National Radio Astronomy Observatory
Socorro, New Mexico

VLA Test Memo No. 207

Investigation of Antenna Hard Stops and Additional Counterweight

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1.0 INTRODUCTION

The elevation brake and drive system on antenna #15 was disabled by a series of errors and equipment failures in December 1996. The reflector assembly was thus uncontrolled in elevation and slowly fell from its stow position to a point where it contacted the antenna yoke structure. Fortunately, friction in the elevation gearbox restrained the speed of the fall so that no damage occurred. However, this fall could have been catastrophic if the antenna fell toward the "Up" side, where it is possible for the antenna to drive off the end of the gear sector and become totally unrestrained in elevation. Catastrophic damage also could have occurred, if the overturning moment on the reflector was sufficient to overcome the gearbox friction to the extent where the reflector fell with excessive velocity. In this case, the inertia loads resulting from the sudden stop when the reflector interfered with the yoke arm could cause damage to the structure as well as other antenna systems.

This test memo estimates the velocities and forces involved with this type of failure and researches structural improvements that will reduce the possibility of damage to the telescopes in the event of similar failures.

2.0 COUNTERWEIGHT IMBALANCE

The VLA telescopes were designed to be counterweight heavy by 55,000 ft-lbs measured at the elevation axle allowing them to seek stow position using gravity in the event of a brake/drive failure. The counterweight imbalance of the antennas (measured by T. Frost) listed in Table 1 clearly shows that all of the antennas are lacking sufficient counterweight. Antenna #15 is almost 15000 ft-lbs dish heavy. The incident listed above would not have occurred if antenna #15 had the specified counterweight imbalance.

Table 1, Antenna Counterweight Imbalance

Antenna #	Imbalance (ft-lbs)
6	2955
7	-433*
10	1757
11	-16554*
13	-6500*
15	-15759*
20	-14183*
26	-2512*
Average	**-6400***

* Negative number means dish heavy

The most convenient location to add additional counterweight is on top of the existing counterweight which gives us a moment arm of approximately 8.5 feet. Thus, an additional 7200 lbs of counterweight per antenna is needed to meet the original 55000 ft-lb counterweight heavy specification.

2.1 Counterweight Effect on Antenna Performance

Finite Element Analysis on an antenna model at 45 degree elevation showed that adding an additional 82000 ft-lbs. of counterweight had negligible effect on the structural performance of the antenna. The change in the dish surface due to the additional counterweight was less than 17 µm. The change in the RMS half path length error was negligible. The normal modes were also unaffected by the additional counterweight.

2.2 Counterweight Costs

7200 lbs of steel per antenna at $0.25/lb is required to bring the counterweight up to the original 55000 ft-lb counterweight heavy specification. This will cost approximately $50,000 for 28 antennas. It has been suggested that we use surplus 85 lb/yard rail as counterweight. This would require approximately 250 ft of rail per antenna. The use of rail as counterweight may be aesthetically displeasing. Another alternative would be to find a large quantity of steel plate on the government surplus lists. However, the shipping cost for 100 tons of steel will not be insignificant.

It is possible to decrease the amount of steel required by removing weight at the apex. A 100 lb weight savings at the apex yields a 550 lb savings at the counterweight. We can also relax our requirement on the amount of imbalance required. We could bring the antennas to a 20,000 ft-lbs counterweight heavy imbalance with a steel cost of approximately $20,000 dollars.

3.0 HARD STOPS

Counterweight imbalance does not guarantee that the antenna will not travel past its limits in the case of a drive/brake failure. Viscous friction within the gearbox limits the reflector speed as long as it is coupled to the reflector through the gear sector. When the antenna travels past the upper limits, it can drive off the gear sector and be completely unrestrained in elevation. If the antenna is dish heavy, it will fall freely until it contacts the yoke structure. The inertia loads resulting from the sudden stop when the reflector interferes with the yoke arm could cause catastrophic damage to the structure as well as other antenna systems. If a counterweight heavy antenna is driven off the gear sector, damage can still occur as the antenna is buffeted in the wind. Therefore, mechanical hard stops will be installed on the antennas during overhauls after January 1998.

A mechanical hard stop is not required on the down side because the reflector contacts the yoke structure before it drives past the gear sector. The "up" side hard stop consist of two 1.5" thick steel blocks welded to the stow pin housing that contact two 1.5" thick steel blocks welded to the elevation gear sector as shown in Appendix A. Stress analysis (Appendix A) shows that hard stops are required on both sides of the gear sector to withstand the force from the drive motors. This ensures that the reflector can not be accidentally driven off the gear sector in the case of a limit switch failure.

3.1 Hard Stop Inertial Loads

When the antenna contacts the hard stops it is subjected to severe inertia loads. It is not known how fast an antenna can hit a hard stop without causing damage. There have been occasions where the brakes have been engaged while the antenna was slewing at 20 degrees/min (0.33 degrees/sec) without causing damage. This is probably close to an upper limit on the rate that we can crash without damage.

