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Options for VLBA Antenna Surface Measurement

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Introduction

We would like to have an accurate measurement of the deviations of the main reflector and subreflector surfaces of the VLBA and VLA antennas from ideal. Such measurements could be used to adjust the panels of the main reflectors, and possible to make adjustments to the subreflector, in order to obtain the best possible performance of the antennas. Such measurements and adjustments have been done on the main reflectors of the VLA antennas, yielding significantly improved high frequency performance. We would like to do a similar thing for the VLBA antennas, especially given that 86 GHz receivers are beginning to be installed on these antennas. The apparent efficiency of the VLBA antennas is currently $\sim$ 10% at 86 GHz. It is thought that with a good readjustment of the main reflector panels, this number may become as good as 25% (although the original estimates of efficiency near 86 GHz were $\sim$ 18% [VLBA Project Book, p. 5–9], but see also Walker and Bagri [1989]). The purpose of this report is to examine different options of measuring the surface of the main reflectors of the VLBA antennas (and possibly of the subreflectors). While the focus is on the VLBA aspects of the measurement problem, much of it is also applicable to the VLA antennas, and even to the proposed MMA antennas.

The main reflector of the VLBA antennas was designed as a 25–m diameter surface of revolution, with maximum deviations above and below a best–fit parabola of 1.7 cm and 1.8 cm (at radii of 9.09 m, and 12.5 m). The surface is obtained by using 200 panels of no larger than 1.8 X 2.1 m. Each panel has four supports and is made of doubly curved aluminum skin. A shaped rotating subreflector (about 3.2 m max diameter) is used to focus the radiation onto the phase center of the feeds on the feed ring of the antennas. See Napier *et al.* (1994) for a general description of the VLBA antenna and system design.

The large and small scale deviations of the true shape of the main reflector from the ideal shape are determined by several factors:

- surface of the individual reflector panels and variation with:
  - gravity
  - thermal loading
  - wind loading
- setting of the panels
- deformation of the entire antenna structure with:
  - gravity
  - thermal loading
  - wind loading

When considering the performance of the antenna as a whole, the subreflector must also be included:

- intrinsic quality of the subreflector surface
  - does it have the correct overall shape
  - surface rms
- relative position of subreflector and main reflector and changes with:
  - gravity
  - thermal loading
  - wind loading

I will briefly describe each of these elements now.

intrinsic quality of the reflector panels

The manufactured reflector panels have some deviation from their designed doubly curved (and absolutely smooth) surface. The individual panels themselves also change their properties with gravity, thermal, and wind loading.

Little can be done about this, short of replacing all of the panels, so I will ignore it in this report, except to note what the actual number is. Note that this number is the absolute best we can ever expect the small-scale surface rms to be.

setting of the panels

The individual panels are attached to the backup structure through four supports, all of which can be adjusted (by turning screws) in order to make the collection of panels conform to the desired overall main reflector shape. Incorrect setting of these four supports results in a deviation of the true shape from the desired shape. It is the measurement of this deviation and corresponding resetting of the panel supports based on that measurement that this report is mainly concerned with.

deformation of the entire antenna structure

The overall shape of the main reflector changes with changing conditions in gravity, thermal, and wind loading. These changes are in addition to the changes in the individual panels. It may take considerable effort to try to compensate for these (that is the domain of active or adaptive optics), but at the very least, it is desirable to know what the changing shape *is* as a function of different loads.

intrinsic quality of the subreflector surface

Upon manufacture, the shaped subreflector has some deviation from its designed figure. This can be both an overall large scale deviation (e.g. that which might cause astigmatism), and a deviation from a perfectly smooth surface (rms roughness of subreflector surface). Like the antenna structure deformation, it may not be possible to correct for these deviations, but it is desirable to know what they are.

relative position of subreflector and main reflector and changes with gravity, thermal and wind loading

In order to operate at high frequencies, it is very important to have the subreflector positioned accurately with respect to the main reflector (and the feeds) in all 3 dimensions. Misalignment causes a loss in gain and the appearance of coma lobes in the beam pattern. A measurement of the relative position of the subreflector is therefore desired. This relative position also changes with gravity, thermal and wind loading. A measurement of this change is also desired, but is more difficult (at least for the thermal and wind parts). Note that because the 43 and 86 GHz feeds are near the elevation axis on the feed circle, the subreflector position change due to changing gravity may be compensated for by rotating the subreflector, if the magnitude of that change is known.

History

'ancient'

The original specifications on the above factors for the VLBA main reflectors at 50 deg were (VLBA project book):

- surface panels
  manufacturing: 125 μm
  gravity: 75 μm
  temperature: 50 μm
  wind: 40 μm
  surface panel RSS subtotal = 160 um
- measuring and setting: 125 μm
- reflector structure
  gravity: 140 μm
  temperature: 125 μm
  wind: 55 μm
  reflector structure RSS subtotal = 196 μm

So the main reflector total RSS surface accuracy was spec'ed to be 282 μm. The panels were set initially by the manufacturer, via theodolite and tape (see below for description). Initial measured accuracies for the 10 stations are shown in Table I. It should be noted that the intrinsic measurement error is not accounted for in the numbers in Table I, and as such, these

Table I. Measured initial panel and setting deviations

antenna	panel accuracy (μm)	setting accuracy (μm)
PT	117	103
KP	112	107
LA	107	91
FD	107	75
NL	???	100
BR	???	120
OV	???	115
SC	???	107
MK	???	110
HN	???	91

numbers should be considered as absolute best case estimates. The initial measurement was also done by placing the targets on the surface and measuring the distances to them (via invar tape) when the antenna was pointed at zenith. The theodolite measurements were then taken at a zenith angle of $\sim 50°$. This will certainly introduce more uncertainty into the numbers in Table I. The estimate of the accuracy of the initial measurement by the manufacturers was $\sim$ 150 μm (Helmick 1986), accounting only for the estimated errors in the taping and theodolite angle measurements. A more realistic estimate might be as much as twice this amount, accounting for all error sources.

The original specification on the subreflector surface accuracy was 150 μm RMS, with a goal of 100 μm. The first delivered subreflector (PT) was measured by the manufacturer and claimed to have 143 μm RMS. When measured independently, however, this value was 190 μm, and when measured independently at twice the resolution, the value went up to 248 μm. Subsequent subreflectors were measured and shown to meet spec. In order to accurately match the design surface profile, the manufacturer sanded down high areas, and filled in low areas with a conductive material. However, later tests showed that the conductive material was actually lossy enough that it was affecting the performance of the antennas. In order to fix this problem, the subreflectors were swapped off of the antennas and taken into the lab, where the original conductive fill-in material was replaced. This means that some of the subreflectors are not currently in their original locations. Subreflector #1 (originally at PT) was replaced with the spare (#11) sometime prior to 1992. It was refurbished and then replaced the subreflector at NL in Nov 1994. The original NL subreflector was then refurbished and replaced the subreflector at SC in Feb 1995. The original SC subreflector was refurbished and replaced the subreflector at LA in Jul 1995. The original LA subreflector was refurbished and is now the spare. Although the subreflectors all seemed to meet spec when originally measured, note that it is possible that the subreflectors have changed overall shape with time, or that the mounting in the antenna structure changes the shape.

'recent'

In the past few years, Tony Beasley has been performing occasional tests of some of the above quantities by doing one type of measurement (holography via astronomical (maser) and satellite sources, see below for general description). This has proven quite effective in providing subreflector offsets, and subsequent adjustment of the subreflector position has shown the expected increase in gain. These measurements have never been used to actually adjust the setting of the panels, however, as certain problems have prevented that (again, see below). These tests have shown, however, that there is a hint of a signature in the aperture phase of most (all?) of the antennas which looks somewhat like astigmatism caused by the subreflector. Tests to determine exactly where this originates have been unsuccessful. The holography tests have shown that the typical rms deviation of the main reflector surfaces are on the order of 450 μm. This is much larger than the spec'ed rms (282 μm), and also much larger than the initially measured accuracy (see Table I). It is not clear where the excess deviation originates, whether in large scale offsets (like that caused by the possible astigmatism), in errors in the panel setting, or in errors in the measurement/derivation. It is the accurate determination of this number, and then figuring out where the errors come from and fixing them if possible, that we are interested in here.

