projects and New Initiatives for Radio Telescopes

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Abstract With the development of radio, X-ray and gamma ray astronomy, observation now is covering the whole band of electromagnetic radiation. In the radio band, a lot of research interest lies in the millimeter and sub-millimeter wavelength range, requiring new and more powerful observing facilities. This paper reviews current projects and new initiatives for radio telescopes, including telescopes working at the millimeter and sub-millimeter wavelength bands. The paper also describes key technologies and special considerations in new telescope design, such as surface accuracy, thermal control and other issues. Finally the paper lists all current radio telescope programs in China.

1 Introduction

Radio wave bands are not only complementary but also unique compared with optical band in some fields of astrophysics. Due to the expansion of the universe, relic radiation emitted from the Big Bang has been shifted to the radio regime, and now is detected as the cosmic microwave background, whose intensity distribution allows astronomers to study the large-scale structure of the universe (NRC 2001). The Earth's atmosphere which is opaque to many wavelengths is almost transparent to radio waves, which enables astronomers to have a clear view to those optically "unseen" astronomical objects. Hence, almost all radio telescopes are ground-based, and it is possible to build very large dishes and complex instruments.

The last century has seen a variety of radio telescopes built, from the Arecibo 305 m reflector to 100 m fully steerable dishes at Effelsberg and Green Bank, from separated single dishes to big interferometry arrays, which cover a wide radio band of electromagnetic radiation. However, there is still a "gap" from the far infrared to sub-millimeter and to millimeter sections of the electromagnetic spectrum. The astronomy at these wavelengths is particularly informative to study the early stage of star formation (Kärcher & Baars 2000). In recent years, many radio telescopes and arrays have been designed for these sub-millimeter and millimeter wave bands, such as the SMA, LMT, ALMA and EVLA (Expanded VLA). Because of shorter wavelengths, the design of such telescopes is difficult, involving a number of new technologies to achieve an all-weather, stable surface, and good pointing accuracy. To attain these goals, either new thermally stable carbon fiber reinforced plastic material is used or an active surface technology is employed. At the same time, corresponding receiver instruments and facilities are in development. In this short waveband, absorption of the atmosphere is serious. Therefore site selection is also important. It is expected that many new discoveries will be made with all these new telescopes.

2 Current Projects and New Initiatives

In 2001, the US National Research Council reviewed all the existing radio facilities and recommended a number of projects and new initiatives in the centimeter, millimeter, and sub-millimeter wavebands. Table 1 lists the major projects and new initiatives in the centimeter waveband, and Table 2 lists those in millimeter and sub-millimeter wavebands (NRC 2001). Some of them are currently under construction or in upgrading.

2.1 Projects in Centimeter Waveband

Table 1 Major centimeter waveband telescopes

Project	Nations Involved	Aperture	Wavelength Range (cm)	Angular Resolution (arcsecond)
Existing and approved				
ATCA(ATNF)	Australia	6 × 22 m	0.3 to 20	0.1
Parkes(ATNF)	Australia	1 × 64 m	1.3 to 90	50
Arecibo	United States	1 × 300 m	6 to 90	60
Effelsberg	Germany	1 × 100 m	0.4 to 30	10
GBT	United States	1 × 100 m	0.3 to 150	10
GMRT	India	30 × 45 m	21 to 300	2
HALCA	Japan, United States	1 × 8 m	6 to 20	10^{-3}
1HT	United States	500 × 5 m	3 to 30	3
MERLIN	United Kingdom	6 × (25-76) m	1.3 to 200	0.01
Nancay	France	1 × (35×300) m	9 to 21	100
VLBA	United States	10× 25 m	0.4 to 90	10^{-4}
VLA	United States	27 × 25 m	0.7 to 400	0.04
Westerbork	Netherlands	14 × 25 m	6 to 150	4
New Initiatives				
EVLA	United States	37 × 25 m	0.7 to 400	0.007
ARISE	United States	1 × 25 m	0.3 to 3	10^{-5}
LOFAR	Netherlands, United States	10^6 m^2	200 to 1,000	1
Technology Development				
SKA	International	10^6 m^2		

For a radio telescope facility, there are two major concerns in its design: the sensitivity and the angular resolution. The former is the telescope's ability to detect very faint signals, while the latter is its ability to see the fine details in the celestial objects. Higher sensitivity requires a larger collecting area. Higher resolution requires longer baselines if the wavelength is fixed, shorter wavelenth if the baseline is fixed. All the proposed telescopes listed in both Tables 1 and 2 are fit with these requirements. They have either a larger collecting area or a longer baseline. Other new projects are in the shorter millimeter and sub-millimeter wavebands.