At the 0.33 degree/second maximum crash rate described above, the gearbox frictional torque is 85,000 ft-lbs. Therefore, the maximum crash rate would be achieved if the antenna was 85,000 ft-lbs dish heavy. Wind, ice and snow can also cause the antenna to exceed the maximum crash rate. If the antenna is in a worst case orientation, the maximum crash rate corresponds to a wind speed of 24 mph for a balanced antenna. The charts on the following page show the crash speed in degreees/sec versus the wind velocity in mph for a balanced, 20,000 ft-lb counterweight heavy and a 55,000 ft-lb counterweight heavy antenna.

3.2 Hard Stop Costs

The cost of the steel for the hard stops is approximately $20 per antenna.

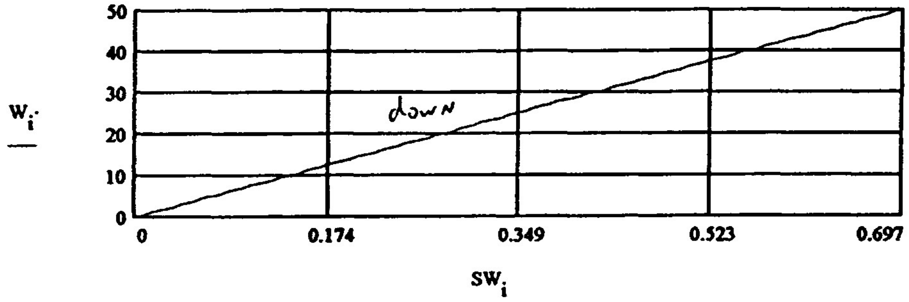
Hydraulic shock absorbers could be used to increase the maximum crash rate. Four shock absorbers would be required at a cost of $1700 each. The total cost for the array would be $190,000. Since the probability of a crash with a high crash rate is low, it is hard to justify the additional expense of shock absorbers.

4.0 RECOMENDATIONS

The cost of installing the mechanical hard stops without the shock absorbers is negligible. Installation of these stops should begin as soon as possible.

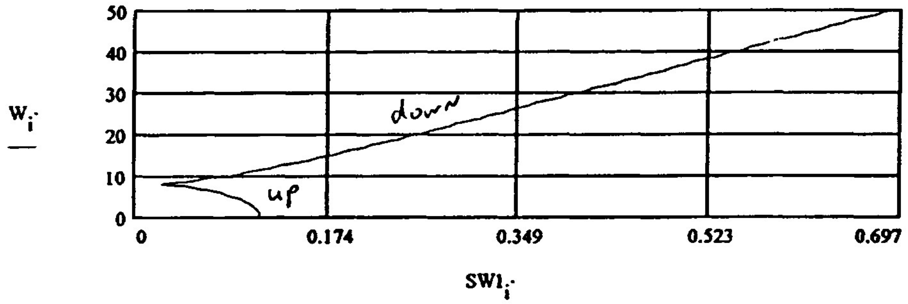
We should add enough counterweight to the antennas to ensure that they are counterweight heavy. However, the 55,000 ft-lb requirement is probably not necessary. 20,000 ft-lbs should ensure reasonable safety.

Antenna Backdrive Speed VS. Wind Speed
120 Degree Elevation
Worst Case Wind Direction



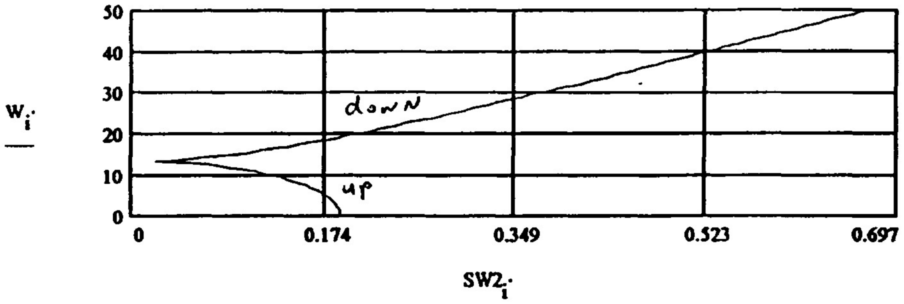
Balanced Antenna

Wind Speed (mph) vs Elevation Axle Free-Wheel Speed (deg/sec)



20,000 ft-lbs CW heavy

Wind Speed (mph) vs Elevation Axle Free-Wheel Speed (deg/sec)



