Some Thoughts on an Active Surface, Pointing Accuracy, and the Offset-Feed Design for the Green Bank Antenna.

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April 13, 1989

I. Reliability and Maintenance of an Active Surface.

The decision on whether to use an active surface on the Green Bank antenna seems to me to be of comparable importance to the decision on whether to use an offset-feed or symmetrical design. The surface question has, however, received relatively little detailed attention. It has been assumed in the report by the NRAO Technical Study Group dated Feb. 20, 1989 (hereafter referred to as "the Report") that an active surface would be used. However, the reliability and maintenance of this feature need to be considered.

The use of an active surface, adjustable by computer during observations, has an immediate appeal as the state-of-the-art way to go about making a large antenna for short wavelength operation. A high degree of homology is no longer needed, which simplifies the structural design. The surface adjustment is principally intended to compensate for gravitational deflections, but it might also be used for thermal deflections if the thermal behavior of the antenna becomes sufficiently well understood. Thus an active surface adds a degree of flexibility that is in keeping with NRAO's history of learning to improve the performance of its telescopes over the years.

Implementation of an active surface requires the inclusion of a large number of adjustment mechanisms which I shall refer to as positioners. I envisage a positioner as being a small unit with a mounting bracket at either end. The distance between the brackets is adjustable over a range of a few inches by means of an internal electric motor. In preliminary presentations by two different manufacturers (TIW and RSI), the number of surface adjustment points has been estimated as about 2000 in one case and about 280 in the other, depending on whether single panels or rafts of panels were to be adjusted. For the antenna proposed in the Report, 2700 adjustment points were estimated. In any case a large number of active positioning units are required, and these should be capable of operation with a minimum of maintenance for many years under the usual outdoor conditions of temperature extremes, blowing dust, (acid) rain, etc. As far as I know there is no information on the reliability of such mechanisms when used on an antenna. At this time one could only guess at what the mean time between failures of the positioners would be, but it would be wise to assume that at any given time some fraction of those on an antenna would not work and would be stuck at some point within their range of travel. For example, suppose that 2% of the positioners are non-operational. Then something like 2% of the surface cannot be adjusted. In terms of degradation of sensitivity, the result is most serious if at some particular frequency the signal component from the non-adjustable part of the surface arrives at the feed with a 180 deg. phase difference from the signal from the rest of the surface: this occurs when the position of the non-adjustable part is a quarter wavelength from the required position. The main beam gain would then be reduced by about 4%. Since it is unlikely that all of the bad positioners would introduce errors of similar magnitude, a loss equal to twice the non-adjustable area is an extreme worst case. In general one might be prepared to tolerate a 5% loss in gain, but since the surface errors would contribute to near-in sidelobes, only a small percentage of non-adjustable surface is likely to be acceptable.

At the longest wavelengths the effect of some non-operational positioners will clearly be negligible. As one goes to shorter wavelengths their effect on the gain becomes more serious, and let us suppose that the largest effect is to reduce the gain by 5%. For comparison, in a fixed-surface antenna gravitational distortion will reduce the gain by 5% when the rms surface error is about 1/56 of a wavelength, i.e. at a frequency of about 1/4 to 1/5 of the maximum useful operating frequency. (I take the maximum useful frequency to be that at which surface errors reduce the efficiency to 30%, which occurs for an rms of about 1/12.7 of a wavelength.) For frequencies a little greater than that at which the 5% loss occurs, one would expect to be better off with the active surface design, since the better accuracy of the adjustable part of the surface should more than offset the effect of the part with bad positioners. Consider, for example, the VLBA antennas. For these the rms accuracy of the surface panels alone is 0.16 mm (see VLBA Project Book, version 7, section 3). The accuracy of the support points resulting from the setting accuracy and the effects of gravity, temperature, and wind on the backup structure is 0.232 mm rms, and the overall surface accuracy is 0.282 mm rms. Now suppose that one installed active surface positioners on a VLBA antenna, and that this allowed the support points to be adjusted to 0.1 mm rms. The 0.1 mm rms corresponds to the full effect of wind and 2/3 of the effects of temperature as estimated for the VLBA antennas, but excludes the effects of gravity and initial setting errors. The overall surface errors would then be reduced from 0.282 to 0.189 mm rms. The maximum operating frequency would be increased from 84 GHz to 125 GHz, and, for example, at 84 GHz the efficiency factor resulting from surface errors would be increased from 0.30 to 0.62 . Thus near the high frequency end of the operating range the improvement in efficiency would be large, and much more than one would obtain, for example, by eliminating aperture blockage from a VLBA antenna. For larger antennas the benefit of the active surface should be even greater, since the gravitational deformations that it compensates are larger. In the 100 m designs presented by TIW and RSI, and in the Report, the rms surface errors are reduced by factors of 3 to 4 relative the same structures with fixed surfaces.