Vivek Dhawan has also been testing the rotation of the subreflector with elevation, to test the compensation for gravity loading. These tests have only been moderately successful, however, as the subreflector rotation does not seem to improve the gain curve of the antennas.

Goals

- desired setting accuracy and measurement precision
  To obtain $\lambda/16$ operation at 86 GHz requires a total rms deviation of 220 μm. However, given just the RSS of panel errors and structure errors (160 and 196 μm respectively) gives an RSS of 253 μm, even with *zero* setting error. I suspect that it will necessarily be sufficient to get to the spec'ed 282 microns of total deviation, which leaves the spec'ed 125 μm rms for the panel setting. At the very best (with no gravitational, thermal, and wind terms in the error budget), the measuring and setting errors (125 μm) and the intrinsic panel errors (also 125 μm) combine for an RSS of about 180 μm. A 100 μm measurement precision gives nearly 2σ for this error, which is the commonly accepted criterion for these types of measurements (see e.g., Greve 1986).

- elevation considerations
  It is clear that the 86 GHz performance will change considerably as a function of elevation. Because we do not have a good model of the structure of the VLBA antennas and how they deform with elevation (Peter Napier, personal communication), I think it is imperative that we have the capability to make the reflector surface measurements at many elevations.

- how often
  After an initial "good" measurement, we will want to make subsequent measurements on a regular basis. Occasional measurements will probably be necessary to investigate problems, or when significant changes are made to the any of the antennas.

- related issues
  Aside from the main reflector surface setting, there are directly related issues involving holography. There are also many indirectly related issues (including pointing) which I will not consider in detail here. A separate subreflector measurement should be considered very high priority. This will help in diagnosing problems like the astigmatism. Measurement and adjustment of the subreflector position is also high priority.

What determines the "best" technique?

Before describing the currently available techniques available for antenna surface measurement, it should be noted what the factors are which determine the attractiveness of a given technique. In fact, the final approach may be through some combination of different techniques. The most important items which I think should affect the decision on which technique(s) to choose are:

- accuracy - does it reach our measurement error goal?
- are the other goals achieved by the system (subreflector measurement, measurement at many elevations, etc...)?
- how complex is designing and building the system, if necessary?
- how complex is installing or incorporating the system?
- complexity of the measurement itself, i.e., do people or equipment need to be transported to each of the sites every time a new measurement is desired?
- is the technique risky, i.e., is it something which has not previously been done?
- how long does the measurement take, and how does this affect scheduling of the instrument?
- is the measurement operationally difficult (does it require the presence of an "expert")?
- how long will the system last, and will it be upgradable?
- how much does the entire system cost, including design and construction, moving, operating, upgrading, etc...?

And now on to a discussion of the currently available techniques.

Techniques

I will split my discussion of techniques into two broad sections - *direct* methods (direct surface deviation measurement), and *indirect* methods (surface deviation inferred from measurement of EM characteristics of the antenna). Note that in the literature, sometimes this scheme is used, and sometimes the opposite notation is used (where *indirect* methods indicate those that measure the surface itself, and *direct* methods indicate use of the EM measurement to infer the surface profile - e.g., Kummer and Gillespie 1978).

direct methods

These techniques measure the actual reflector surface directly in one way or another, i.e., true measurements of the three dimensional coordinates of the surface locations are obtained. These are all mechanical or mechano–optical techniques. Good reviews of these methods (excepting the photogrammetry) are contained in Findlay (1971) and Baars (1983).

templates

Smaller reflector surfaces can be measured quite accurately by using a template of the shape of the reflector which carries some precise measuring instrument (see e.g. Pearson *et al.* 1966). This technique was used to very accurately measure the surfaces of the OVRO antennas (Woody *et al.* 1994) and the NRAO 12–m antenna (Findlay and Payne 1983; Lasenby 1985; Payne 1989). Measurement accuracy was of the order of 10–15 μm in both of these cases. The use of templates becomes increasingly complex with larger antenna size, however, and has therefore not been used to measure large antennas with high accuracy. This, in combination with other problems (e.g., measurement only at zenith, portability, excessive cost, etc...) make this technique unattractive for measurement of the VLBA antennas.

spherometers

In this technique, the curvature of the antenna is measured along a number of radii along the surface. These measures of curvature are then transformed into the surface profile by two integrations (see e.g., Kummer & Gillespie 1978). The instrument bears a close relation to an optician's spherometer, hence the name (Payne *et al.* 1976). This technique was used to measure the surface of the NRAO 11–m antenna, where the actual measurement of the curvature along the radii was obtained by pulling a specially built cart along the surface (Payne *et al.* 1976). An average measurement accuracy over the entire dish of about 37 μm was obtained. The measurement error near the dish edge (5.16 m) was about 90 μm. There is also mention of the development of such an instrument to measure the IRAM 15–m dishes (Delannoy 1985). Claimed accuracy was 20 μm, but the instrument had not been finished at the time. There are many things which make this an unattractive method for measuring the VLBA antennas, but the primary one is that the measurement accuracy is not sufficient. Taking the values in Table 1 of Payne *et al.* (1976) and fitting a parabola and extrapolating gives a measurement error of about 3000 μm at 12.5 m radius. With better electronics, a current system might perform somewhat better than the one built previously, but probably not well enough to obtain our desired measurement accuracy.

surveying methods

These methods all draw heavily from traditional surveying methods, where distances and angles must be measured very accurately. The fundamental idea is that the surface profile may be accurately measured if distances and angles to a number of points on the reflector surface from some absolutely known (in the geometry of the antenna) location are measured accurately. There is nothing tricky about the concept (it is strictly geometry) but the very accurate distance and angle measurements are technically challenging given the accuracy we would like to obtain. Most of these techniques are unattractive for the VLBA since they are not sufficiently accurate. In addition, most of them would require the removal of the feed cone for the measurements. Those that are accurate enough suffer from complexity of construction and operation, portability, and other problems.

theodolite and tape

This is the most commonly used measurement technique for initial measurement of large reflector surfaces. An accurate theodolite is placed at a known height above the antenna vertex. At that height, the angle between vertical and a particular point on the surface is measured with the theodolite. The distance to that point is then measured accurately with a surveyors tape. The distance may be measured either from the vertex along the reflector surface, from the vertex directly, or from the location of the theodolite directly. Typical measurement accuracies for this technique are of order several hundreds of μm at a distance of 12.5 m (Findlay 1971). Somewhat better accuracy has been obtained recently (e.g., Kesteven *et al.* 1988; Greve *et al.* 1994), by a factor of a few. Better accuracy (of the order of 50 μm) has been achieved in one particularly careful measurement (Brenner *et al.* 1994). In this measurement of the Onsala antenna, the accuracy was probably only achieved because the antenna is protected from the elements by a radome, which makes it inapplicable to the VLBA measurement. Greve *et al.* (1994) give a good recent description of the achievable surface rms via the theodolite and tape method, indicating that this technique will not yield our required accuracy.

pentaprism

As an improvement on the theodolite and tape method, the angle measurement can be done with a pentaprism or set of pentaprisms instead of a theodolite. Each pentaprism targets a specific angle from vertical, so each pentaprism measures a ring of points at constant distance. This technique was used extensively for antenna measurement in the 1960's (see e.g., Weiss *et al.* 1969; Robinson 1966; Kühne 1966). Typical accuracies were of order a few hundred μm for antennas of order 25–m diameter.

laser

As a further improvement, the distance measurement can be done optically, e.g. with a modulated laser, instead of by steel tape. Very high distance precision can be obtained in this manner (e.g. $\sim$ 80 μm at 60 m distance [Payne 1973] or $\sim$ 10 μm at 6 m [Eom *et al.* 1997]). Justice & Charlton (1966) report such a system which measured a 3.1–m diameter antenna to an accuracy of 250 μm, and claimed that it could be done much more accurately. When combined with a rotating stack of pentaprisms, the laser ranging system in one case resulted in an accuracy of 130 μm over a 27.4–m diameter antenna (Pearson *et al.* 1966).