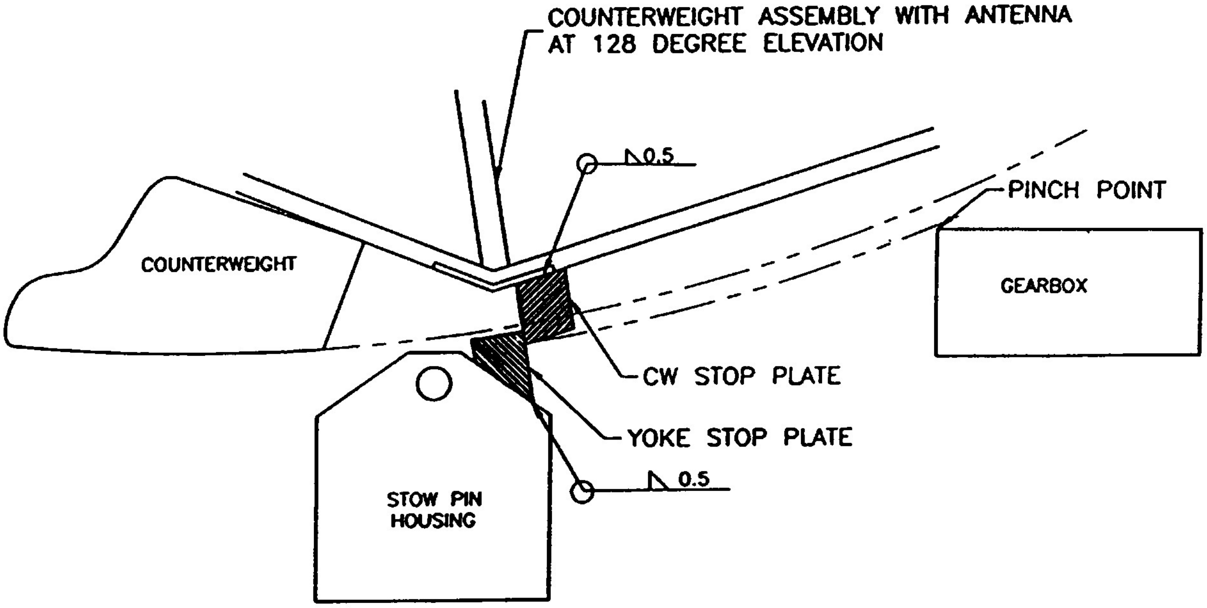
55,000 ft-lbs CW heavy

Wind Speed (mph) vs Elevation Axle Free-Wheel Speed (deg/sec)

APPENDIX A

STRESS ANALYSIS

ANTENNA HARD STOP INSTALLATION



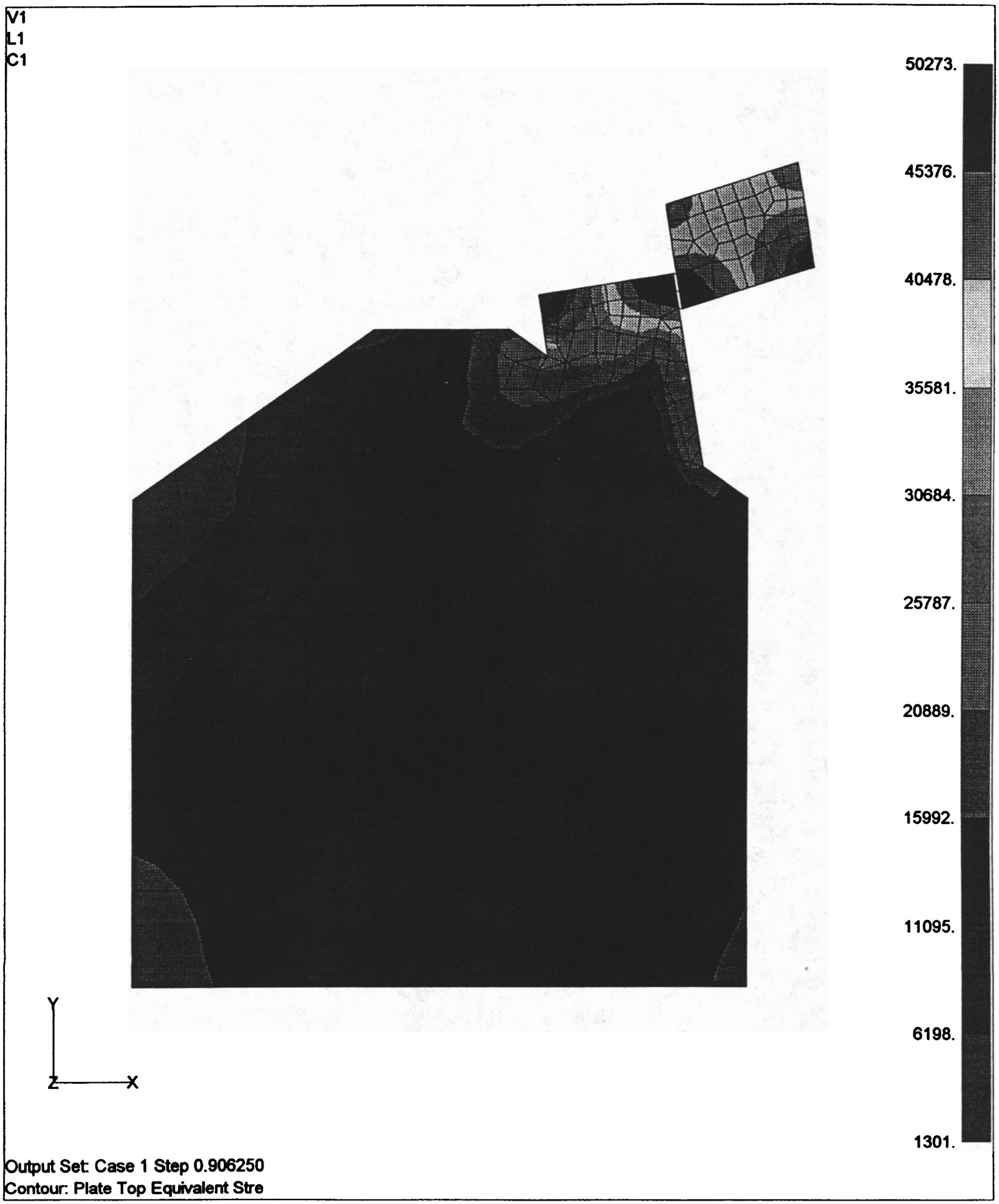
NOTES:

