CURRENT PROBLEMS AND PROGRESS IN HIGH-PERFORMANCE ASTRONOMICAL ANTENNAS

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ABSTRACT

The design of large astronomical antennas requires the application of a wide range of disciplines to provide large collecting areas which will gather radio signals with high efficiency and with very precise pointing. This review looks at recent progress and trends in a number of these fields including optics, active surface control and active pointing correction, the use of composite materials and techniques of surface measurement. The goals and prospects for future developments are also considered.

INTRODUCTION

In general the most important requirements in the construction of antennas for radio astronomy are simply to obtain the largest possible collecting area for the lowest cost. Recently, however, other factors have started to become important: on the Green Bank Telescope (GBT) for example, the need to reduce the interference which could be scattered off the subreflector to very low levels led to the adoption of an off-axis design; the requirement for a very wide field of view on the Planck telescope was met by using a modified Gregorian design which is non-stigmatic; and the specifications for making aperture synthesis “mosaics” and for frequent phase calibrations have placed unusually high demands on the pointing accuracy and dynamical performance of the ALMA antennas. This paper outlines these developments, some of which will be treated in more detail in other papers in this session, and goes on to discuss active control systems and surface measurements.

OPTICS

The possibility of using of off-axis reflectors to give a completely clear apertures and therefore very “clean” beams has been known for some time: a method of minimising the effects of asymmetry in dual-reflector antennas was worked out by Dagone [1] and Mizugutch et al. [2] in the 1970’s and was implemented on the Bell Labs 7-metre antenna. These designs employ a parabolic primary and an ellipsoidal or hyperbolic secondary whose axis is tilted with respect to that of the primary by an amount which depends on the magnification of the system. The difficulties created by the asymmetric form of the structure had, however, inhibited the application of this approach to very large antennas until the 1990’s, when NRAO took the brave decision to use it on the 100-metre GBT [3]. This has now been completed successfully, but is clear that the mechanical complications resulting from the off-axis design were indeed quite severe.

At the other end of the size scale, the Planck telescope [4], which has an aperture diameter of only 1.5 metres, also employs an off-axis design (in this case, and on the GBT, a Gregorian with both mirrors concave) to provide a clear aperture and hence the “clean” beams essential for high-precision measurements of the Cosmic Microwave Background radiation. In this case however the design requires a very large field of view (nearly 5 degrees across) to accommodate a large number of detectors in the focal plane. This has been achieved by using ellipsoidal mirrors for both reflectors, in a manner analogous to the Ritchey-Chrétien design for optical telescopes. The result is a design which does not have a perfect focus at any point in the field of view (i.e. it is “non-stigmatic”) but which provides good performance over a larger field than the classical parabola/ellipsoid combination. This project illustrates an important trend in antenna design – the increasing use of very powerful software packages to analyse and optimise antenna designs to meet specific design requirements. For the first iterations it proved best to employ programmes developed for analysis at optical wavelengths, which include very general optimisation capabilities but tend to be based on ray-tracing and therefore have to be used with caution at long wavelengths, and then to use packages based on physical optics and/or

GTD for the final stages. For Planck a very intensive effort along these lines has provided a useable field of view that is nearly 8 degrees in diameter.

A further, if much more modest, example of such an optimisation was carried out at MRAO for the antennas used for source subtraction on the Very Small Array (VSA) and for the Arcminute Microwave Imager (AMI). Here (for cost reasons) an existing 3.7m parabolic design was used for the primary, but all other parameters, including the size and shape of the subreflector and off the feed-horn, and the description of a shield added to the edge of the primary, could be chosen freely. In this case it proved possible to perform a physical optics analysis of the key quantities – essentially the peak gain, averaged of a wide frequency band, and the spillover in certain directions – with sufficient speed that the calculation could be carried out inside the loop of a general-purpose optimisation routine. The programme could then be left running to find the best values of the free parameters. This resulted in an over-sized subreflector with a somewhat unusual shape, but gave an aperture efficiency which is nearly 10% higher than that of the classical design.

ACTIVE CONTROL SYSTEMS

The possibility of using active mechanisms to keep the surfaces of a large reflector to the desired shape has been discussed for a long time. (At least one large project based on this principle was started as long ago as the 1960's.) Although a number of existing antennas have remotely controlled actuators which are capable of making the necessary adjustments, this has in fact been little used so far. In fact the technology employed in radio astronomy now lags far behind that used by our optical colleagues, who routinely adjust the shape of their primary mirrors by means of very precise actuators and even correct for the wavefront errors caused by the atmosphere (usually by making rapid adjustments to the shape of a small mirror some way down the optical chain.) This situation is finally being changed with the completion of the GBT and the construction of the Large Millimeter Telescope / Gran Telescopio Milimetrico (LMT/GTM) [5], which are both antennas where active surface control has always been a key part of the design. Other talks at this session will be describing those projects in detail, so I will restrict myself to some general comments about active surface control:

1. The reason why radio telescopes have lagged behind their optical counterparts is not, of course, due to the difficulty of providing the adjustment, but due to the difficulty in sensing the errors which are to be corrected. For optical telescopes there are a huge number of bright point sources in the far-field (stars!) which can be used to determine the surface errors. It is also very helpful that large-format imaging detectors are also available and can be used in suitable optical arrangements to show the wavefront errors. None of these things exist for radio telescopes. Instead the GBT team have had to develop its own sophisticated surface measurement system, based on laser metrology, to provide the necessary feedback. The LMT/GTM will rely on look-up tables of the expected gravitational errors and on a temperature measuring system together with finite element analysis to know what adjustments to make to their telescope. Even with these tools, there will still in practice be a need to make checks on the shape of the surface under operational conditions. As receiver technology and control systems improve it is becoming possible to do this in ways which mimic those used at optical wavelengths. One of the poster papers in this session [6] shows how reasonably high resolution maps of the surface errors on both the James Clerk Maxwell Telescope and the GBT can be obtained from observations of astronomical sources.