others

Other specialized measurement devices have been used to measure the surfaces of antenna reflectors. The Parkes antenna was measured with $\sim$ 1500 μm accuracy for some time with a combined system of theodolite plus autocollimator, camera, and stretched wire (Minnett *et al.* 1969). Brownless (1966) reported the measurement of a millimeter antenna with a rotating arm plus optical measuring device which measured a 4.6–m antenna to an accuracy of 130 μm. The Nobeyama 45–m antenna was measured with a specially built optical instrument (Kaifu 1985). This instrument measured the range with a modulated laser and the angle with an autocollimator to many targets on the antenna surface, with a measurement accuracy of $\sim$ 150 μm. In a measurement of the IRAM 30-m telescope, a modified laser/theodolite/tape system was used (Greve 1986). The rms at the worst radius was $\sim$ 120 μm, with an overall rms of $\sim$ 75 μm. The Nobeyama and IRAM systems are very similar. This type of system (or a modification thereof) is one of the few direct methods which might be accurate enough for our purposes, especially given recent improvements in distance measurement (Eom *et al.* 1997) and angle measurement (Sohn *et al.* 1998). However, it is incredibly complex, and would be difficult to build, maintain, transport, etc... Because of this, it seems an unattractive system for the VLBA.

digital photogrammetry

In this technique, a specially built photogrammetric camera is used to photograph targets placed on the surface of the reflector from several locations, at several angles. Three dimensional coordinate data are determined from the two dimensional photographs via optical triangulation. This is called "convergent photogrammetry", to distinguish from "stereo photogrammetry", where only two camera locations are used, with the camera axes parallel. This technique has been increasingly used in industrial applications, including antenna reflector measurement (Fraser 1986, 1993). The technology is referred to by several names including non–topographic photogrammetry, terrestrial photogrammetry, close–range photogrammetry, and industrial photogrammetry. Originally, the photographs were recorded on thick glass plates, since glass was more stable than film. These stability problems were eventually overcome, and until recently the photographs were recorded on film. Recently the trend has been to record the data digitally on a CCD, hence the name "digital" photogrammetry (also commonly called video–grammetry). The concepts remain the same, however.

The accuracy obtained is strictly proportional to the size of the imaged surface. Accuracy as good as 1000000:1 has been obtained measuring a 17 X 15 m antenna (Fraser 1992). Accuracies this good have only been obtained under special circumstances, however. Film systems are somewhat more accurate than digital systems, with current typical accuracies of about 250000:1. Current typical digital system accuracy is about 100000:1. With either system, the accuracy obtained may be improved by essentially "mosaicing" (what the photogrammetric folk call "subsectioning") the imaged surface. Accuracies of 500000:1 for film, and 250000:1 for the digital system are routinely obtained for 2 X 2 or 3 X 3 mosaics. Note that an accuracy of 250000:1 gives 100 μm for the 25 m VLBA reflector surfaces (the desired measurement accuracy). Note also that an accuracy of 100000:1 gives about 30 μm rms for a measurement of the subreflector. These systems are strictly off–the–shelf, and can be purchased right now (see below).

The photogrammetry technique requires placement of retro–reflective "targets" on the reflector surface. These small targets are then illuminated by a strobe colocated with the camera. Included among the normal targets are some number of control targets, with special, easily recognized shapes. Measurements of the surface are obviously only made at the positions of the targets. Some investigation of exactly where to put these targets on the VLBA antennas would certainly have to be done, but, as a first guess, if 1 m resolution was desired, then around 500 targets would need to be placed. Another alternative might be to place the targets at the panel support locations, which would imply 4 targets per panel, or 800 targets. For twice the resolution in this case (16 targets per panel), 3200 targets might be needed. In any case, we should be aware that several thousand targets may have to be placed on each antenna. The placement of the targets for the first measurement might take some significant amount of time, but, once they are placed, they can be left there indefinitely (the targets are small, and geometrically block only a very small part of the reflector surface). That means that if it is desired to do another measurement, say in a years time, the targets should not have to all be replaced.

The photos are typically taken at a distance away from the target which is equal to the target size, i.e., to image the entire VLBA reflector surface in 1 photo, the camera would be placed about 25 m away from the vertex. On the order of 10's of pictures are required, and they are typically taken at an angle of about 40 deg. So, some type of crane or cherry picker would be required at the individual sites to place the camera. One big advantage of this system is that the reflector surface could be imaged at any desired elevation (as long as the camera can be placed in the right positions). It is unclear how long it would take to place the camera and take the photographs. The placement of the camera does not have to be particularly carefully done, however, and the measurement can actually be done under somewhat adverse weather conditions (it can be windy, e.g.). This is because the control targets are used to locate the coordinate system. For subreflector measurement, the camera would need to be located about 3 m away from the subreflector. It is not clear if this could be done with the subreflector in place, but it seems likely that it could be done.

After the pictures have been taken, the processing of the information from the digital system takes only on the order of 1 hour. That time is much longer for the film system. The film must first be sent away to be processed, which may take many days. Once processed, the film must be read into a computer, which may take several more days. The processing involves particularly specialized proprietary software which does the following steps: target location; exterior orientation (based on control targets); spatial resection and triangulation; and bundle adjustment (essentially a self–calibration).

The current industry leader in providing photogrammetry systems is Geodetic Services, Inc. (GSI), in Melbourne Florida. They can provide a refurbished film system for approximately \$150000. Among the other drawbacks of the film system, it is fairly bulky. These drawbacks probably make it unsuitable for use in measuring the VLBA reflector surfaces. GSI will provide a digital system which includes the photogrammetric camera, strobe, notebook computer, and proprietary software for \$150000. The entire digital system fits into a carrying case, with total weight of about 15 pounds (they claim it will fit under an airplane seat). Cost of the targets is about \$150 for 2000 targets. A maintenance contract is \$2000 per year. Without the mainenance contract, help is available on a contracted basis, for \$1000 per day.

Note that the GBT had its subreflector measured by GSI (well, actually by a subcontractor to GSI) with photogrammetric techniques. They payed \$54000 to have this done, to a spec'ed accuracy of 1 thousandth of an inch (about 25 μm). A film system was used to do the actual measurement, and the achieved rms was better than spec'ed - about .4 thousandths of an inch (10 μm) (Rich Lacasse, personal communication). The subreflector size is 8 meters, so the achieved accuracy was about 800000:1. If we assume that the digital system will be half as good, this is easily within our required accuracy. Jon Thunborg recently produced estimates of the cost of measuring the subreflectors of the VLBA antennas. These estimates range from \$17000 (plus 8.5 man–months) for a measuring machine built by NRAO, to \$65000 for Milliflect to measure the subreflectors for us, to \$450000 for a coordinate measuring machine (accuracy 25 μm). The ability to measure the subreflector separately from the main reflector would be a big advantage of the digital photogrammetric technique.