A remaining concern is the amount of effort likely to be required for maintenance of the positioners. The rate of replacement will depend on the mean time between failures of the positioners, which is not known. If, for example, this mean time were 10 years for a single positioner, with 2000 positioners the mean failure rate would be one every two days. One maintenance day per month should be adequate in such a case. However, we want to avoid a hazardous work situation, so some thought should be given to the accessibility of the positioners. Suppose that the antenna can rotate about the elevation axis through 180 deg., i.e. from one horizon to another. Then any part of the structure can be brought to a height of only a little more than one dish radius above the ground. Even so, the height range of up to about 150 ft required is probably outside the range of any available cherry picker. Thus if the positioners are only accessible from the back of the reflector surface, some special system of lifts or walkways would have to be designed into the backup structure. A better alternative would seem to be to make the positioners accessible from the upper side of the surface when the antenna is pointing to the zenith. This could be done by having a small removable panel immediately above each support point where the corners of four main panels come together, as shown in Fig. 1. The access hole to the positioner could be as large as 1.5 ft square, i.e. just small enough to avoid the danger of a person falling through. Special equipment or tools could be developed for walking on the surface, releasing and refastening the positioners, and supporting the surface while the positioner is removed. If a positioner could be released by removing a single pin or bolt at either end, and removing one electrical connector, one can envisage the process of replacing a positioner taking less than half an hour.

The effect of non-operational positioners will depend upon how far out of adjustment they happen to be. This will in turn depend in some way upon the range of adjustment provided. Thus it is desirable to have some element of homology in the antenna design, to limit the required range of travel of the positioners. The range of adjustment required will be smallest at the center of the dish and greatest at the edges, so there might be some benefit in progressively constraining the range of adjustment in the central parts. Also, if the readout mechanisms on the bad positioners still worked, then the computer could adjust the remaining positioners to give a paraboloidal surface with the best rms fit to the non-adjustable points, which would be better than simply ignoring such points. The computer could also indicate the improvement from replacing any particular failed positioner, which would be valuable in deciding when and what to repair. Thus it might be worthwhile to put a second, redundant position readout on each positioner, to minimize the likelihood of having it stuck in an unknown position.

II. Conclusions on the Active Surface.

(1) The rather simple considerations discussed above provide reason to believe that the use of an active surface would very significantly improve the performance of a large telescope at all but the low frequency end of its range. This appears to be true even if a "realistic" number of positioners are non-operational, based on some guesswork in lieu of any real data on the reliability. By incorporating into the antenna design a scheme for easy replacement of positioners, it should be possible to avoid a large increase in the maintenance load resulting from the active surface. It appears that an active surface should be a major design feature in a new antenna.

(2) Any proposal from an antenna manufacturer should include an estimate of the failure rate of positioners, the time and manpower required to replace positioners, and the loss in aperture efficiency at various frequencies for various percentages of non-operational positioners randomly distributed over the surface. It should also include a description of the procedure for accessing and replacing positioners.

(3) The reliability and maintainability of the positioners in too important to be entrusted solely to the antenna manufacturer. NRAO should be supplied with samples of the positioners as early as possible within the contract, and should subject them to accelerated life testing. This would include continuous operation under load, in various orientations, and under various environmental conditions.

III. Pointing Accuracy and the Offset-Feed Design.

With active surface correction the accuracy of the surface depends principally upon that of the surface panels, since the gravitational distortion of the support points is largely compensated for. Thus the maximum operating frequency is very much less dependent on the size of the antenna than is the case for a fixed surface. One would therefore expect that as the size of an active-surface antenna is increased, factors other than the surface accuracy will at some point limit the maximum usable frequency. One such factor is likely to be the pointing accuracy.