2. The adoption of active surface control is far from universal. The antennas for ALMA, for example, are required to maintain the shape of their surfaces to high precision under a range of very tough conditions for periods of several years without any active intervention. Even when it is planned to use active control, my impression is that the adoption of it is not really whole-hearted. All the existing designs still put a great deal of effort into making the telescopes operate as well as possible without bringing the active systems into play. To this end they still use very elaborate and massive structures built to high precision to support the surface, often employing homology principles to a considerable extent. If the designers were confident that the active systems would work, they should be able to make large savings by building much less perfect backing structures, which really only need to be strong enough to stand up to survival conditions and stiff enough to give reasonable lowest resonance frequencies. As already noted, the principle problem is really in sensing the errors rather than applying the corrections. Here a lot depends on which errors one is trying to correct. A system like that on the GBT should certainly be fast enough to deal with gravitational and thermal errors, but probably not fast enough to deal with wind-induced errors on an open-air dish. A possible alternative approach, which could prove economical in that case, would be to provide the metrology reference frame by building a light but stable non-load-bearing structure interwoven with the steel framework which provides the basic support. Carbon fibre reinforced plastic (CFRP) would be the obvious choice

of material for such a reference framework. Related ideas have been considered for improving the pointing of the Atacama Large Millimetre Array (ALMA) antennas [7] and there is no fundamental reason why this technique should not be extended to the case of measuring the deformations in the backing structure supporting the reflector surface.

This second point brings up the other major application of "active" control in the field of antenna engineering: that of achieving accurate pointing. Here again the problem is not in the control aspect – telescope drive systems are of course already "active" – but in sensing the pointing errors. Traditional systems simply rely on encoders measuring the rotations of the axes of the mount. Clearly this will leave out errors occurring in other parts of the system – above, below and between the axes – as well as being subject to various offsets, drifts and other inaccuracies. Two approaches to improve this situation are being contemplated. In the first of these, the encoders still perform the main task but various sources of additional information, e.g. from tilt-meters in the base and thermometers and strain gauges in the structure, are used with models to estimate corrections to be applied to the servo. In the second approach one by-passes as much as possible of the problem and attempts to measure the orientation of the dish directly. Three possible ways of doing this are:

1. to measure the location of points on the dish relative to targets on the ground using laser metrology (planned for the GBT);
2. to use an optical and/or IR telescope mounted on the dish and observe stars (used for testing of many telescopes but never, to my knowledge, adopted as the main pointing tool); and
3. to attach laser gyros to the dish and use these to control the pointing.

The problems with these are, in turn, that 1) is complicated, 2) doesn't work when it is cloudy, and that 3) can only provide very accurate (<< 1 arc sec) pointing for periods of a few minutes. Given that with good dynamics and modern computer control it should be possible to check the pointing on a nearby calibration source in a few seconds, the use of laser gyros is now becoming a serious possibility. As with the active surface control, the whole-hearted adopted of such a scheme might provide substantial overall savings in future projects.

COMPOSITE MATERIALS

The use of composite materials, principally CFRP, is now well established in antennas having been proven in the IRAM 15-metre antennas and the Heinrich Hertz Telescope [8]. This brings many benefits: the material has very high stiffness to weight ratio, so that low gravitational deflections can be achieved and high natural frequencies are obtained; it also has very low coefficient of thermal expansion so that deformations due to thermal gradients are minimised. There is however one negative factor which should not be ignored: exposed CFRP can absorb water and if it does so it expands. Conversely in a dry atmosphere it will loose water and shrink. These effects will usually be slow, especially at low temperatures, but if the design is such that critical components absorb water by differing amounts it is possible that quite substantial deformations will occur. I believe that designs need to take account of these effects and that steps may need to be taken to ensure that any absorption or drying out takes place uniformly or, in extreme cases, that the CFRP structures are sealed completely with an impervious layer.

FUTURE PROSPECTS

The absolute size of radio astronomy antennas has seen rather little increase for nearly 30 years, but of course the real performance in terms of diameter over shortest useable wavelength has increased dramatically. Projects like the GBT, the upgraded Arecibo telescope and the LMT/GTM are all good examples of recent progress in that direction. With our optical colleagues contemplating telescope diameters as large as 30 or even 100 metres, we cannot however afford to rest on our laurels. It seems to me that as far as ground based systems are concerned the most important advances are likely to come through finding large savings in cost per unit collecting area. This, when applied to mass production systems, will make possible the major next generation projects such as the Square Kilometre Array. The other obvious frontier, is in space. Given that the reflecting surfaces themselves only need to be a few microns thick, it ought to be possible to construct, in the absence of gravity and wind, very large, accurate, light-weight antennas using active control mechanisms. Clearly the demands here are very different from those on traditional antennas but it seems to me that there is a great deal of scope here for original ideas.

REFERENCES

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[3] Much information on the GBT can be found at: http://www.gb.nrao.edu/GBT/GBT.html
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