SECTION 4.0

NATIONAL RADIO ASTRONOMY OBSERVATORY
POST OFFICE BOX 2
GREEN BANK, WEST VIRGINIA 24944
TELEPHONE ARBOVALE 456-2011

PROJECT: 300 FT. DIA. HOMOLOGY TELESCOPE

SUBJECT: GEAR TRAINS

4.0 GEAR TRAINS

PREPARED BY O. R. Heine APPROVED BY ________ SUBMITTED BY S.D.L.

OPERATED BY ASSOCIATED UNIVERSITIES, INC., UNDER CONTRACT WITH THE NATIONAL SCIENCE FOUNDATION

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4.1 DRIVE REQUIREMENTS

4.1.1 POWER REQUIREMENTS :

a) ACCELERATION TORQUE :

ASSUME MAX. TRACKING ACCELERATION TO BE : $.01\ ^\circ/\text{SEC}^2$

THEN $\epsilon = \frac{.01}{57.3} = 1.75 \times 10^{-4}$ RAD/SEC²

INERTIA @ ELEVATION : 3.2×10^{8} SLUG-FT² *

INERTIA @ AZIMUTH : 3.0×10^{9} SLUG-FT² *

THUS : $M_{tA\,ELEV.} = 3.2 \times 1.75 \times 10^{-4} \times 10^{8} = 5.6 \times 10^{4}$ FT-LBS

$M_{tA\,AZ.} = 3.0 \times 1.75 \times 10^{-4} \times 10^{9} = 52.5 \times 10^{4}$ FT-LBS

b) FRICTION TORQUE @ AZ-PLANE

$F = \frac{KL}{r}$; $M_{tF} = FR$

$M_{tF} = \frac{KL}{r} R$

F = FRICTIONAL RESISTANCE
K = FRICTION COEFF.
L = LOAD
r = WHEEL RADIUS
R = TRACK RADIUS

* FROM DATA SUPPLIED BY S.V. HOERNER

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ASSUME : $K = .01$
$L = 2{,}500$ TONS (5×10^6 LBS)
$r = 19$ IN
$R = 173.25$ FT

$$M_{tF_{AZ}} = \frac{.01 \times 5 \times 10^6}{19} \, 173.25 = \underline{45.6 \times 10^4 \text{ FT-LBS}}$$

c) WIND TORQUE :

AT TRACKING CONDITION , $M_{W18} = \underline{2.81 \times 10^6 \text{ FT-LBS}}$
AT DRIVE TO STOW " , $M_{W45} = \underline{17.50 \times 10^6 \text{ FT-LBS}}$
AT SURVIVAL " , $M_W = \underline{81.50 \times 10^6 \text{ FT-LBS}}$

SUMMARY OF TORQUES

1.) ELEVATION :
TRACKING (@ 18 MPH) : $5.6 \times 10^4 + 2.81 \times 10^6 = \underline{\underline{2.87 \times 10^6 \text{ FT-LBS}}}$
DRIVE TO STOW (@ 45 MPH) : $5.6 \times 10^4 + 17.50 \times 10^6 = \underline{\underline{17.56 \times 10^6 \text{ FT-LBS}}}$

2) AZIMUTH :
TRACKING (@ 18 MPH) : $(.52 + .46 + 2.81)\, 10^6 = \underline{\underline{3.79 \times 10^6 \text{ FT-LBS}}}$
DRIVE TO STOW (@ 45 MPH) : $(.52 + .46 + 17.5)\, 10^6 = \underline{\underline{18.48 \times 10^6 \text{ FT-LBS}}}$

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HP-OUTPUT REQUIREMENTS :

a) TRACKING AT 10 TIMES SIDEREAL VELOCITY :

$$V = 10\frac{360}{24(60)} = 2.5^\circ/\text{MIN}$$

$$N = \frac{\sum M_t \; V\,(12)}{63{,}000 \times 360} = \frac{\sum M_t \; V}{1.89 \times 10^6}$$

