National Radio Astronomy Observatory
Socorro, New Mexico

VLA Test Memo No. 209

Development of Finite Element Model of VLA Antenna Structure

J. E. Thunborg
January, 1998

1.0 INTRODUCTION

As an antenna rotates in elevation, the changing gravity load causes the parabolic reflecting surface to deform. Deviations of the reflecting surface from perfect geometrical accuracy have a significant affect on the efficiency of the antenna system. The residuals from the best fit parabola are responsible for variations in the pathlengths of microwaves from the affected parts of the surface. The VLA telescopes structural members were proportioned so that the telescope would maintain a parabolic surface with varying focal length, at all angles of elevation. Small changes to the antenna structure can significantly affect the structures ability to maintain this parabolic surface.

The VLA has been in operation for many years. During this time many changes have been made to the antennas. Upgrades that required additional equipment in the vertex room and at the antenna apex have been incorporated. These upgrades have increased the weight so much that additional counterweight is now required to maintain proper balance at the elevation axle. It has also been proposed to upgrade the VLA and increase its usefulness as a scientific instrument. This upgrade will also include many structural changes that may affect the structural performance of the antenna. Because of the complexity of the structure, a computer model is needed to understand the effect of these structural modifications on antenna performance.

E-Systems used a finite element method program called SPACE (Structural Preprogrammed Analysis Capability for Engineers) to perform the original structural analysis of the VLA antennas. The original model was recorded on TPR tape and is not compatible with today's hardware or software. Since the original model can not be used, we were forced to develop a new Finite Element Model. This report documents the progress of the new NASTRAN model.

2.0 DESCRIPTION OF FEA MODEL

In order to create a finite element model, the entire antenna geometry and the structural properties of each beam and plate must be calculated and entered into a computer. Modern Finite Element Analysis (FEA) software can then divide the structure into a set of simultaneous linear equations that describe the behavior of every joint (node) in the structure. The computer then calculates displacements and stress for any given set of loads on the structure. The software used for the finite element analysis was MSC/NASTRAN for Windows. This section describes the element properties and choice of finite elements types used to model the structure.

The antenna foundations were not modeled and the antenna was assumed to be rigidly attached (0 degree of freedom) at its base. The lower pedestal room was also omitted, as its contribution to the structural stiffness is negligible. It is customary to take advantage of structural symmetry to reduce the model size and computational effort required for analysis. However, in this case the entire structure was modeled. This is because modern computers are sufficiently fast that the computational penalty due to the increased model size is not severe. The advantage of modeling both halves of the structure, is that it allows for easy detection of nonsymmetrical modeling errors. The finite element model is shown in Figure 2.1.

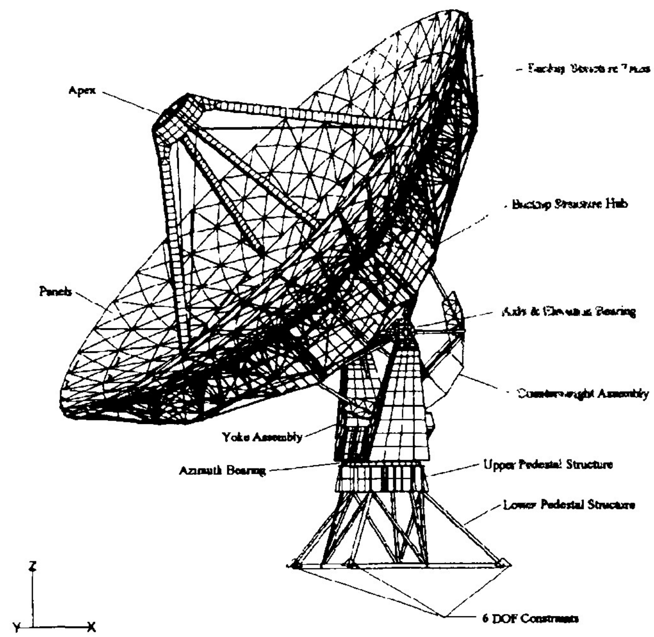

Figure 2.1, NASTRAN model of VLA antenna structure.