A) PAINT WHITE AFTER INSTALLATION WITH BLACK/YELLOW STIPES ON CW STOP PLATE AND AT PINCH POINT ON GEARBOX. STENCIL AND PAINT "PINCH POINT" ON TOP OF GEARBOX

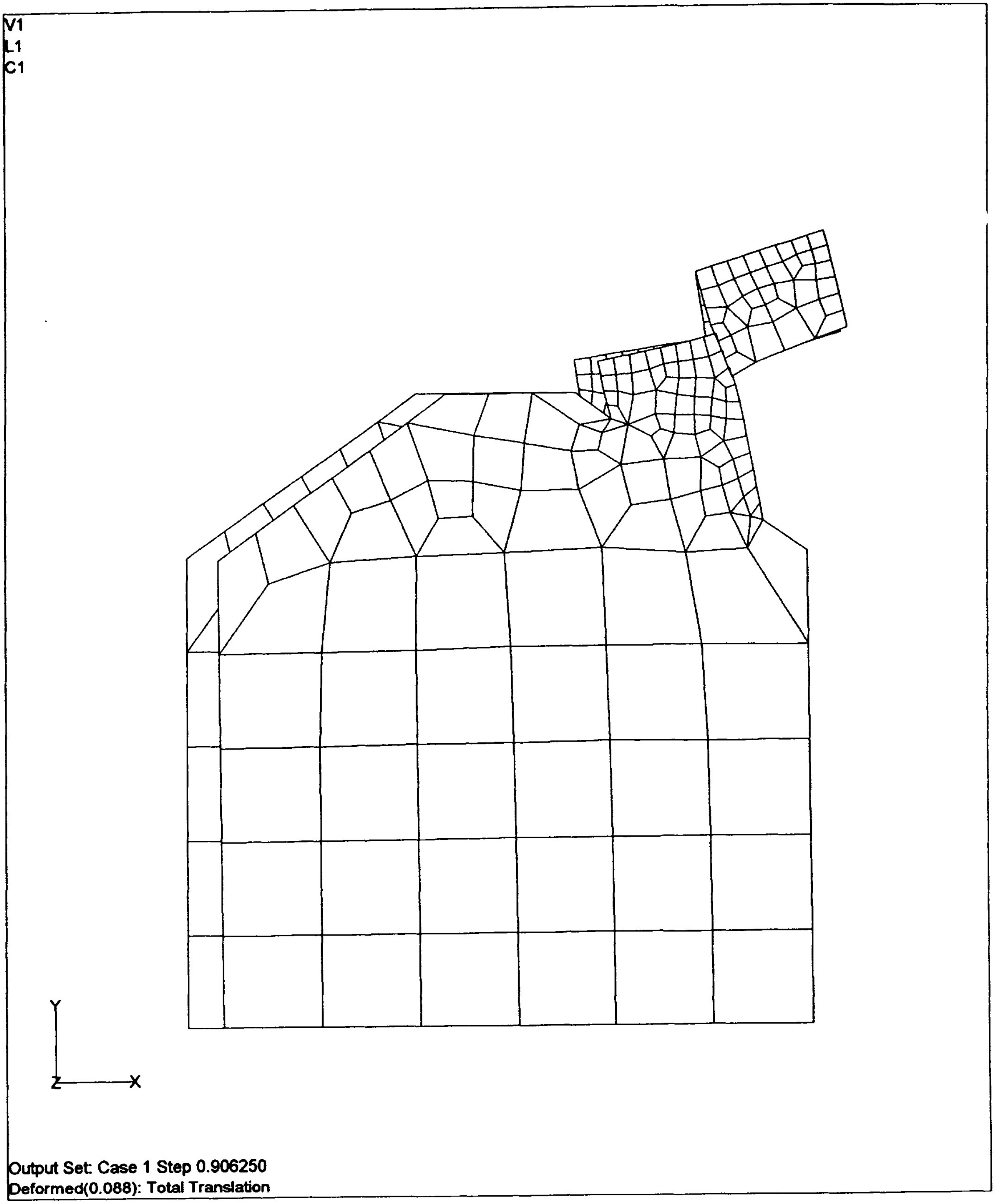
B) RUN ANTENNA TO BOTH LIMITS TO ENSURE PROPER CLEARANCE. (FIELD FIT AS REQUIRED)

C) GRIND SHALLOW CONCAVE SURFACE ON YOKE STOP PLATE AND CORRESPONDING CONVEX SURFACE ON CW PLATE AT INTERFACE.