1) IN ELEVATION : $N_{E18} = \frac{2.87 \times \cancel{10^6} \times 2.5}{1.89 \times \cancel{10^6}} = \underline{\underline{3.8 \text{ HP}}}$

2) IN AZIMUTH : $N_{E18} = \frac{3.79 \times \cancel{10^6} \times 2.5}{1.89 \times \cancel{10^6}} = \underline{\underline{5.0 \text{ HP}}}$

b) DRIVE TO STOW AT 6.3° MIN (.105°/SEC) :

3) IN ELEVATION : $N_{E45} = \frac{17.56 \times \cancel{10^6} \times 6.3}{1.89 \times \cancel{10^6}} = \underline{\underline{58.3 \text{ HP}}}$

4) IN AZIMUTH : $N_{E45} = \frac{18.48 \times 10^6 \times 6.3}{1.89 \times 10^6} = \underline{\underline{61.5 \text{ HP}}}$

INPUT HP-REQUIREMENTS :

ASSUME DRIVE EFFICIENCY TO BE 95 %

1) N_{E18} - ELEV. $= \frac{3.8}{.95} = \underline{4.0 \text{ HP}}$

2) N_{E18} - AZIMUTH $= \frac{5.0}{.95} = \underline{5.3 \text{ HP}}$

3) N_{E45} - ELEV. $= \frac{58.3}{.95} = \underline{62.0 \text{ HP}}$

4) N_{E45} - AZIMUTH $= \frac{61.5}{.95} = \underline{65.0 \text{ HP}}$

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SELECTED POWER UNITS :

a) ELEVATION : 4 MOTORS @ 20 HP @ 850 RPM

b) AZIMUTH : 16 MOTORS @ 5 HP @ 850 RPM

4.2 GEAR TRAIN SIZING :

4.2.1 AZIMUTH AXIS TYPE OF DRIVE : FRICTION DRIVE

$$i_{\text{TOTAL REQ'D}} = \frac{850}{.0175} \cong \underline{48{,}600 : 1}$$

$$i_{\text{TRACK/WHEEL}} = \frac{173.2 \times 12}{19} = \underline{109.4 : 1}$$

$$i_{\text{GEAR TRAIN REQD}} = \frac{48{,}600}{109.4} = \underline{444 : 1}$$

ASSUME 3 STAGE GEAR BOX.

$$i_1 = \frac{i_2}{\sqrt{2}} \quad ; \quad i_2 = \frac{i_3}{\sqrt{2}}$$

$$i_{GT} = 444:1 = i_1 \cdot i_2 \cdot i_3 = \frac{i_3}{2} \times \frac{i_3}{\sqrt{2}} \times i_3 = 2\sqrt{2}\,(i_3)^3$$

$$i_3 = \sqrt[3]{2\, i_{GT} \sqrt{2}} = \sqrt[3]{1260} = \underline{10.8 : 1}$$

$$i_2 = \frac{10.8}{\sqrt{2}} = \underline{7.65 : 1}$$

$$i_1 = \frac{10.8}{2} = \underline{5.4 : 1}$$

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OUTPUT STAGE :

ASSUME MAX. TOOTH STRESS TO BE 50,000 PSI.

$$\sigma_B = \frac{F_T P}{F \gamma}$$

$M_{t\,MAX} \cong 19 \times 10^6$ FT-LBS ; $P_{D\,GEAR} \cong 32$ IN

$$F_{T_3} = \frac{19.0 \times 10^6}{173.2 \times 16}\left(\frac{19}{16}\right) = \underline{8,200 \text{ LBS}}$$

N_{PIN} = 18 TEETH MIN.