Beam elements (CBEAM of MSC/NASTRAN) capable of undertaking shear and moment in addition to tension and compression were used to model the lower pedestal structure. The upper pedestal structure was modeled with plate elements (CTRIA3 and CQUAD4 of MSC/NASTRAN). The use of plate elements as stiffeners may cause this part of the model to be excessively stiff. This is because a stiffener should resist load by bending action, which requires a cubic displacement function to model. Plate elements in membrane action are capable of representing only linear displacement (1). Excessive stiffness in this part of the structure has no impact on the dish deformation which is our primary concern. It will only slightly affect the normal modes analysis. Since plate elements are planar and do not have thickness, rigid elements (RBE2 elements of MSC/NASTRAN) were used to connect adjacent thick plates. This enabled the proper model geometry to be maintained.

The azimuth bearing rollers were simulated by using beam elements released in a direction tangent to the bearing circle. The yoke assembly was modeled using plate elements. Plate elements were also used as stiffeners inside the yoke to simulate the stiffening plates of the structure.

The axle was modeled using both beam and plate elements. Plate elements were used to model the axle stiffening plates at the transition between the axle and the backup structure hub. The plate elements that connect the axle to the backup structure hub are stiffened with offset beams. The axle is attached to the yoke assembly with rigid elements released in rotation about all axes to simulate spherical roller bearings. On one side of the axle the rigid element is released in the direction along the axle to simulate a floating bearing.

The tubes on the counterweight assembly were modeled with beam elements. Plate elements were used to model the lower structure where the counterweight is attached. The counterweights are simulated with large thick plate elements. The thickness of these plates was adjusted to simulate 15000 ft-lbs of counterweight heavy torque on the axle when the antenna points at the horizon.

The shear webs in the backup structure hub assembly were modeled with plate elements stiffened with offset beams. The backup structure truss assembly is modeled with beam elements. The stiffening plates that are welded at some of the joints on the truss were also modeled. However, the existence of these plates greatly increased the analysis processing time and had negligible affect on the results. Therefore, these plates were deleted. On the VLA antenna backup structure round tubes with smashed ends were used at some of the bolted connections. The smashed ends of these tubes were simulated with short, flat beam elements connected between the ends of the beam elements used to simulate the round tubes and the node at the bolted connection.

The VLA panels are attached in such a way that they do not stiffen the structure. Their weight, however, has a large influence on the deformation of the dish. VLA panels weighing approximately 2.5 lb./ft^2 were simulated with 4 inch thick plate elements with the appropriate density to yield the correct weight. In the current model, these panels are excessively stiff. This will be corrected in the future by developing a very detailed model of a VLA panel. This panel model will then be used to generate global panel material properties (modulus of elasticity, thermal conductivity etc.) that can be used in the full antenna model.

The quad legs are modeled as plates with offset beam elements at the corners to simulate the steel angle used in fabrication. The guy rods are modeled with a decreased modulus of elasticity to compensate for the sag in the thin rods. This method of decreasing the modulus of elasticity is presented by von Hoerner (2). Since the actual guy wire tension on the VLA telescopes is not well known, experimental data will be used to adjust the elastic modulus in the model.

A point mass was added at the apex to simulate the focus rotation mount and subreflector mass. Point masses were also used to simulate the receivers, electronic racks, ladders, walkways and other nonstructural equipment.

3.0 COMPARISON OF FEA MODEL WITH EXPERIMENTAL DATA

3.1 Reflector Surface Deformation Magnitude

The RMS surface error normal to the reflector surface was mapped using X-band holography for several antennas at 37, 50 and 77 degree elevation angles. The 50 degree data point was used as a reference to eliminate the panel setting and subreflector surface errors that may be included in the holography data. The corrected 37 and 77 degree data points were calculated by taking the square root of the difference of the squares with respect to the 50 degree data. These data are plotted in Figure 3.1. Curves representing the RMS error (normal to the reflector surface) calculated by the NASTRAN model are also shown in Figure 3.1. The lower curve assumes a ideally stiff backup structure. The other curve is from a more conservative analysis that assumes that the outer backup structure stiffness is reduced by 10% due to loose bolted connections and deviations from homology attributable to manufacturing tolerances and gravitation sag of long thin members. It is evident from Figure 3.1 that the RMS surface error is closely approximated by the more conservative analysis.