The largest fully steerable antennas are the 100 m Effelsberg and Green Bank telescopes. The Effelberg 100 m dish, is a symmetrical design and has used the so-called homology technique which enables it to observe at the shortest wavelength of ∼4 millimeter. The Green Bank Telescope is an offset design and it uses an active control method to improve its surface accuracy. The two giant antennas are useful tools for studying complex or weak radio sources requiring various frequencies and a large collecting area. For compact, smaller-scale radio sources, interferometry is necessary. The MERLIN, VLBA and VLA can provide spatial resolutions of 0.1 arcseconds or better.

For studying the star formation and supermassive black holes in powering luminous active galactic nuclei, extremely fine angular resolution is needed. The Expanded VLA (EVLA) will be the answer. The EVLA will have one order higher sensitivity and angular resolution of the VLA. It will be possible to combine the EVLA and VLBA systems to enhance VLBA's field of view and sensitivity.

The Advanced Radio Interferometry between Space and Earth (ARISE) project includes a 25-m-class space antenna. The space antenna will be linked with the VLBA. ARISE will achieve the highest spatial resolution which is about six times better than that of the VLBA. It will be used for studying compact objects and will be operated at about the 3 mm waveband.

SKA (Square Kilometer Array), at present, is under coherent technology development. It is extremely important for studying how the first galaxies condensed out of vast clouds of atomic hydrogen. It is also capable of studying the distribution of dark matter on the largest scales by means of gravitational lensing.

Many of the current telescopes and arrays, such as EVLA, VLBA, LOFAR and the privately funded 1HT, could be linked together to form the foundation of ground-based interferometric centimeter-wave astronomy for the new decade.

2.2 Projects in Millimeter and Sub-millimeter Wavebands

Table 2 shows all major projects and initiatives in the millimeter and sub-millimeter wavebands. Among the projects, ALMA (Atacama Large Millimeter Array) is the first-ranked "new initiative" of radio projects started a decade ago. It is an international collaboration among the United States, Canada, and Europe. Japan has also expressed interest in participating in the project. And Chile, as a host nation for ALMA, participates in the project by making available the superb high dry astronomical site under the southern sky in the Atacama Altiplano. ALMA is an array of 64 dishes with 12 m aperture making a total area of 7,200 m^2. It will image at 1 mm wavelength with an angular resolution as high as 0.01 arcseconds that will be achieved by the optical Next Generation Space Telescope (NGST). At present, the celestial sky at sub-millimeter wavelengths can only be studied from space with small orbiting telescopes. Telescopes like the Far Infrared and Sub-millimeter Telescope (FIRST) can only provide a coarse angular resolution and a limited sensitivity. ALMA will bring to millimeter and sub-millimeter astronomy the aperture synthesis techniques. This enables precision imaging on sub-arcsecond angular scales. ALMA will also observe at short centimeter and millimeter wavelengths, with the same image detail and clarity as its optical and radio counterparts do. ALMA is to be the most powerful complete imaging instrument accessible to astronomers.

To be complementary to ALMA, a new initiative CARMA (Combined Array for Research in Millimeter-wave Astronomy) is recommended on the northern hemisphere. It is actually a hybrid array comprising nine of the current 6-m BIMA (Berkeley Illinois Maryland Association) antennas, six 10.4-m OVRO (Owens Valley radio Observatory) dishes, and ten new 2.5-m small antennas in California.