γ = .308

i = 10.8 : 1

$D_{P\,PIN} = \frac{32}{10.8} \cong \underline{3.0 \text{ IN}}$

$$\frac{P}{F} = \frac{50{,}000 \times \overset{(.289)}{.308}}{8{,}200} = \overset{(1.76)\ \text{FOR } N = 15}{1.88}$$

P	6	5
F	3.25	2.85
$N_{PIN.}$	18	15
N_{GEAR}	194	162
$D_{P\,GEAR}$	32.33	32.4

USE $\underline{P = 6}$

$\underline{F = 3.25 \text{ IN}}$

$$i = \frac{194}{18} = \underline{10.777 : 1}$$

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SECOND STAGE:

$$M_{t_3} = \frac{19.0 \times 10^6}{173.2 \times 16}(19) = \underline{130{,}000 \text{ IN LBS}}$$

$$M_{t_2} = \frac{M_{t_3}}{.99} \; \frac{1}{10.78}$$

$$= \frac{130{,}000}{.99 \times 10.78} = \underline{12{,}300 \text{ IN LBS}}$$

USE 30,000 PSI MAX. TOOTH STRESS.

ASSUME $P_{D\,GEAR} \cong 19.0$ IN

$$F_{T_2} = \frac{M_{t_2}}{9.5} = \frac{12{,}300}{9.5} = \underline{1300 \text{ LBS}}$$

$$P_{D\,PIN.} = \frac{19.0}{7.65} \cong \underline{2.50 \text{ IN}}$$

$$\frac{P}{F} = \frac{30{,}000 \times .340}{1300} = 7.85$$

P	10
F	1.3
$N_{PIN.}$	25
N_{GEAR}	191
$P_{D\,GEAR}$	19.1

$$i = \frac{19.1}{2.5} = \underline{7.65 : 1}$$

USE $\underline{P = 10}$
$\underline{F = 1.5 \text{ IN}}$

$$M_{t_1} = \frac{12{,}300}{.99 \times 7.65} = \underline{1630 \text{ IN LBS}}$$

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NATIONAL RADIO ASTRONOMY OBSERVATORY
POST OFFICE BOX 2
GREEN BANK, WEST VIRGINIA 24944
TELEPHONE ARBOVALE 456-2011

REPORT NO. H79-8
CONTRACT NO. RAP-79
PAGE 4.8 OF 19
DATE 1-14-69

PROJECT: 300 FT. DIA. HOMOLOGY TELESCOPE
SUBJECT: GEAR TRAINS

FIRST STAGE:

$\sigma_{MAX} = 30{,}000$ PSI

$P_{D\,GEAR} = 16.0$ IN (ASSUMED)

$F_{T_1} = \frac{1630}{8} = \underline{204 \text{ LBS}}$

$P = 20$

$F = .32$ IN

$N_{PIN} = 60$

$N_{GEAR} = 324$

$P_{D\,PIN.} = 3.0$

$P_{D\,GEAR} = 16.2$

$\frac{P}{F} = \frac{30{,}000 \times .421}{204} = 62$

$i = \frac{16.2}{3.0} = \underline{5.40 : 1}$

USE $P = \underline{20}$

$F = \underline{.50 \text{ IN}}$

$M_{t\,INPUT} = \frac{1630}{.99 \times 5.4} = \underline{306 \text{ IN LBS}}$

MAX TORQUE AVAILABLE:

$M_{t\,MAX\,INP.} = \frac{5 \times 63{,}000}{850} = \underline{370 \text{ IN LBS}}$ OK

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REPORT NO. H 79-8
CONTRACT NO. RAP-79

DATE 1-14-69

PROJECT: 300 FT. DIA. HOMOLOGY TELESCOPE

SUBJECT: GEAR TRAINS

GEAR BOX SUMMARY :

$i_1 = 5.40 : 1$

$i_2 = 7.65 : 1$

$i_3 = 10.78 : 1$

$i_{TRACK/WHEEL} = 109.40 : 1$

$i_{TOTAL} = 5.4 \times 7.65 \times 10.78 \times 109.40 = \underline{48,628 : 1}$

$i_{GEARTRAIN} = 5.4 \times 7.65 \times 10.78 = \underline{444.62 : 1}$

GEAR NO.	PITCH	NO. OF TEETH	P_D	F
1	20	60	3.0	.50
2	20	324	16.2	.50
3	10	25	2.5	1.50
4	10	191	19.1	1.50
5	6	18	3.0	3.25
6	6	194	32.33	3.25