The Report indicates (Table 5) that with an active surface the shortest operating wavelength would be 7 mm, with further reduction as the correction of the surface becomes better understood. At 7 mm wavelength the beamwidth is about 17 arcsec, so pointing to 1/10 of a beamwidth calls for an accuracy of better than 2 arcsec. Pointing errors are assumed in the Report to result primarily from thermal effects is the pedestal and yoke, based on experience with the VLA antennas. Instability of the dish and the prime-focus structure is not considered as an additional source of pointing error. If this approach is to be valid, then the angular position of the focus structure must be stable relative to the dish to within 1-2 arcsec. In the case of the offset feed design (see Fig. 5 of the Report), the angular position of the 60 m long arm or tower that supports the focus equipment must be determined to, say, 1.5 arcsec, which corresponds to 0.44 mm in lateral position at the focus. Since any rigid connection from the focus to other parts of the backup structure (other than those close to the base of the arm) would violate the unblocked aperture requirement, the stability of the arm must depend on its own rigidity and that of the backup structure in the area near its base. The 1.5 arcsec requirement does not seem to me to be feasible for such an arm. It has been suggested that the stiffness of the arm could be improved by cables with relatively small scattering cross section running from the focus to points at the edge of the reflector. Such cables would have to be something like 100 m long, and it seems doubtful that they would be any help in constraining the position of the focus structure to less than 0.5 mm, i.e. to less than 10**-5 of the cable length. Wind induced vibrations in such cables could even make the stability worse. It will no doubt be pointed out that the position of the end of the arm can be measured and controlled by some system of laser beams and servomechanisms. However, this would increase risk factors, design development time, and maintenance requirements.

In the on-axis design the distance from the focus to the surface is reduced to about 35 m, and the focal structure is supported by a tripod or quadruped in which rigid members are connected to points widely spaced around the outer parts of the backup structure. With regard to stability of the focus structure, this is clearly a superior design. One would therefore expect that the on-axis design will lead to larger viable antennas than the offset feed design. An accurate comparison of the two designs will require detailed structural analyses. However, a simple investigation of thermal effects can be based on the feed support models shown in Fig. 2. Fig. 2(a) represents the structure for an on-axis antenna. If one leg is elongated from L to $L+\delta$, the apex is shifted laterally by $L\delta/d$, where L and d are defined in the figure, and $\delta << L$. If δ results from a 1 deg. C increase in temperature in one leg (assumed made of steel), then $\delta \sim$ (10**-5)L. The angular shift of the focal structure relative to the vertex is approximately (10**-5)L/d = 1 arcsec, which is just tolerable. Here we have used L=37 m and D=70 m. For the arm of the offset-feed antenna a simple model is provided by the uniform braced- girder structure in Fig. 2(b). If one side expands by an amount δ, the girder bends into a circular arc, and the lateral shift of the end is $L\delta/2d$. For a 1 deg. C change in temperature of one side, the angular shift of the end of the arm is (10**-5)L/2d = 6 arcsec for L=60 m and d=10 m. This is about six times worse than for the structure in Fig. 2(a), and four times the tolerable limit for the 100 m antenna. Thus I tentatively conclude that with the 100 m diameter we have exceeded the size for which we can use the offset-feed design and still take full advantage of the state-of-the-art surface accuracy. This applies to straightforward steel construction without special materials, servomechanisms, etc.

IV. Conclusion on the Antenna Design.

On the assumption that the principal requirement for the 100 m antenna is that it should operate satisfactorily to as high a frequency as possible, I conclude that it should incorporate an active surface, but not an offset feed configuration. The successful implementation of an active surface alone on a 100 m antenna would make it a unique forefront instrument. Thus we should go for a symmetrical, on-axis design, and the active surface and the pointing will provide as much scope for innovation as we can realistically handle.