Finally, note that photogrammetric methods have been used in the past to measure radio telescopes, with mixed results (see e.g., Kenefick 1972; Kummer & Gillespie 1978; Hills & Lasenby 1988; Gilmore & Rudduck 1989). Given the advances in this technology in the last 10 years, it seems that many of the problems which prevented measurements accurate enough for our application from being taken in the past are no longer problems. However, a clear demonstration of the capability of such a system to measure a VLBA or VLA antenna main reflector (and subreflector) to the required accuracy would be absolutely necessary before any commitment to purchase.

miscellaneous methods

There are several direct methods which have been developed which fit into none of the above categories, but are worth mentioning. The panels for the OVRO antennas were initially cut to shape, measured, and initially set all in one process (Leighton 1978; Woody *et al.* 1994). This system was very accurate (of order 10 μm rms panel error) but is not feasible for the already constructed VLBA antennas. Such a system should be considered for the MMA antennas, however. A method which employed a bar of accurately known length and carrying an inclinometer was used to measure the NRAO 140-ft antenna (Findlay and Ralston 1977). This method provided a claimed accuracy of 25 μm rms across the main reflector surface. A method combining two laser interferometers carried by a cart which was moved radially above the surface of the main reflector surface was developed for the measurement of the JCMT antenna (Shenton and Hills 1976). Laboratory tests indicated an accuracy of 20 μm rms, but it is not clear if the instrument was ever actually used for measurement of the main reflector surface (Hills and Lasenby 1988).

indirect methods

These techniques use the fact that the radiation pattern of the antenna is related to the current distribution on the aperture surface via the diffraction integral (e.g., Silver 1949;

Paris 1968; Johnson *et al.* 1973; Southwell 1981):

$$U(x,y,z) = \frac{1}{4\,\pi} \int_a F(\xi,\eta) \frac{e^{-ikr}}{r} \left[\left(ik + \frac{1}{r} \right) \mathbf{i}_z \cdot \mathbf{r}_1 + ik\mathbf{i}_z \cdot \mathbf{s} \right] d\xi d\eta \quad , \tag{1}$$

where U is the radiation pattern, and F is the complex aperture current distribution. This is the scalar version of the integral relation, which holds for the cases we are concerned with here. The current distribution can be broken into amplitude (A) and phase (ψ) components:

$$F(\xi,\eta) = A(\xi,\eta)\, e^{-i\psi(\xi,\eta)} \quad . \tag{2}$$

The phase of the current distribution is related to deviations of the surface from its ideal (see e.g., Rahmat–Samii 1985). Equation 1 can be simplified through some manipulation and assumptions (which hold in most cases) to:

$$U(x,y,z) = \frac{i}{\lambda R} \int_a F(\xi,\eta) e^{ikz\rho} d\xi d\eta \quad , \tag{3}$$

for the radiation pattern at distance R. The quantity ρ is given by:

$$\rho = \left[1 + \frac{(\xi - x)^2 + (\eta - y)^2}{z^2} \right]^{1/2} \quad . \tag{4}$$

Using the binomial expansion of ρ and keeping only terms up to the second order gives:

$$\rho = 1 + \frac{(x-\xi)^2 + (y-\eta)^2}{2\,z^2} \quad . \tag{5}$$

If we make a change to spherical coordinates for the radiation pattern, with those coordinates defined as:

$$\begin{array}{rcl} x & = & R \sin\theta \cos\phi \;\; = \;\; R\,u \\ y & = & R \sin\theta \sin\phi \;\; = \;\; R\,v \\ z & = & R \cos\theta \end{array} \tag{6}$$

then the relation becomes:

$$U(u,v) = \frac{i}{\lambda R}\, e^{-ikR} \int_a F(\xi,\eta) e^{ik\rho'} d\xi d\eta \quad . \tag{7}$$

Where the quantity ρ' is (substituting into equation 5 to change coordinates, and assuming that $\sin^2\theta/2 \ll 1$):

$$\rho' = (u\xi + v\eta) + \frac{\xi^2 + \eta^2}{2\,R} \quad . \tag{8}$$

In the case where R is sufficiently large, $\rho' \rightarrow (\xi u + \eta v)$, and the relation becomes an exact 2–D Fourier relation between the far–field radiation pattern (U_f) and the aperture current distribution:

$$U_f(x,y) = \frac{i}{\lambda R}\, e^{-ikR} \int_a F(\xi,\eta) e^{ik(\xi u + \eta v)} d\xi d\eta \quad . \tag{9}$$

If the distance is not so great, then the quadratic phase term must be retained, but that can just be folded into an effective aperture current distribution:

$$F'(\xi,\eta) = F(\xi,\eta)\, e^{-ik(\xi^2+\eta^2)/2R} \quad , \tag{10}$$

which can be substituted for F in equation 9. In either case, the Fourier relation can be inverted, so given a measurement of U_f, $\psi(\xi,\eta)$ can be determined and hence the distribution of surface errors ($\epsilon(\xi,\eta)$).

The relationship between the surface errors and the aperture phase is given by (see e.g., Rahmat–Samii 1985; Rochblatt and Seidel 1992):

$$\epsilon(\xi,\eta) = \frac{\lambda}{2\,\pi}\,\frac{1}{2\,\cos(\gamma/2)}\;\psi(\xi,\eta) \quad , \tag{11}$$

where γ is the angle formed from feed to subreflector to surface point. For a parabolic reflector with an on–axis feed, this reduces to:

$$\epsilon(\xi,\eta) = \frac{\lambda}{4\,\pi}\,\sqrt{1+\frac{\xi^2+\eta^2}{4\,f^2}}\;\psi(\xi,\eta) \quad , \tag{12}$$

where f is the focal length. For shaped reflectors like those of the VLA and VLBA antennas, equation 11 should be used. If equation 12 is used instead (as is the case if HOLGR is used to process holographic data in AIPS), a maximum relative error of about 7% will occur for the VLBA (given a maximum value of $\gamma \sim 80°$, and $f \sim 8.4$ m).

Note that for measurements of this type, the deviations of the subreflector and the main reflector are inextricably tied together, so the derived deviations are some combination of the two. In theory, if observations of this type can be done with high SNR at two or three frequencies (i.e., at two or three different subreflector rotation positions), the combination can be separated, but it is not clear that anybody has ever *done* this. In some sense, we may not *care* that the two are tied together, since, if our goal is strictly to obtain good operation at 86 GHz, then we should just do the measurement at that frequency (if it is possible to do so), adjust the main reflector to compensate for the combined errors of the two, and live with any errors introduced at other frequencies. It may not be possible to do the measurement at 86 GHz, however, and in any case, it seems that it is still better to *know* where the errors are.

The basic steps for any of the indirect methods are conceptually as follows:

1- the antenna radiation pattern is measured

2- if necessary, a conversion from near–field to far–field radiation pattern is performed

3- the far–field radiation pattern is used to derive the aperture current distribution in one of 2 ways:

   a- if phase data is available, a 2-D Fourier transform is performed

   b- if no phase data is available, some phase recovery technique must be used

4- a geometric transform is used to obtain the surface errors from the aperture current distribution

5- if desired, another geometric transform yields the necessary screw turns to adjust the surface

There are variations on this, most notably when the actual main reflector panel locations and sizes are taken into account in an iterated version of the above steps (e.g., the "successive projections" technique of James *et al.* [1993], or the "best–fit panel model" technique of Deguchi *et al.* [1993]), but the essence of all of the methods is similar. The main decision to be made is how to go about item 1 above, i.e., how to measure the antenna radiation pattern. There are many alternatives, and the choice between them is really determined by the same factors that were considered in the section above. Most of these factors will be discussed in the subsection describing each technique, but the raster size, and many of the accuracy issues are common to several techniques, so will be discussed here.

raster size

The measurement of the antenna radiation pattern yields some effective spatial resolution on the surface of the main reflector. What is the spatial resolution required to obtain measurements which can be used to reliably adjust the panel corners? Bennett and Godwin (1977) performed a detailed analysis of this problem, and came to the conclusion that "the smallest significant panel dimension must contain a minimum of four resolution elements." For the VLBA antennas, the smallest panel segment is ~ 0.7 m, which implies that a raster of size $\gtrsim 140$ is required. A slight relaxation of this (to get to a power of 2) implies a raster size of 128X128. James *et al.* (1993), on the other hand, assert that it is sufficient to measure at least 3 points per panel (because there are three unknowns per panel - the phase offset and tilts in two directions). If the distance between samples is $\lesssim 1/2$ of the smallest dimension, then this criterion is met. This would imply a raster size of $\gtrsim 70$. Again, a slight relaxation of this to a power of 2 gives a 64X64 raster. It seems preferable to do the larger 128X128 raster, when possible. Time constraints may make it unfeasible to make a raster that large, however, in which case the 64X64 must be used. For the purposes of surface measurement to be used for panel adjustment, less than 64X64 makes no sense, at least for the VLBA (and similarly the VLA) antennas.

accuracy

The accuracy with which a given indirect technique can determine the errors on the main reflector surface (effective errors, since the subreflector is folded in) is determined by many factors. I list below what I think are the most important here, which is a list taken from Morris (1984) but modified and added to.