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CONTRACT NO. RAP-79

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4.2.2. STIFFNESS OF AZIMUTH GEARTRAIN:

1.) TORSIONAL STIFFNESS OF DRIVE AXLE:

MIN. DIA., d = 8.0 IN
LENGTH, ℓ = 28.0 IN (℄ TO WHEEL CENTER)

$$\theta = \frac{M_t \, \ell}{I_p \, G \, 2} \qquad G = 11.5 \times 10^6 \ \mathrm{LBS/IN^2}$$

$$K_\theta = \frac{M_t}{\theta} = \frac{2 I_p G}{\ell}$$

$$I_p = \frac{\pi d^4}{32} \ ; \qquad K_\theta = \frac{2 \frac{\pi d^4}{32} \, 11.5 \times 10^6}{28}$$

$$K_\theta = \frac{\pi (8)^4 \, 11.5 \times 10^6}{28 \times 16} = \underline{330 \times 10^6 \ \mathrm{IN\,LBS/RAD}}$$

AT 19" WHEEL RADIUS:

$$K = \frac{330 \times 10^6}{19^2} = \underline{.91 \times 10^6 \ \mathrm{LBS/IN}}$$

FOR 16 UNITS:

$$K = 16 \times .91 \times 10^6 = \underline{\underline{14.6 \times 10^6 \ \mathrm{LBS/IN}}}$$

$$K_\theta = 14.6 \times 10^6 \, (173.2)^2 \, 12 = \underline{\underline{5.25 \times 10^{12} \ \mathrm{FT\text{-}LBS/RAD}}} \ *$$

$\underline{\underline{\text{USE } 4.8 \times 10^{12}}}$ TO ACCT. FOR BENDING STIFFNESS

*(REFERRED TO ANTENNA AXIS)

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2.) STIFFNESS OF OUTPUT STAGE :

$$\Delta \cong \frac{F_T\ 18.5}{F\ E} \quad ; \quad \theta \cong \frac{F_T\ 18.5}{FE\ P_D/2} \cong \frac{F_T\ 37}{FE\,P_D}$$

$$M_t = \frac{F_T\ P_D}{2} \quad ; \quad F_T = \frac{2\ M_t}{P_D}$$

$$K = \frac{M_t}{\theta} \quad ; \quad \theta = \frac{2\ M_t\ 37}{FE\,(P_D)^2} = \frac{74\ M_t}{F\,E\,(P_D)^2}$$

$$K_\theta = \frac{\cancel{M_t}\ F\ E\ (P_D)^2}{74\ \cancel{M_t}} = \frac{FE\ (P_D)^2}{74} \left(\frac{\text{IN LBS}}{\text{RAD}}\right)$$

$$K_{\theta_3} = \frac{3.25 \times 30 \times 10^6\ (32.33)^2}{74} = \underline{1.37 \times 10^9\ \text{IN LBS/RAD}}$$

$$= \underline{1.14 \times 10^8\ \text{FT LBS/RAD}}$$

3.) STIFFNESS OF SECOND STAGE :

$$K_{\theta_2} = \frac{1.5 \times 30 \times 10^6\ (19.1)^2}{74} = \underline{2.22 \times 10^8\ \text{IN LBS/RAD}}$$

$$i = 10.78 : 1$$

$$K_{\theta_2} \text{ REF. TO OUTPUT AXIS} = 2.22 \times 10^8 \times (10.78)^2 = \underline{2.58 \times 10^{10}\ \text{IN LBS/RAD}}$$

$$= \underline{21.5 \times 10^8\ \text{FT-LBS/RAD}}$$

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4.) STIFFNESS OF FIRST STAGE :

$$K_{\theta_1} = \frac{.50 \times 30 \times 10^6 (16.2)^2}{74} = \underline{5.3 \times 10^7 \text{ IN LBS/RAD}}$$

$$i = 10.78 \times 7.65 = 82.5:1$$

$$K_{\theta_1} \text{ REF TO OUTPUT AXIS} = 5.3 \times 10^7 \times (82.5)^2 = 36 \times 10^{10} \text{ IN LBS/RAD}$$

$$= \underline{300 \times 10^8 \text{ FT-LBS/RAD.}}$$

5.) STIFFNESS OF INPUT SHAFT :