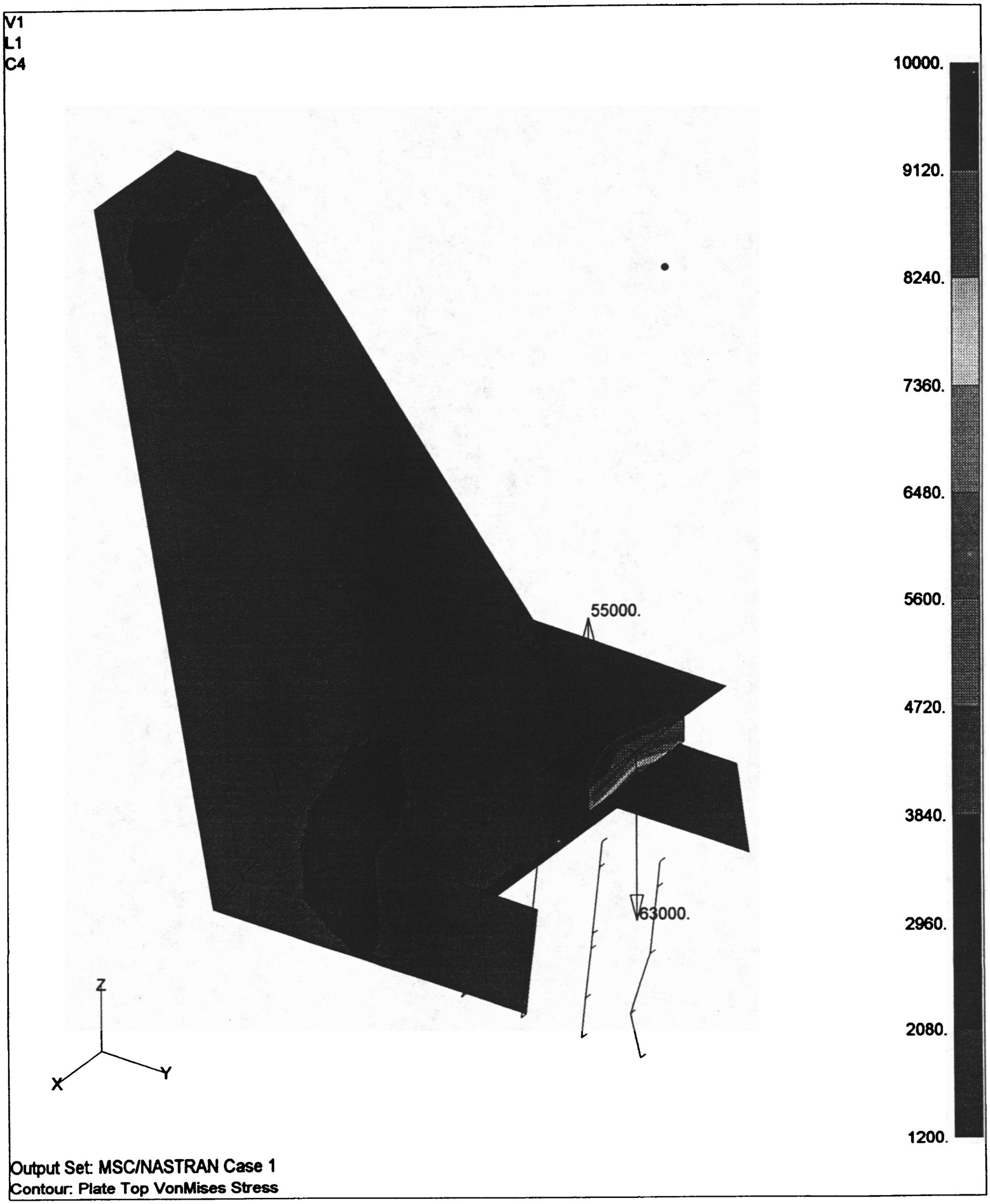
D) A REPRESENTATIVE FROM THE SERVO GROUP MUST BE PRESENT WHILE THE ANTENNA IS ROTATED PAST THE SECOND LIMIT.