To cover all the sky, the South Pole Sub-millimeter-wave Telescope (SPST), a 7- to 10-m aperture sub-millimeter-wave telescope, is recommended. Thanks to its low opacity and stable seeing, the South Pole is the best site in the world for ground-based observations at sub-millimeter wavelengths. SPST would be equipped to survey the dusty universe and to study the distortion of the cosmic microwave background caused by clusters of galaxies. Its survey capability will make the SPST an important complement to ALMA.

The Large Millimeter Telescope (LMT), is a joint project between Mexico and the US. It is a 50 m telescope operating at millimeter wavelengths (Kärcher & Baars 2000; Eisenträger & Süβ 2000). It is to be equipped with multi-beam receiving systems to make full use of its great sensitivity. The LMT, as the biggest single dish working at millimeter band with high

Table 2 Major ground based millimeter and sub-millimeter telescopes

Project	Nations Involved	Aperture	Wavelength Range (cm)	Angular Resolution* (arcsecond)
Existing and approved Interferometers				
ALMA	United States Europe, Japan	64 × 12 m	Millimeter	0.003(λ /0.3mm)
BIMA	United States	10 × 6 m	Millimeter	0.2(λ /1mm)
IRAM	Europe	5 × 15 m	Millimeter	0.6(λ /1.5mm)
Nobeyama	Japan	6 × 10 m	Millimeter	1.5 (λ /3mm)
OVRO	United States	6 × 10.4 m	Millimeter	0.5(λ /1.5mm)
SMA	United States, Taiwan	8 × 6 m	Sub-millimeter	0.1(λ /0.3mm)
New Initiatives				
CARMA	United States	25 × (2.5 to 10) m	Millimeter	0.1(λ /1mm)
Existing and approved Single dishes				
CSO	United States	10.4 m	Sub-millimeter	7(λ /0.3mm)
FCRAO	United States	14 m	Millimeter	50(λ /3mm)
Hertz(SMT)	Germany, United States	10 m	Sub-millimeter	7(λ /0.3mm)
IRAM	Europe	30 m	Millimeter	25 (λ /3mm)
JCMT	United Kingdom, Netherlands, Canada	15 m	Sub-millimeter	5(λ /0.3mm)
LMT	United States, Mexico	50 m	Millimeter	7(λ /1.5mm)
Nobeyama	Japan	45 m	Millimeter	16(λ /3mm)
New Initiatives				
SPST	United States	7 to 10 m	Sub-millimeter	7(λ /0.3mm)

* The wavelength is scaled to the shortest operating wavelength and the number in front of the parenthesis is the angular resolution at that wavelength in arcseconds.

resolution, involves special technical considerations and material selections in achieving its design goals.

3 Key Technology Related to Millimeter and Sub-millimeter Wavelength Telescopes

The difficulties in the design of millimeter and sub-millimeter telescopes are intrinsically associated with the comparatively short wavelengths. Gravity, wind, and especially thermal effect tend to be very serious sources of surface, phase, pointing, and tracking distortions. In order to overcome such problems to achieve several tenths RMS surface accuracy and $\sim$1 arcsecond pointing accuracy under all operating conditions, various measures are taken into consideration. These include: special structure design, material selection, active feature, thermal control, combination of open-loop and close-loop compensation control, site investigation, etc.

Traditionally, the surface accuracy of radio telescopes is achieved passively by homology and the pointing accuracy by a two-axes control system with encoders for measurement. The Effelsberg 100 m dish has been notably successful for its elegant homologous design making it capable of 4 mm observation. However, the homology concept may be limited due to the laws of mechanics. So, a new design concept or additional active features, including active surface control and active sub-reflector, have to be introduced to some new sub-millimeter telescopes. For very large reflectors, it is impossible or impractical to achieve and to maintain a higher accuracy by constructing sufficiently stiff truss for their dish structures. Therefore, some antennas will have dishes involve not only truss members. On some antenna design, it becomes beneficial to deliberately make pliable homologous backup structure. With this concept, taking advantage of the inherent pliability of the trusswork, control efforts may contribute to couple drivers electronically by encoders (Kärcher & Baars 2000; Yang 2002).