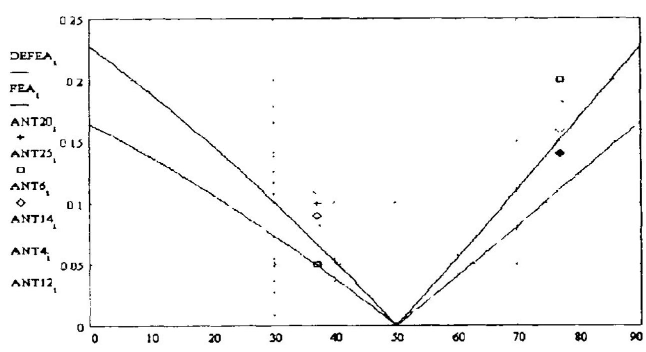

Figure 3.1, RMS error (normal to surface) minimized with respect to focal length change Vs elevation angle (50 degree rigging angle). RMS values are in mm units.

3.2 Reflector Surface Deformation Shape

The RMS surface error data illustrates that the magnitude of the surface error calculated by the NASTRAN model approximates the magnitude of the surface error measured experimentally. Holography was used to determine if the deflected shape of the reflector was accurately predicted by the NASTRAN model. The reflector shape at different elevation angles was measured using holography. The change in reflector shape due to a changing gravity vector was found by comparing the data to a reference elevation. Figure 3.2.1 shows the results from X- band holography at 80 degree elevation using 23 degree elevation as a reference. The Data presented is from a 16 antenna average.