1- SNR

For indirect methods in which a reference antenna is used to provide a phase measurement (not phase–retrieval methods), the accuracy of the aperture measurement is given by:

$$\epsilon^{a}_{err} = \frac{\lambda}{2\,\pi}\;\psi_{err} \quad , \tag{13}$$

where ψ_{err} is the error in the aperture phase distribution. In the case of high SNR (which is the only case we are interested in), the error in the aperture phase distribution is:

$$\psi_{err} = \frac{N}{\mathrm{SNR}} \quad , \tag{14}$$

where N is the number of samples on each side of the square sampling grid, and SNR is the signal to noise ratio when both antennas (the reference and the one being measured) are pointed directly at the source. The accuracy on the reflector surface is related to the accuracy on the aperture by:

$$\epsilon^{s}_{err} = \frac{\epsilon^{a}_{err}}{2\,\cos(\gamma/2)} \quad , \tag{15}$$

where γ is the angle formed from feed to subreflector to surface point. The worst case is then at the dish edge, where for the VLBA antennas, $\gamma \sim 80°$ (the dish edge on the opposite side of the vertex relative to the feed), so the worst surface accuracy is:

$$\epsilon^{s'}_{err} \equiv \epsilon_{err} \sim \frac{\epsilon^{a}_{err}}{1.5} \quad . \tag{16}$$

Substituting the above relations gives:

$$\epsilon_{err} \sim \frac{\lambda\,N}{3\,\pi\,\mathrm{SNR}} \quad . \tag{17}$$

This can be used to determine the required SNR for a given desired surface measurement accuracy, wavelength, and raster size.

Putting in the numbers:

Using a value of $N = 128$ (see *raster size* section above) and a measurement accuracy of $\epsilon_{err} = 100\ \mu$m, we have:

$$\mathrm{SNR} \sim 140\,\lambda_{mm} \quad , \tag{18}$$

where λ_{mm} is the wavelength in mm. So, if the observation is done at 86 GHz (3.5 mm) we need SNR $\gtrsim$ 500. At the lower frequencies, we need: SNR $\gtrsim$ 1000 at 43 GHz (7 mm); SNR $\gtrsim$ 2000 at 22 GHz (13.6 mm); SNR $\gtrsim$ 5000 at 8.5 GHz (35 mm); SNR $\gtrsim$ 8500 at 5 GHz (60 mm). In 9 hours, a 128X128 raster can be done on the VLBA, with about 2 seconds per pointing. The noise on an individual baseline in 2 seconds, for 128 MHz bandwidth, is about 25 mJy at 6 and 3.5 cm, about 80 mJy at 1.36 cm, and about 120 mJy at 7 mm (Wrobel 1997). This value is unknown at 3.5 mm, but might be as bad as 500 mJy (using the value at 7 mm and assuming system temperature and aperture efficiency are twice as bad at 3.5 mm). So, to obtain the necessary SNR requires a source of about 250 Jy at 86 GHz, 120 Jy at 43 GHz, 160 Jy at 22 GHz, 125 Jy at 8.5 GHz, and 210 Jy at 5 GHz. Astronomical sources that have this strength on VLBA spatial scales in the continuum are nonexistent (the planets have this much flux density, but are entirely resolved out on VLBA spatial scales), so maser sources are required. For maser sources, the typical line widths are of order 100 kHz, which means that the noise will be about a factor of 40 worse ($\sqrt{128/.1} \sim 40$). This means that the required maser source flux density is about 10000 Jy at 86 GHz, 4800 Jy at 43 GHz, 6400 Jy at 22 GHz, 5000 Jy at 8.5 GHz, and 8500 Jy at 5 GHz. H_2O masers at 22 GHz can be this strong, so they are good candidates to use. SiO masers at 43 GHz are close to this strong, at times, so it may be possible to use some of them. Unfortunately, the SiO masers at 86 GHz are probably never strong enough to satisfy this SNR criterion, and so will probably never be satisfactory as sources to use for the indirect methods. Most satellites have sufficient radiated power to satisfy this source strength criterion, as do ground based beacons.

Note that if the phased VLA is used as the reference antenna, the SNR increase per baseline is a factor of ~ 4.5, so maser sources which are 2200 Jy at 86 GHz, 1100 Jy at 43 GHz, 1400 Jy at 22 GHz, 1100 Jy at 8.5 GHz, and 1900 Jy at 5 GHz would have sufficient SNR. This makes more sources suitable, but still does not make the 86 GHz SiO masers usable as sources for this technique.

Note also that the upgrade to the VLBA recording system to make 512 Mbps rates possible will make continuum bandwidths of 256 MHz possible, which will result in an additional $\sqrt{2}$ reduction in the noise. Combined with the phased VLA as reference, the required continuum source strength is about 40 Jy at 86 GHz, 19 Jy at 43 GHz, 25 Jy at 22 GHz, 20 Jy at 8.5 GHz, and 33 Jy at 5 GHz. This is getting close to the source strength of the strongest of the sources with significant flux density on VLBA spatial scales, but is still slightly too large.

As a final note, these required flux densities are all reduced by a factor of 4 if a 64X64 map is used (one factor of 2 strictly from the smaller N, and one factor of 2 from the fact that the time per point is increased to 8 seconds from 2 seconds). If it were decided that holography using astronomical sources were the preferred technique, then it may be that it is necessary to suffer this reduced resolution on the antenna surface for the additional accuracy per point.

2- pointing errors

Random pointing errors cause some uncertainty in where the physical aperture really is (averaged over the raster). The worst error occurs at the edge of the antenna, where the pointing error can be thought of as effectively displacing the surface by an amount $\theta D/2$, for rms pointing error θ on an antenna of diameter D. In fact, detailed treatment of the problem indicates that the error is about a factor of 4 less than this (Morris 1984), i.e.,

$$\epsilon_{err} \sim \frac{\theta D}{8} \quad . \tag{19}$$

Note that if phased measurements are used, and both the reference antenna and the test antenna have similar pointing errors, the net effect is to increase the error by $\sqrt{2}$. In theory, a constant pointing offset (on either or both of the antennas) should not affect the accuracy of the indirect methods, since it manifests itself as a simple phase gradient across the aperture current distribution.

Putting in the numbers:

The typical raw pointing accuracy on the VLBA antennas is of order $10''$ (over several hour time scales), which produces an error of about 150 μm. For observations where a VLBA antenna is used as the reference, this will increase to about 210 μm. Even if the rms pointing errors were as good as $4''$, the surface measurement error would be about 85 μm (using a VLBA antenna as reference). This situation might be improved by using referenced pointing throughout an observation (which does not currently work but may in the future).

3- atmospheric errors

This can be broken into three effects: angle of arrival fluctuations, amplitude variations (scintillation), and the phase stability between the two elements being used to measure phase (if it is even being measured). Angle of arrival fluctuations can be considered as an additional part of the pointing error, so can be included as part of that error source.

Atmospheric scintillation will cause fluctuations in the measured radiation pattern amplitude which will manifest themselves as errors in the derived aperture phase (and hence errors in the derived surface deviation distribution). To first order, these fluctuations can be thought of as limiting the SNR of the observations. In fact, it's a bit trickier than that, since the noise adds to both amplitude and phase variations in the measured signal, but the amplitude fluctuations don't affect the phase. This makes amplitude fluctuations a factor of 2 better in the resultant measurement error. Also, the measurement error in the amplitude fluctuation case doesn't depend on the raster size. So, the resultant maximum surface deviation measurement error is:

$$\epsilon_{err} = \frac{a_s \, \lambda}{6 \, \pi} \quad , \tag{20}$$

where a_s is the magnitude of the fluctuations (e.g., for 1% amplitude fluctuations, a_s = 0.01).