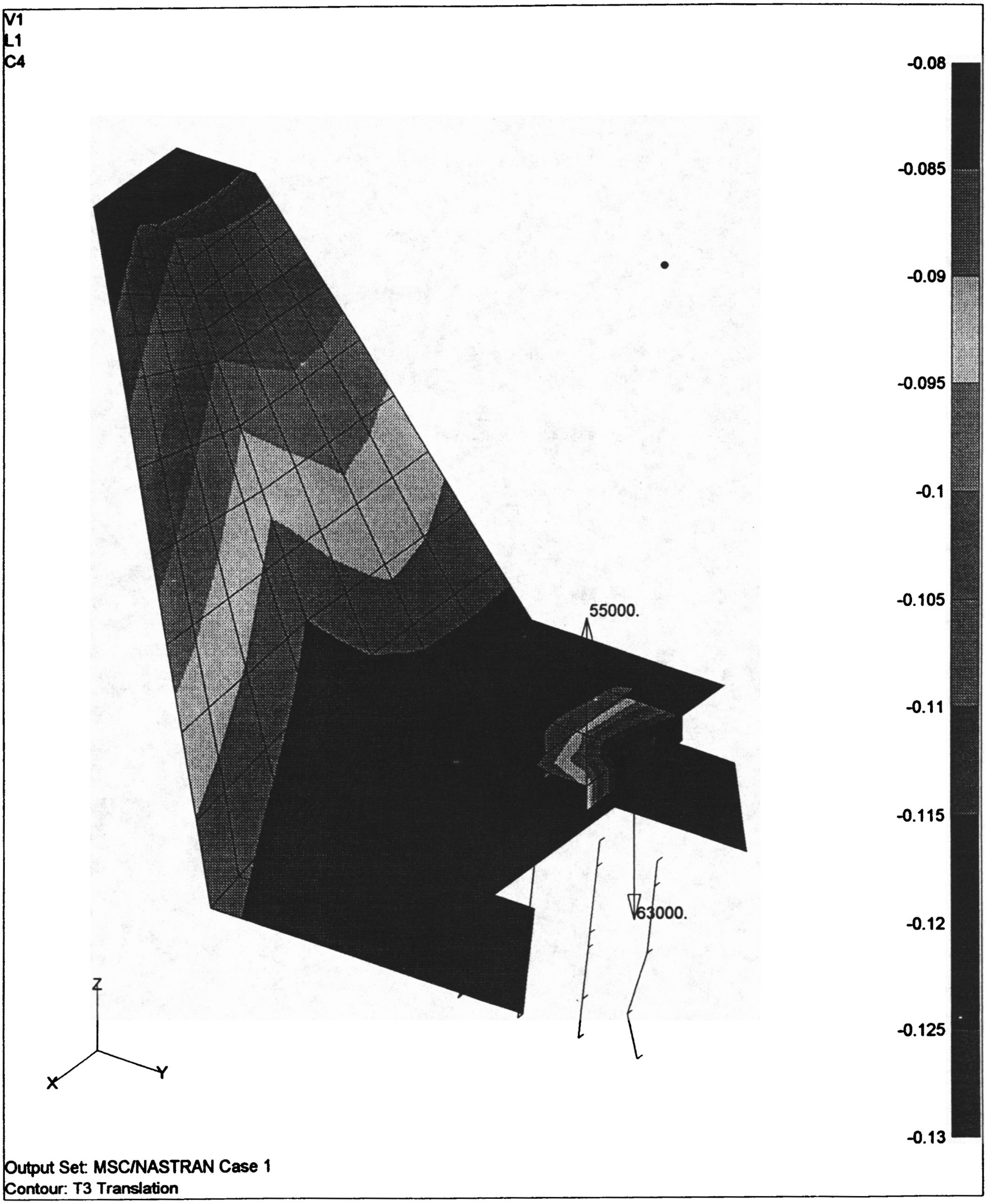
Single Hard Stop Stress - 90% Load



Single Hard Stop Deformation - 90% max load



Single Hard Stop Yoke Stress



Single Hard Stop Yoke deflection

VLA Antenna Hard Stop Analysis
Gearbox Back Drive Speed

$\mathrm{Dist} := 139\cdot \mathrm{in}$ Distance from axle to hard stop

$\mathrm{Gr} := 20700$ Elevation Axis Gear Ratio

$\mathrm{imax} := 100$ Number of plot points

$\alpha := 120\cdot \mathrm{deg}$ Antenna Elevation Angle

$\mathrm{Wmax} := 50.0\cdot\frac{\mathrm{mile}}{\mathrm{hour}}$ Maximum Wind Speed

$\mathrm{WTC} := \frac{149\cdot \mathrm{ft}\cdot \mathrm{lbf}}{\left(\frac{\mathrm{mile}}{\mathrm{hour}}\right)^2}$ Wind Torque Constant

$\mathrm{CW1} := 20000\cdot \mathrm{ft}\cdot \mathrm{lbf}$
$\mathrm{CW2} := 55000\cdot \mathrm{ft}\cdot \mathrm{lbf}$ Counterweight imbalance

$\mathrm{Nc} := 1150\cdot\frac{\mathrm{rev}}{\mathrm{min}}$ E-Systems speed

$\mathrm{Vf} := .45\cdot \mathrm{hp}$ Viscous Friction at 1150 RPM (E-Systems Advanced Stress Report)

$i := 0 .. \mathrm{imax}$ $\quad W_i := \mathrm{Wmax}\cdot\frac{i}{\mathrm{imax}}$

$\mathrm{Tm} := \frac{5\cdot \mathrm{hp}\cdot 1.5}{1300\cdot\frac{\mathrm{rev}}{\mathrm{min}}}$ $\quad \mathrm{Tm} = 30.301\cdot \mathrm{lbf}\cdot \mathrm{ft}$ Maximum drive motor torque 150%

$\mathrm{Tdrive} := 2\cdot \mathrm{Tm}\cdot \mathrm{Gr}$ $\quad \mathrm{Tdrive} = 1254447.019\cdot \mathrm{lbf}\cdot \mathrm{ft}$ Maximum torque at axle from drive motors

$\mathrm{Tforce} := \frac{\mathrm{Tdrive}}{\mathrm{Dist}}$ $\quad \mathrm{Tforce} = 108297.584\cdot \mathrm{lbf}$ Force on hardstop from drive motors

$\mathrm{Smax} := \frac{\mathrm{Nc}}{\mathrm{Gr}}$ $\quad \mathrm{Smax} = 0.333\cdot\frac{\mathrm{deg}}{\mathrm{sec}}$ Elevation speed with motor at 1150 rpm