In the concept of active surface control, actuators are installed at each corner of surface panels and focusing-centering device is to be implemented for actively correcting sub-reflector position. For compensating the gravitational deflection, an open-loop control and a look-up table are possibly a solution. Gravity loads are repeatable as well as predictable. The deflection pattern for a series of elevation angles can be calculated or be measured using some kind of laser range system. Correspondingly, the control of each surface actuators can be derived or pre-stored in a control computer. As to the deflection of sub-reflector, the same idea is applicable. The deflection can also be calculated by finite element method or measured by 5D or 6D laser metrology system (Chen et al. 2000).

Radomes had been used for comparatively small astronomical antennas in the past to shield wind disturbance and solar radiation. However it is not practical for very large antennas. Radome also causes serious signal loss resulting lower sensitivity of the telescope in the shorter wavelength. For this reason, new antennas all adopt exposed configuration. These antennas have to undertake severe open environment, such as wind, solar and infrared radiation. Nonuniform temperature field will cause deformations of telescope surface. It also produces pointing and phase errors. Like gravitational deflections, the thermal deformations may produce problems in large bull gear as well. A special technique like "buoyant" pinion carriage for elevation drivers is necessary for large antennas (Yang 2002). Unlike gravitational loads, thermal effect is randomly distributed. Thanks to its low frequency behavior, it is possible to employ a close-loop correction, namely to perform a real-time finite element model (FEM) calculation with actually measured temperature field by thermal sensors. These sensors are installed over the telescope structure (Eisenträger & Süβ 2000). The calculation will provide axes' misalignments, pointing error and surface error. Therefore, the surface error can also be corrected for by surface actuators while axes' misalignments and pointing error may be compensated with control effort. Thermal treatments for alleviating radiation induced surface error are advisable. Temperature changes between the surface and backup structure due to solar radiation during day and infrared radiation at night can be tempered by cladding the panel units. Ventilation system, for example, the forced air cooling, can be used to get a better thermal performance of the telescope structure. For overcoming wind effect, it is recommanded that the telescope should be strong enough to work for maximum operational wind velocity and to keep the wind-introduced errors within budget. Also, for large reflectors, the site wind behavior needs to be investigated carefully as it may cause inadmissible deflections of axes, especially that of elevation axis. Some of the structural deflections can be detected by inclinometers and be evaluated by FEM model. From these measurement and calculation pointing error can be compensated for by the same idea as discussed above.

To reduce deflections and various errors, carbon fiber reinforced composites (CFRP) are widely selected for some existing and newly designed telescopes at these short wavelengths (Cheng 2000; Cheng 2002). CFRP has a high stiffness over weight ratio and a low thermal expansion coefficient. It has a density of $2268\,\mathrm{kg/m^3}$ and a thermal expansion less than 2×10^{-6}. As an aniostropic material, its dominant Young's modulus can be higher than that of steel. These features of CFRP enable it to be used for fabricating new telescope structure, especially, reflector back-up structure. The disadvantage of using CFRP material consists in complexity of CFRP joints and high material and labour cost.

Because the sub-millimeter wave band is the shortest radio wave window opened up to the ground, in order to minimize the high absorption of the earth's atmosphere of millimeter and sub-millimeter radiation, sites for locating telescopes at these wavelengths need to be high and dry with low level man-made radio frequency interference (RFI). The harmful RFI has been increasing dramatically in recent years with the rapid growth of wireless communications (Kärcher & Baars 2000). Moreover, locally generated RFI at site can be also troublesome, so remote control and operation may preferable to keep the RFI sources at a minimum level (Jewell 2000) .

4 Radio telescope programs in China

In the past century, several radio telescopes have been built at observatories of China. The largest dishes are two 25-m centimeter wavelength telescopes, one is situated near Urumqi and another in Shanghai. Both are part of international VLBI cooperation. A 13.7 m enclosed millimeter wavelength dish was built in Delinha in 1986. And a meter-wave aperture synthesis array is operated at Miyun station of NAOC.

At present, a 50-m pulsar radio telescope is underway at NAOC and hopefully to be erected in 2 years. The Five hundred meter Aperture Spherical Telescope (FAST) is, under feasibility study, as an effort for the international cooperation in the Kilometer Square Array-SKA.

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