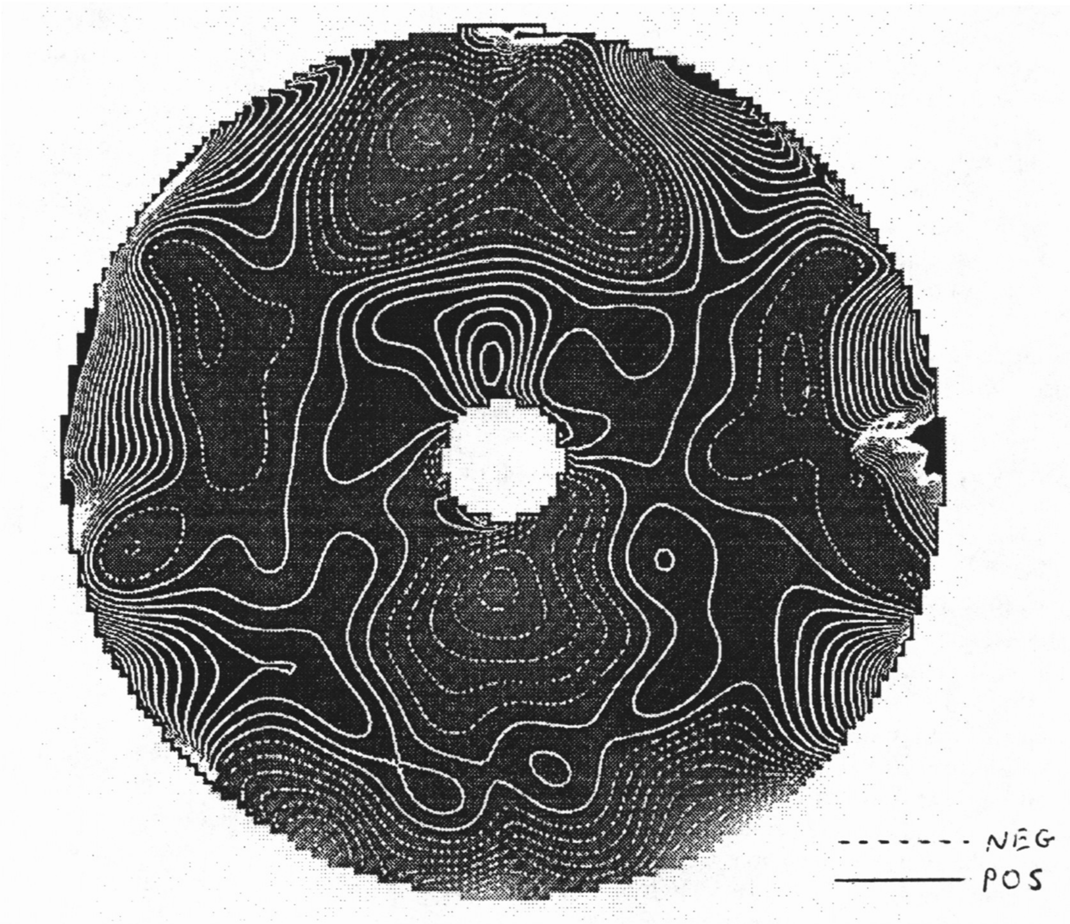

Figure 3.2.1, Surface change (normal to reflector) from gravity at 80 - 23 degrees. Results from 16 antenna average X-band holography. Horizontal and vertical resolution = 1.8 meters. Contour interval = 0.1 mm.

Gravity loads at 80 and 23 degree elevation were examined using the NASTRAN model. These deflections were entered into a best fit parabola program capable of surface error minimization with respect to focal length change and the resulting change in surface due to the changing gravity vector is shown in Figure 3.2.2 and Figure 3.2.3 for ideal and reduced stiffness outer backup structures, respectively. The contour lines in the NASTRAN model are calculated from the panel corners and center and are not continuous because of the separations between the reflector panels.

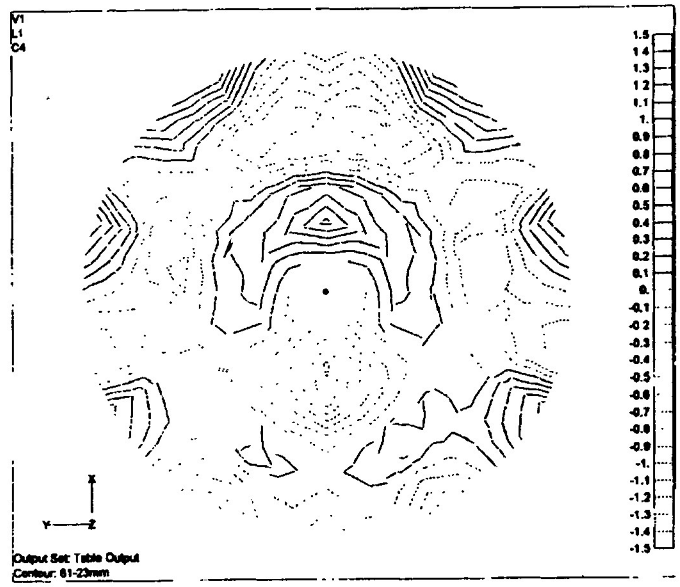

Figure 3.2.2, Surface change (normal to reflector) from gravity at 80 - 23 degrees. Results from NASTRAN analysis with ideal backup structure stiffness. Contour interval = 0.1 mm.