$\mathrm{Tm} := \frac{\mathrm{Vf}}{\mathrm{Nc}}$ $\quad \mathrm{Tm} = 2.055\cdot \mathrm{ft}\cdot \mathrm{lbf}$ Frictional Torque per motor at 1150 rpm

$\mathrm{Te} := \mathrm{Tm}\cdot \mathrm{Gr}\cdot 2$ $\quad \mathrm{Te} = 85084.233\cdot \mathrm{ft}\cdot \mathrm{lbf}$ Total Gearbox Frictional torque at 1150 rpm

$\mathrm{TW}_i := \mathrm{WTC}\cdot\left(W_i\right)^2$ $\quad \mathrm{TW}_{\mathrm{imax}} = 372500\cdot \mathrm{ft}\cdot \mathrm{lbf}$ Torque from wind (worst case @ Wmax)

$\mathrm{TWforce} := \frac{\mathrm{TW}_{\mathrm{imax}}}{\mathrm{Dist}}$ $\quad \mathrm{TWforce} = 32158.273\cdot \mathrm{lbf}$ Force on hardstop from wind at Wmax

$\mathrm{NW}_i = \mathrm{Nc}\cdot\sqrt{\frac{\mathrm{TW}_i}{\mathrm{Te}}}$ $\quad \mathrm{NW}_{\mathrm{imax}} = 2406.226\cdot\frac{\mathrm{rev}}{\mathrm{min}}$ Motor backdrive speed for balanced antenna

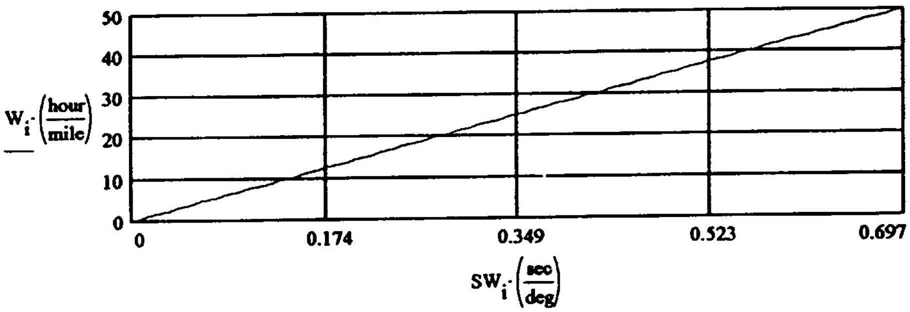
$\mathrm{SW}_i := \frac{\mathrm{Nc}}{\mathrm{Gr}}\cdot\sqrt{\frac{\mathrm{TW}_i}{\mathrm{Te}}}$ $\quad \mathrm{SW}_{\mathrm{imax}} = 0.697\cdot\frac{\mathrm{deg}}{\mathrm{sec}}$ Elevation speed for balanced antenna

$\mathrm{SW1}_i := \frac{\mathrm{Nc}}{\mathrm{Gr}}\cdot\sqrt{\frac{\left|\mathrm{TW}_i - \mathrm{CW1}\cdot\sin(\alpha - 90\cdot \mathrm{deg})\right|}{\mathrm{Te}}}$ $\quad \mathrm{SW1}_{\mathrm{imax}} = 0.688\cdot\frac{\mathrm{deg}}{\mathrm{sec}}$ Elevation speed with CW1 counterweight

$\mathrm{SW2}_i := \frac{\mathrm{Nc}}{\mathrm{Gr}}\cdot\sqrt{\frac{\left|\mathrm{TW}_i - \mathrm{CW2}\cdot\sin(\alpha - 90\cdot \mathrm{deg})\right|}{\mathrm{Te}}}$ $\quad \mathrm{SW2}_{\mathrm{imax}} = 0.671\cdot\frac{\mathrm{deg}}{\mathrm{sec}}$ Elevation speed with CW2 counterweight

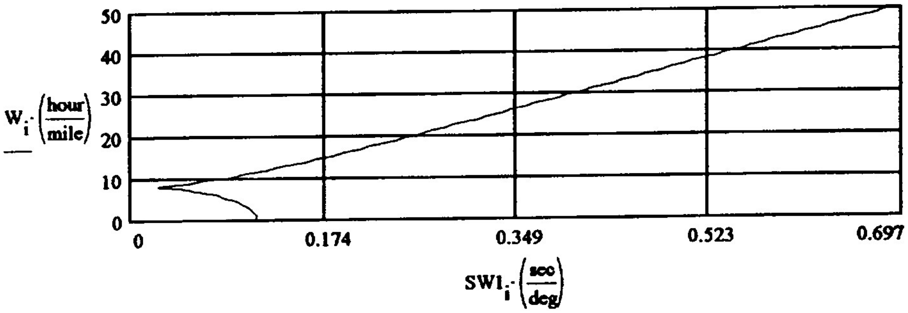
Antenna Backdrive Speed VS. Wind Speed
120 Degree Elevation
Worst Case Wind Direction