If phase is being measured, then for a given rms phase fluctuation between the two antennas (ϕ_{rms}), the maximum surface deviation measurement error is:

$$\epsilon_{err} = \frac{\phi_{rms} \, \lambda}{6 \, \pi} \quad . \tag{21}$$

Putting in the numbers:

Amplitude fluctuations: for $a_s = 0.02$, a measurement error of only 14 μmresults at 13.6 mm. This should be a small part of the total measurement error budget.

Phase fluctuations: for $\phi_{rms} = 0.5$ radian ($\sim 30°$), the measurement error is ~ 360 μm at 13.6 mm, ~ 190 μm at 7 mm, and ~ 90 μm at 3.5 mm. Note that the mean phase must also be tracked through the experiment, which involves some reference calibration. The approach to getting around this significant source of error seems to be to simply keep doing the experiments and waiting until a "good" phase stability run occurs. This is expensive in setup and scheduling time, however, and observing sessions in which the phase is more stable than 0.5 radians over the VLBA are rare indeed.

4- near–field corrections

If the measurement of the radiation pattern is done with the source in the near–field, then error is introduced into the derived values of surface deviation. If the measurements are done in the region within a few wavelengths of the aperture, then the assumptions made in going from equation 1 to equation 3 break down, and a much more detailed analysis must be done. In this case, the field amplitude and phase are usually fitted by using a wave expansion which is appropriate for the measuring geometry (planar, cylindrical, or spherical). After finding the expansion coefficients on the measurement surface, the field at the aperture can then be calculated. A general description of this technique can be found in Johnson *et al.* (1973). I assume that we will not be performing such a measurement, so will not examine the errors associated with this particular case of near–field measurement (e.g., the error introduced by truncation of the wave expansion coefficients). In the case where the measurements are done further away than this very near–field zone, the general method is to apply some correction, then proceed as if the far–field radiation pattern had actually been measured (do the Fourier transform to get the aperture phase). In order to examine where this region is, and the error introduced by the correction, we need to have a closer look at equation 4 and its expansion (e.g. into equation 5). If we retain all of the terms in the binomial expansion, we have:

$$\begin{aligned} \rho \;=\; & 1 + \frac{1}{2}\frac{(x-\xi)^2 + (y-\eta)^2}{z^2} - \frac{1}{8}\left[\frac{(x-\xi)^2 + (y-\eta)^2}{z^2}\right]^2 + \\ & \frac{1}{16}\left[\frac{(x-\xi)^2 + (y-\eta)^2}{z^2}\right]^3 - \dots \quad . \end{aligned} \tag{22}$$

The generally accepted criterion for the source to be in the far–field is that the maximum error in retaining only the first order terms in this expansion is less than $\lambda/16$ (which produces a $\pi/8$ phase error at the edge of the antenna). This can be written (using spherical coordinates):

$$|\, r - [R - (\alpha\xi + \beta\eta)]\,|_{max} < \frac{\lambda}{16} \quad , \tag{23}$$

which demands a minimum distance between source and antenna:

$$R \gtrsim \frac{2\,D^2}{\lambda} \quad . \tag{24}$$

This is the well–known "far–field criterion" in antenna measurement (e.g., Rhodes 1954; Hacker & Schrank 1982), which can also be derived from strictly geometric argument.

In fact, given that we want to achieve a particular maximum measurement error (ϵ_{err}), we can relate that to the maximum allowable phase error in the aperture distribution (ψ_{err}) using the same arguments as for the SNR and phase error cases above:

$$\psi_{err} \sim \frac{3\,\pi}{\lambda}\,\epsilon_{err} \quad . \tag{25}$$

The maximum phase error in the aperture distribution can also be related to the error in the truncation of the expansion as:

$$\psi_{err} \sim \frac{2\,\pi}{\lambda}\,\left|\, r - [R - (\alpha\xi + \beta\eta)]\,\right|_{max} \quad . \tag{26}$$

Equating these two gives:

$$\left|\, r - [R - (\alpha\xi + \beta\eta)]\,\right|_{max} < \frac{3}{2}\,\epsilon_{err} \quad . \tag{27}$$

This criterion results in a minimum distance of (for $\epsilon_{err} = 100$ μm):

$$R \gtrsim \frac{3\,D^2}{\lambda} \quad . \tag{28}$$

This has only a very weak dependence on raster size, but of course depends linearly on the required measurement error (e.g., if $\epsilon_{err} = 50$ μm, then $R \gtrsim 6D^2/\lambda$). If the quadratic phase term is retained in the binomial expansion of r (see equation 8), then we have:

$$\left|\, r - \left[R - (\alpha\xi + \beta\eta) + \left(\frac{\xi^2 + \eta^2}{2\,R}\right)\right]\,\right|_{max} < \frac{3}{2}\,\epsilon_{err} \quad . \tag{29}$$

This relationship cannot be expressed as simply as in the case where the quadratic term is not retained, but for cases of interest for this investigation ($R = 25$ m, $\lambda \lesssim 13.5$ mm, measurement error $\epsilon_{err} = 100$ μm, and $N < 128$) the minimum distance is between 300 and 500 m. For a measurement accuracy twice as good, the minimum distance is between 350 and 750 m.

5- polarization effects

For the VLA and VLBA, where circular feeds are used, there can be a problem related to polarization variation across the aperture. Since the feeds are never exactly circularly polarized, the polarization response is an ellipse. If the ellipticity of the response varies across the aperture, and if the observed source is linearly polarized (as is the case with many astronomical sources, e.g. the maser sources), then differential phase shifts will be introduced over the aperture. Also, if the parallactic angle of the source changes over the course of the observation (as is the case when a celestial source is tracked), amplitude variations will result in the measured radiation pattern. The amount of error introduced by these fluctuations in phase and amplitude will depend on the particulars of the feed response and the observed source. For the VLA and VLBA antennas, the beams are elliptical with an ellipticity of a few percent at the feed center. To first order, for a holography observation which tracks over the full range of parallactic angle, this produces an equivalent amplitude rms in the measured radiation pattern which is of order $p_e\, p_s/4$, where p_e is the ellipticity and p_s is the percent linear polarization of the source. In the most extreme cases, the linear polarization can be on the order of 100% (for maser sources), which implies an amplitude rms of about 1-2%, which produces a corresponding surface deviation on the order of 10 μm at 13.6 mm (see the amplitude fluctuation section above). Morris *et al.* (1988) estimated that the peak error introduced by this effect for an observation of the water masers in Orion with the IRAM 30-m antenna was 32 μm.

6- receiver gain stability, linearity, and dynamic range

Since from SNR requirements holography signals are of necessity relatively strong, care must be taken that the receiver system is not driven into the non linear part of its response. In a sense, this is a statement about the required dynamic range of the linear part of the receiving system. If the required SNR for the desired surface accuracy is larger than the dynamic range of the receiving system, there will be obvious problems. This is of particular concern when phase recovery techniques are used, since they require very high SNR (see below). A related issue (since it involves the receiving system) is the overall gain stability of the receiving system as a whole. Such gain variations can be long term drifts, short term random fluctuations, or discrete jumps in gain. The long term drifts are calibrated out (or should be, anyway). The short term random fluctuations simply increase the effective noise, and for the VLA and VLBA (and presumably the MMA) the electronics are designed so that the phase variations of the total system are dominated by the atmospheric fluctuations. The discrete jumps should occur rarely, but will be a problem.

7- phase retrieval related errors

If no phase is measured, and some phase retrieval method is used to estimate the aperture current phase, then there is some uncertainty introduced by this. Morris (1985) and Morris *et al.* (1991) have shown that this uncertainty is of the order of a few times the uncertainty in a similar reduction on data which contains phase information, i.e., the surface deviation measurement error for the phase recovery techniques is several times the measurement error in a similar experiment utilizing phase data.