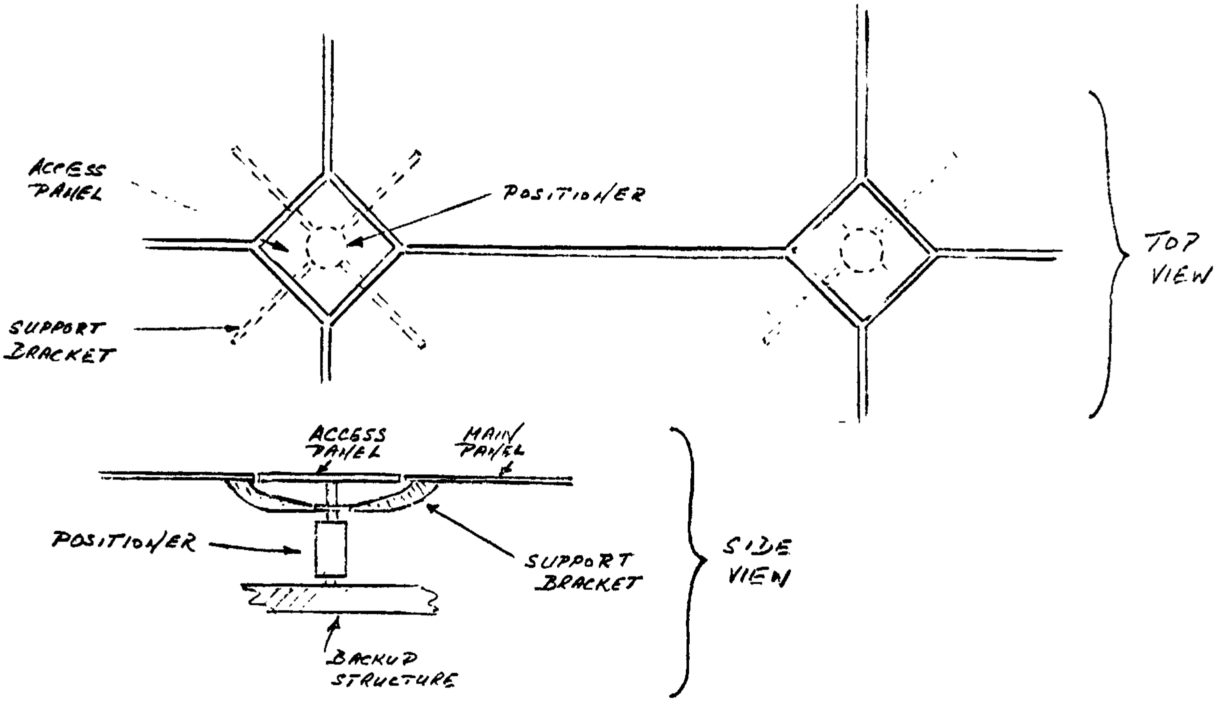

Fig. 1. A possible scheme to allow access to the positioners from the front side of the surface using removable access panels.

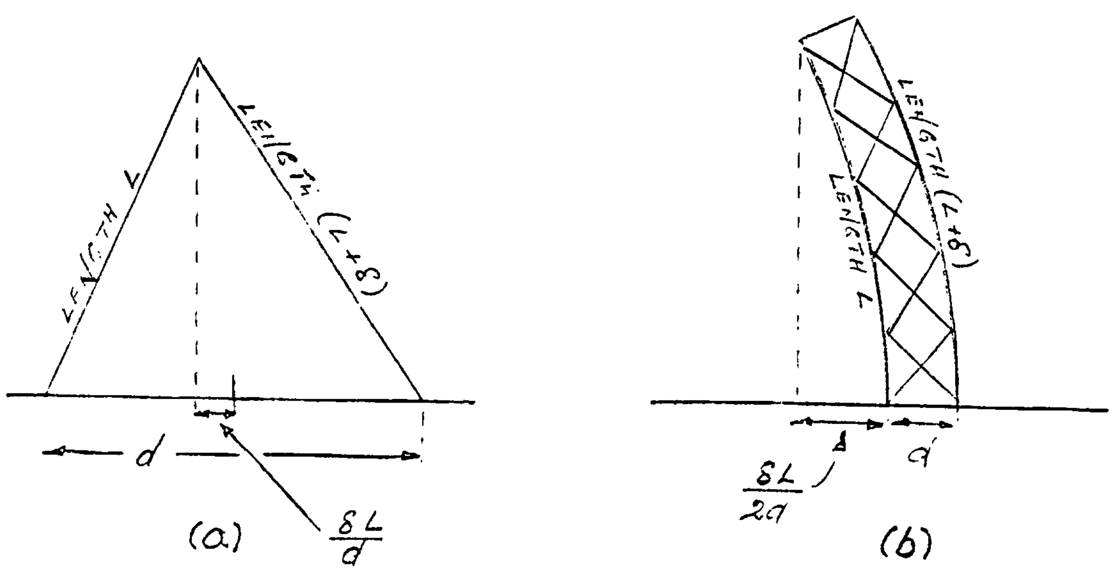

Fig. 2. (a) Lateral displacement of prime-focus support structure for an on-axis antenna resulting from expansion of one leg by an amount δ . (b) Lateral displacemant for an arm or girder of uniform stiffness resulting from a similar expansion of one side.