Balanced Antenna



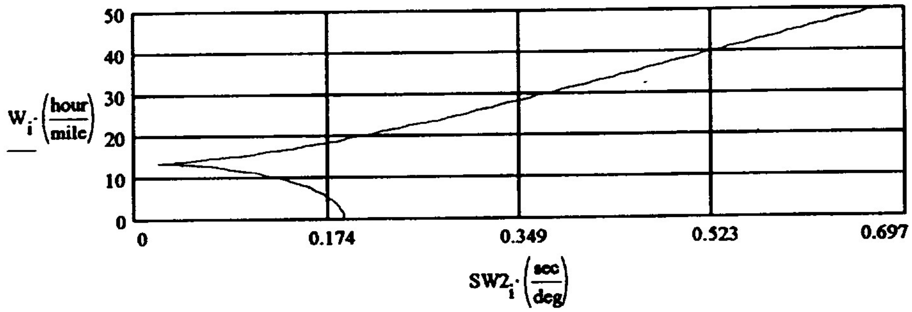
Wind Speed (mph) vs Elevation Axle Free-Wheel Speed (deg/sec)

20,000 ft-lbs CW heavy



Wind Speed (mph) vs Elevation Axle Free-Wheel Speed (deg/sec)

55,000 ft-lbs CW heavy



Wind Speed (mph) vs Elevation Axle Free-Wheel Speed (deg/sec)

ANTENNA CHARACTERISTICS

Elevation Axis Wind Torque Constant - 149 $\frac{\text{ft. lbs.}}{\text{mph}^2}$ Note 1

Azimuth Axis wind torque constant - 172 $\frac{\text{ft. lbs.}}{\text{mph}^2}$ Note 1

Elevation Axis Friction Torque - 42,000 ft-lbs. max Note 2

Elevation Axis Total Loss at Full Speed - 47,000 ft-lbs. max Note 3

Azimuth Axis Friction Torque - 41,000 ft-lbs. max. Note 2

Azimuth Axis Total Loss at Full Speed - 43,000 ft.-lbs max Note 3

Elevation Axis Deadweight Unbalance - 55,000 ft-lbs. Note 3

Elevation Axis Structure and Gearbox Inertia - 4.0×10^6 slug ft^2

Azimuth Axis Structure and Gearbox Inertia- 2.3×10^6 slug ft.^{2}

Minimum AZ Locked Rotor Resonant Frequency 2.15 Hz

Minimum Elevation Locked Rotor Resonant Frequency - 2.2 Hz

Azimuth Drive Gear Ratio	10350:1		
Elevation Drive Gear Ratio	20700:1		
Each Elevation Axis Gear-Train Spring rate	3.9×10^9	$\frac{\text{ft.lbs}}{\text{radian}}$	min.
Each Azimuth Axis Gear-Train Spring Rate	4.4×10^8	$\frac{\text{ft.lbs}}{\text{radian}}$	min.

NOTE 1: Axis Torque = (wind torque constant) (Speed in MPH)^2

NOTE 2: Including geartrain & motor friction at antenna velocity of 0.002 $\frac{\text{deg}}{\text{sec}}$

NOTE 3: Normal, in up direction at 5 degrees elevation angle.

PREPARED BY W.B. SHEARD	**E-SYSTEMS INC.** Garland Division P O Box 6118 • Dallas, Texas 75222 • Telephone (214) 276-7111	PAGE NO. I
CHECKED BY		REPORT NO. 216-15364
DATE 2-8-74		MODEL NO.

ADVANCED STRESS REPORT

1. WIND AND DEAD LOADS
   FOR AZIMUTH BEARING
   AND GEARTRAINS

2. GEARTRAIN ANALYSIS

3. AZIMUTH BEARING ANALYSIS

FOR

VLA ANTENNA

NRAO

REPORT NO. 416-15364

8 FEBRUARY 1974

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DATE 1-5-74		MODEL NO.

GEARBOX VISCOUS FRICTION

ELEVATION

SUBMERGE GEARS

ESTIMATED VISCIOUS FRICTION AT 1150 RPM RATED SPEED = 0.45 HP. (WESTERN GEAR)
12 - -73

$$T_M = \frac{HP \times 5252}{N}$$

$$= \frac{0.45 \times 5252}{1150} = 2.055 \text{ FT-LBS}$$

AT MOTOR (EACH)

TORQUE AT ELEVATION AXIS (20°/SEC)

$$T_E = T_M \times 20{,}700$$

$$= 2.055 \times 20{,}700 = 42{,}541 \text{ FT-LBS}$$

EACH GEARBOX

$$T_E = KN^2$$

$$\frac{T_2}{T_1} = \frac{KN_2^2}{KN_1^2} = \frac{N_2^2}{N_1^2} = \left(\frac{N_2}{N_1}\right)^2$$

ELEVATION SPEED = 10°/SEC

$$T_{10°/sec} = T_1\left(\frac{N_2}{N_1}\right)^2 = 42{,}540\left(\frac{575}{1150}\right)^2 = 10{,}635$$

FT-LBS
EACH GEARBOX

MAX. ELEV. TRACKING SPEED
N_{MOTOR} = 14.36 RPM

TRACKING VISCOUS FRICTION TORQUE

$$T_{TR} = 42{,}540 \times \left(\frac{14.36}{1150}\right)^2 \times 2$$

$$= 13 \text{ FT-LBS}$$