8- bulk reflector shape changes

If the measurement involves the tracking of a celestial source over a large range of elevation angles, then the overall shape of the main reflector and the relative position of the subreflector both change as a function of time. This is not modelled, and will introduce uncertainty in the estimate of the distribution of surface errors. This is relatively hard to quantify, but as a crude estimate, one could use the spec'ed rms of the reflector structure due to gravity as an estimate of the maximum error introduced into the surface deviation map. This is 140 μm, which should certainly be taken as an upper limit on the uncertainty introduced due to this effect.

9- source structure

If the source of radiation which is illuminating the main reflector surface is different than a point source, then the derivation of the surface deviation map becomes more complicated. The actual measured radiation pattern is then a convolution of the source distribution function with the true radiation pattern (e.g., Matt and Kraus 1955; Baars 1973). If this source distribution function is relatively well known and stable over time (e.g., a planet) then this can be accounted for in the reduction. Of course, if the source structure changes as a function of time (e.g., for maser spot sources, where the projected baselines of the interferometer change relative to the source as the source is tracked), then this must be accounted for properly.

10- ground scattering

If a transmitting beacon is used to measure the radiation pattern, then some amount of the transmitted power from the beacon will scatter from the ground into the antenna structure and then into the feed. This will cause a difference in the radiation pattern which is actually entering the feed with that which is assumed to be entering the feed, and will hence introduce uncertainty into the derived surface deviation pattern (e.g., Moeller 1966). This error can be minimized in some cases by choosing the geographical location of the transmitter carefully (e.g., Mayer *et al.* 1983; Morris *et al.* 1988; Hills & Lasenby 1988; Fuhr *et al.* 1993). However, this is not possible in all of the VLBA antenna locations. When this is not possible, ground reflection effects may be minimized by placing a microwave absorber or specially designed diffraction fence on the ground at particular locations around the antenna, including the specular reflection point (Wilson and Joy 1988; Becker and Sureau 1966; Preikschat 1964). Even with these precautions, however, appreciable errors will still be present in almost all cases.

11- EM clutter

This is related to the idea of ground reflections just discussed, but involves the "clutter" introduced by unmodelled reflections and diffractions in the antenna structure itself, e.g., from feed support legs. Some of the reflections and diffractions can be modelled, if a sophisticated enough model can be built, but, no matter how complicated the model, there will always be some unmodelled reflections and diffractions - the "clutter". This obviously introduces error into the derived surface deviation map, since these unmodelled reflections/diffractions introduce phase across the aperture. The magnitude of this effect for the VLA and VLBA antennas is very small, however. There are methods to try to overcome this clutter problem (e.g., Gilmore and Rudduck 1989), but none have been well tested.

near–field techniques

A problem with indirect methods is that the far–field radiation pattern is needed, but it may be difficult to find appropriate sources which are distant enough (see the above discussion), or it may not be feasible to build a system to measure these sources for a given antenna setup. In this case, it may be necessary to make a measurement of the radiation pattern in the near–field, and live with the errors introduced by a near–field to far–field correction. In this section, methods which make measurements in very close proximity to the antenna aperture are considered. The case when the distance is somewhat further will be covered in the next section. It seems highly unlikely that any of these techniques would actually be used for VLBA antenna surface measurement, but this section is included for completeness. Several methods of performing very near–field measurements exist (for a broad description of these, see Johnson *et al.* 1973), of which the three most common are the anechoic chamber, the compact range, and the probe–compensated methods. General descriptions of these techniques and results from various measurements can be found in Johnson *et al.* (1973), Kummer and Gillespie (1978), Paris *et al.* (1978), Joy *et al.* (1978), Repjar and Kremer (1982), Rahmat–Samii and Lemanczyk (1988), and Lee *et al.* (1990).

anechoic chamber

An anechoic chamber is a chamber designed with walls which are very absorbent to microwaves. The antenna to be tested is placed at one end of the chamber, and is illuminated by a special transmitting antenna at the other end. The length of the chamber is such that the transmitting antenna and test antenna are far enough apart that the spherical wave from the transmitting antenna approximates a plane wave at the test antenna location. For this reason, anechoic chambers are not generally used for large antennas (the size of the chamber becomes prohibitively large). For a good general description of these chambers, see Kummer and Gillespie (1978).

probe–compensated

For this technique, power is radiated through the antenna for which the radiation pattern is desired known and the resulting near–field pattern is measured by a probe (see e.g. Joy *et al.* 1978). The probe is moved around to obtain a sample of the pattern, in either a planar, cylindrical, or spherical geometry. The near–field pattern is then transformed mathematically to obtain the far–field pattern (see e.g. Paris *et al.* 1978). It is called probe–compensated because a correction is necessary to account for the distortion of the radiated field by the probe itself. A more recent description of such a measurement is given in Rahmat–Samii and Lemanczyk (1988). This is unworkable for the VLBA without considerable effort.

compact range

Instead of moving the probe around, it is possible to illuminate the antenna by some other means, and move it around to measure the near–field pattern. To illuminate the antenna, a small transmitter illuminates the surface of a reflector or lens which is directed at the antenna to be measured (see e.g., Repjar and Kremer 1982). The reflector or lens may actually be shaped to make the e-m wave which is incident on the antenna planar, which means that the far–field pattern is essentially sampled. One fundamental problem with this technique is that the reflector needs to be at least as large as the antenna being measured, and have a very accurate surface. This makes this technique unworkable for the VLBA antennas.

beacons

If it is possible to take the transmitter to some distance, and illuminate the antenna directly, then the far–field pattern may be estimated. The distance may be great enough that the far–field criterion is met (see above). Early examples of antenna measurement via this technique are described in Ravenscroft (1966) and Jacobs and King (1966). If the distance is not great enough to put the transmitter in the far–field, then some other method must be used to obtain the far–field pattern from the measured near–field pattern. The simplest method is to use the quadratic phase correction described above (e.g., Bennett *et al.* 1976). Alternatively, a method using defocusing may be used. The correction is obtained by focusing the antenna to the distance of the transmitter and measuring the pattern. After refocusing to infinity, a newly measured pattern will describe the far–field pattern, with some errors (Johnson *et al.* 1973). This defocusing technique was used to successfully measure a 4.9 m antenna surface to 4 μm rms (Mayer *et al.* 1983). With either of these techniques, in order for phase to be measured directly, an auxiliary antenna (or horn) must be placed near the antenna to be measured, in order to provide a reference. This antenna can be relatively small, however, so might not be a particular problem. Otherwise, some phase reconstruction technique must be used (see below). The main problem with these techniques for the VLBA antennas is that even though the transmitter need not be as far away as the far–field criterion distance, it must still be placed at some significant distance (e.g., $\gtrsim 300$ m distant - see above). This means that the elevation angle at which the error distribution would be derived would necessarily be very small (since the transmitter could not be raised to great heights). Since we have no good model for how the main reflector shape changes with elevation (Peter Napier, personal communication), using any derived information at very low elevation to make changes in the panel settings would be unwise.

far–field techniques

If an appropriate source can be found which is at a distance greater than the far–field criterion distance, then a direct measurement of the far–field pattern can be made. In order to measure phase, as in the beacon section above, either a small auxiliary antenna must be used, or, in the case of an interferometer like the VLA, VLBA, or MMA, one of the antennas of the array can be used to provide the reference. There are two types of sources which can possibly be appropriate for use in this way: satellites, and astronomical sources. Airplanes and helicopters have also been used in the past, but only for small antennas for which the uncertainty in position of the aircraft was unimportant (e.g., Shanklin 1955; Walker 1966).

In order for a source to be "appropriate", it must have sufficient signal (see SNR discussion above), and have a known or derivable sky brightness distribution. The simplest case of a known sky brightness distribution is a point source, and these are the sources that have been used most successfully (of course, satellites are point sources). Planets and the Sun may be appropriate as well (if the interferometer spacing is small enough), but less work has been done on developing the technique for those sources when they are significantly resolved by the primary beam of the antenna. Other sources with very well known distributions may also be appropriate, but again, there has been little work on this aspect of the problem.

satellites

Since the early 1960's, satellites have been used as the sources for antenna measurement (Brueckmann [1963] is a very early example). The obvious advantages of using a satellite are that the source strength is very high, and that it is definitely a point source. Using satellites for antenna measurement, including surface deviation determination, is currently fairly popular. For descriptions of some of these measurements (not including those which utilize phase recovery) see Lasenby (1985), Godwin *et al.* (1986), Rochblatt and Seidel (1992), Barvainis *et al.* (1993), and Deguchi *et al.* .