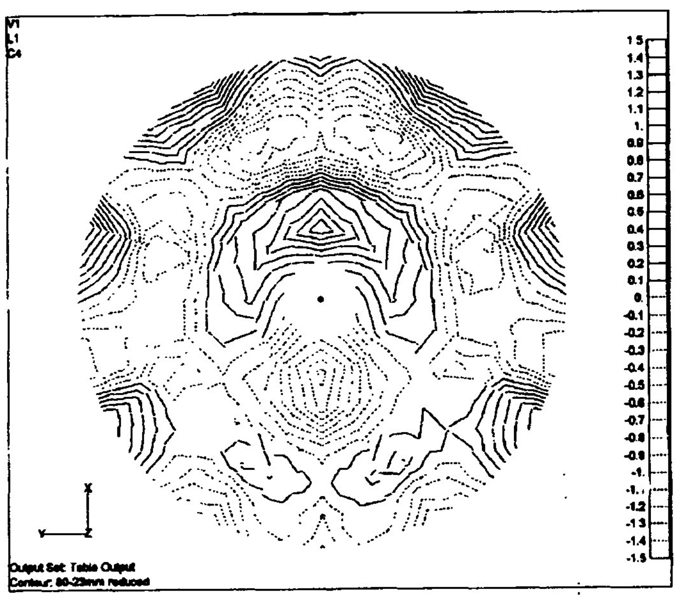

Figure 3.2.3, Surface change (normal to reflector) from gravity at 80 - 23 degrees. Results from NASTRAN analysis with 10% reduced backup structure stiffness. Contour interval = 0.1 mm.

The holography data proves that both NASTRAN models predict the reflector shape reasonably well. The NASTRAN model with the ideal stiffness backup structure does not exhibit as much deflection at the extreme edges of the reflector as was measured using holography. The NASTRAN model with the reduced stiffness backup structure has the same general shape but the magnitude of the deflections more closely approximates the holography data. The reduced stiffness at the outer edge of the backup structure may be the result of the long thin tubes that were used as truss elements in this part of the structure. The axial stiffness of a long thin member is decreased by gravitational sag.

3.3 Dynamic analysis.

Dynamic analysis provides information about the dynamic response of the structure under external perturbations. The dynamic properties of the antenna are important not only under wind loading, but also affect directly the pointing accuracy of the beam while tracking a radio source.

On the VLA antennas the normal modes are found by injecting a low amplitude sinusoidal signal into the rate loop in the antenna drive electronics. The frequency of the injected signal is then gradually increased from 0.1 to 8 Hz . The tachometer output from the drive motors is then monitored. As the antenna is driven through a resonant frequency, the servo system loses control and the tachometer output signal amplitude decreases. When this method is used on the VLA antennas, the first resonant modes are found from 2.1 - 2.4 Hz when excited in azimuth and 2.2 - 2.5 Hz when excited in elevation. The resonance at higher frequencies is not usually recorded. However, resonance data on telescope #1, recorded on 10/27/97, was analyzed and normal modes were found at 2.4, 4.0, 5.0 Hz when excited in azimuth and 2.33, 4.8 Hz when excited in elevation. This agrees reasonably well with the finite element model which calculated resonant frequencies at 2.1, 2.4 and 4.0 Hz. The antenna rocks back and forth horizontally, perpendicular to the axle in the first mode at 2.1 Hz. The antenna rocks parallel to the axle in the second mode at 2.4 Hz and rocks torsionally around the zenith in the third mode at 4.0 Hz.

3.4 400 lb. load test

One of the primary reasons for developing the NASTRAN model was to examine the effect of additional weight at the antenna apex on structural performance . The VLA upgrade design calls for the placement of additional receivers at the antenna apex. The finite element model predicted that the addition of 400 pounds at the apex would have negligible affect on the reflector shape. These results were verified using holography. The shape of an antenna dish was accurately mapped for several elevation angles using holography. A 400 pound dead weight was then installed at the apex of the antenna and the holography was repeated. The change in reflector shape due to the additional weight was less than the 50 microns required to be visible in holography. Pointing tests with the 400 lb weight showed that there was no affect on the antenna pointing parameters including the quadrupod sag term, proving the quadrupod did not sag excessively under the additional weight.