If one of the elements of the VLBA is to be used as the phase reference (rather than a small adjacent auxiliary dish), then the use of satellites as beacons for the VLBA presents some special problems. Some of these are fairly obvious and some are not (which Tony Beasley has discovered through experimentation). One obvious problem is that satellites have significant parallax, and that all satellites move relative to celestial sources, even geostationary ones. This causes special problems for the creation of the antenna control files, and for the correlation of the data. It is not clear at this point that all of the correlation issues have been addressed and solved. Also, the signals from satellites are so strong that we seem to be suffering from gain problems - both non-linear behaviour, and possibly gain compression. If a small adjacent auxiliary antenna is to be used at each of the VLBA sites, then significant design and construction is necessary, mostly for the electronics.

Other aspects of using a satellite as the source are not under our control, but still present problems. One of these aspects is the fact that for a given satellite, a holographic map at only one elevation can be obtained at each antenna. Actually that map is an average over elevations which are covered by the scanning, which may cover several degrees on the sky, depending on the frequency. If there were enough good satellites, we could conceivably do this on each of them to obtain elevation coverage. Unfortunately, that is not the case. Another problem is that we would like to do the holography at the highest frequency possible, meaning currently 43 GHz, and in the future 86 GHz. Unfortunately, there are no satellites visible to most of the VLBA antennas which broadcast near those frequencies. This is a real problem, and it is unclear whether the situation will improve in the future.

astronomical sources

It is sensible that radio astronomers would attempt to use astronomical sources to measure the characteristics of the antennas they use, and this is indeed the case. Since the sources need to have high SNR, the earliest sources used in this manner were the Sun (e.g., Kennedy and Rosson 1962; Jacobs and King 1966) and Cas A (e.g., Ravenscroft 1966).

As antennas and receiving systems improved, fainter sources could be used, including the planets, and strong compact radio sources (e.g., Baars 1973). When radio holography was being developed, strong compact radio sources were natural targets, and were used even in the earliest of these experiments (e.g., Scott and Ryle [1977] used 3C84, and Rahmat–Samii *et al.* [1983] used 3C273). Such sources are currently the chosen ones for VLA holography (Rick Perley, personal communication). However, as noted in the SNR discussion above, such sources do not have enough flux density on VLBA spatial scales to be used for holography.

Observations of H_2O Maser sources have also been used in recent years to do holographic measurements of antennas (e.g., Tarchi and Comoretto 1993; Morris *et al.* 1988). Again, as discussed in the SNR section above, some of these sources do have enough flux density to be useful as holography sources for the VLBA. Tony Beasley has been using these sources to do some holography observations with the VLBA, and has found that positioning the subreflector based on the derived offsets has yielded the expected increase in gain, indicating that they are useful for that particular purpose. However, the repeatability of the derived surface deviation maps from these measurements is not nearly as good as required (repeatability is on the order of 500 μm). I think this is because of a combination of the measurement errors described above, notably the pointing, phase stability, bulk reflector shape changes, and source structure problems.

shearing interferometry

As a special case of holography using an astronomical source (which could presumably also be used when observing a satellite as well, if one broadcast at the right frequency), a technique called "shearing interferometry" has been developed (Serabyn *et al.* 1991). The CSO antenna on Mauna Kea has had its surface measured via this technique, as has the TRAO antenna in Korea (Park *et al.* 1997). In this technique, the two telescopes which might be used for a typical holography analysis are replaced by two images of a single primary mirror. This is effected by using a complicated combination of a beam splitter with several (some movable) mirrors. This is similar to a technique proposed some years earlier, except that in that earlier proposal, two physically distinct feed horns were utilized (von Hoerner 1978). The accuracy obtainable with this technique is similar to that obtained with typical holography, but the optical and mechanical instrumentation is complicated to design and build, and is fairly cumbersome (Masson 1991).

phase reconstruction techniques

Although these techniques fit strictly into one of the above categories (near–field or far–field), they form such a large part of current microwave antenna measurement and holography that it seems warranted to give them their own descriptive section. The fundamental principle on which these techniques were originally based is that if multiple amplitude radiation patterns are measured, with different focus locations, then the aperture phase can be recovered from these amplitude–only radiation pattern measurements. The most common implementation of this principle was borrowed from electron microscopy, and is credited to Misell (1973), so it is often called the Misell technique or the Misell algorithm. The signal source can be a ground based beacon, a satellite, or an astronomical source. Good general descriptions of this technique can be found in Morris (1984, 1985). Examples of such measurements are described in Ellder *et al.* (1984), Hills and Lasenby (1988), Morris *et al.* (1988), Fuhr *et al.* (1993), Tarchi and Comoretto (1993), and Whyborn and Morris (1995). Slightly different phase recovery techniques (which do not use the Misell algorithm) are described in Isernia *et al.* (1991), Hills and Lasenby (1988), and Lasenby (1990). It has also been shown recently that only one amplitude pattern is really required (Hills and Lasenby 1988; McCormack *et al.* 1993). Two measured patterns are still better, however (more data). There are two major drawbacks to these phase recovery techniques: the algorithms often converge on solutions for aperture phase which are only local (not global) minima in parameter space, and very high SNR (and hence receiving system dynamic range) is required.

The convergence on local minima (and hence a strong dependence on the initial estimate) is a serious problem for these techniques. A common attempt to avoid this problem is to average the results of several surface deviation maps obtained with different random initial guesses (Whyborn and Morris 1995; Tarchi and Comoretto 1993; Morris *et al.* 1988; Morris *et al.* 1991). More recently, a method has been proposed to attempt convergence on the global minimum (Morris 1996), however, convergence to that global minumum is still not guaranteed.

The required SNR (and hence dynamic range) is at least 45 dB, and depending on the measurement may be as high as 60 dB (e.g., Morris 1985; Whyborn and Morris 1995). This implies the use of ground based beacons or satellites, with all of the problems involving them listed above. This is the major drawback of the phase recovery techniques as they pertain to the VLBA. Note, however, that there are other problems, notably pointing, atmospheric stability, and elevation considerations. Some of these are lessened if a small auxiliary antenna is used, but in that case we may as well measure the phase and use it.

Conclusions

Given the error sources discussed above, it seems clear that none of the indirect methods which use one of the VLBA antennas as the phase reference will yield the required accuracy. It seems that the only way in which the indirect methods can be used is if small auxiliary antennas are placed at the sites and used for the phase reference. Even in this case, the pointing performance of the VLBA antennas would have to be improved significantly before the required accuracy could be obtained. Some electronics modification may also be necessary. This is in addition to the design of the auxiliary antenna electronics, data acquisition and storage, and possibly the antenna itself (if, e.g., a small lensed horn is used above the subreflector, rather than an adjacent small satellite dish). Because of these considerations, none of the indirect methods seems desirable for VLBA antenna surface measurement.

Of the direct methods, the digital photogrammetry is *clearly* the best choice. It should give the required accuracy, gives an independent measurement of the subreflector, and can be used at many elevations. The system should be relatively simple to use (according to the vendors), is portable, is available as an off-the-shelf system, and used proven technology (though not in this particular context). Since this technique has not been proven for measuring large antenna reflectors to this accuracy, some demonstration of its performance should be requested before the investment of the significant purchase price is made. The best way to do this is probably to use the system to measure a VLA antenna, where the results could be compared to reliable holography results. Note that one drawback of this system is that measurement of the subreflector offset from optimal is probably not possible. However, since it has been shown that the type of holography already being done can reliably measure these offsets, it seems that such measurements should continue for that one purpose.

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