4.0 COMPARISON OF FEA MODEL WITH SPACE MODEL

The result of the original surface error analysis of the VLA antenna structure is documented in E-Systems report number 416-15365, "Analysis of 25 Meter Reflector, Yoke and Pedestal". The deflections of the main reflector derived from the SPACE Structural Analysis Computer Program were entered into a Best Fit Parabola program that assumed a fixed focal length of 354.0 inches. The residuals from the best fit parabola are responsible for variations in the pathlengths of microwaves from the affected parts of the surface. The RMS of these residuals were calculated and normalized to a 50 degree rigging angle. Figure 4.1 shows the original SPACE data as well as the equivalent data from the reduced stiffness and ideal stiffness NASTRAN analysis.

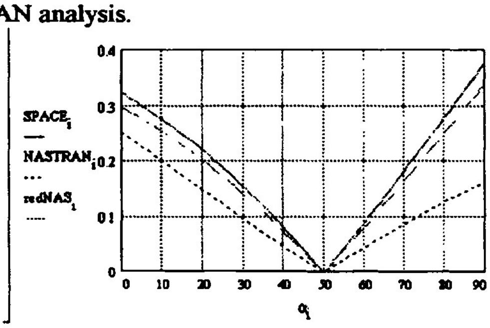

Figure 4.1, RMS half pathlength error minimized with respect to rigid body motion Vs elevation angle. (50 degree rigging angle).

The reduced stiffness NASTRAN analysis closely matches the original. This is because of simplifications in the original SPACE model. The software was very primitive by today's standards and several simplifications had to be implemented in order to accomplish the analysis . Most of these simplifications reduced the stiffness in the outer backup structure. The primary simplification was that the space model ignored bending moments in the backup structure truss. The truss elements used to model the backup structure were assumed to be capable of transmitting only axial loads and welded connections in the backup structure were modeled as pin connections that also could not transmit bending moments.

5.0 CONCLUSION

Figure 5.1 shows the RMS half pathlength error minimized with respect to focal length change for the ideal stiffness and the reduced stiffness NASTRAN models. The ideal stiffness model (the lower curve) assumes a ideally stiff backup structure. The other curve is from a more conservative analysis that assumes that the outer backup structure stiffness is reduced by 10% due to loose bolted connections and deviations from homology attributable to manufacturing tolerances and gravitational sag. The reduced stiffness NASTRAN model closely approximates the structure as verified by the experimental data. This model should be more than adequate for evaluating the effect of structural modifications on antenna performance.

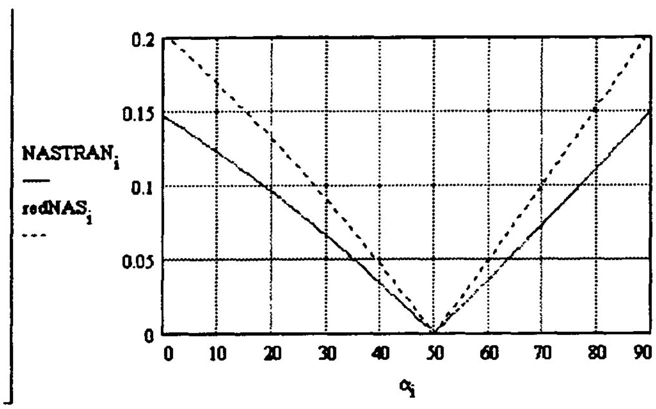

Figure 5.1, RMS half pathlength error minimized with respect to focal length change Vs elevation angle. (50 degree rigging angle).

Although the NASTRAN model currently approximates the structure quite well, the accuracy of the model will improve as the model is refined. Several refinements can be done which will increase the accuracy of the model. The first of which is to refine the reflector panel properties so that they more accurately match the actual structure. It is also evident from the holography data, that the stiffness should be reduced only at the extreme edges of the backup structure. This part of the backup structure consist of long thin tubes, that may sag excessively under gravity. The model will be refined to show these changes in the near future. Then it will be used to evaluate antenna performance with the different quad leg and subreflector configurations required for the VLA upgrade.

1) MSC/NASTRAN for Windows, Version 2.1 Update, Volume II, 1996.

2) von Hoerner, S., "Elasticity of long ropes", LFST report, National Radio Astronomy Observatory, May 1966.