ASSUME DIA. = 1.5 IN , ℓ = 5.0 IN

$$K_{\theta_0} = \frac{\pi d^4 G}{32 \ell} = \frac{\pi (1.5)^4 11.5 \times 10^6}{32 \times 5} = \underline{1.14 \times 10^6 \text{ IN LBS/RAD}}$$

$$i = 444.62 : 1$$

$$K_{\theta_0} \text{ REF. TO OUTPUT AXIS} = 1.14 \times 10^6 (444.62)^2 = \underline{22.5 \times 10^{10} \text{ 1\#/RAD}}$$

$$= \underline{187 \times 10^8 \text{ FT-LBS/RAD}}$$

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National Radio Astronomy Observatory
Post Office Box 2
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TELEPHONE ARBOVALE 456-2011

REPORT NO. H79-8
CONTRACT NO. RAP-79
PAGE 4.13 OF 19
DATE 1-15-69

PROJECT: 300 FT. DIA. HOMOLOGY TELESCOPE

SUBJECT: GEARTRAINS

6.) COMBINED GEAR TRAIN STIFFNESS :

$$K_{\theta\,COMBINED} = \frac{1}{\frac{1}{K_{\theta_3}} + \frac{1}{K_{\theta_2}} + \frac{1}{K_{\theta_1}} + \frac{1}{K_{\theta_0}}}$$ (TOOTH STIFFNESS) ONLY

$$K_{\theta\,COMB.} = \frac{10^8}{\frac{1}{1.14} + \frac{1}{21.5} + \frac{1}{300} + \frac{1}{187}}$$

$$= \frac{10^8}{.880 + .047 + .003 + .005} = \frac{10^8}{.935}$$

$$K_{\theta\,COMB} \cong \underline{1.0 \times 10^8 \text{ FT-LBS/RAD}}$$

IN A WELL DESIGNED GEAR BOX THE GEAR TOOTH DEFLECTION ACCOUNTS FOR ABOUT 25% OF THE TOTAL DEFLECTION.
THEREFOR WE CAN ASSUME :

$$K_{GB} = .25 \times 1.0 \times 10^8 = \underline{\underline{25 \times 10^6 \text{ FT-LBS/RAD}}}$$

AND REFERED TO ANTENNA AXIS

$$K_{GB} = 25 \times 10^6 \times (109.4)^2 = \underline{\underline{3.0 \times 10^{11} \text{ FT-LBS/RAD}}}$$

$$\text{FOR 16 UNITS} = \underline{\underline{4.8 \times 10^{12} \text{ FT-LBS/RAD}}}$$

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7.) COMBINED STIFFNESS OF TRUCK-GEARTRAIN & AXLE

K_θ TRUCKS $= 12 \times 10^6$ #/IN

$= 12 \times 10^6 \, (173.2)^2 \, 12 = \underline{4.30 \times 10^{12} \text{ FT-LBS/RAD}}$

K_θ AXLES $= \underline{4.80 \times 10^{12} \text{ FT LBS/RAD}}$

K_θ GEARTRAINS $= \underline{4.80 \times 10^{12} \text{ FT LBS/RAD}}$

$$K_{\theta \, AZ.} = \frac{10^{12}}{\frac{1}{4.3} + \frac{1}{4.8} + \frac{1}{4.8}} = \frac{10^{12}}{.66}$$

$$K_{\theta \, AZ} \cong \underline{\underline{1.5 \times 10^{12} \text{ FT-LBS/RAD}}}$$

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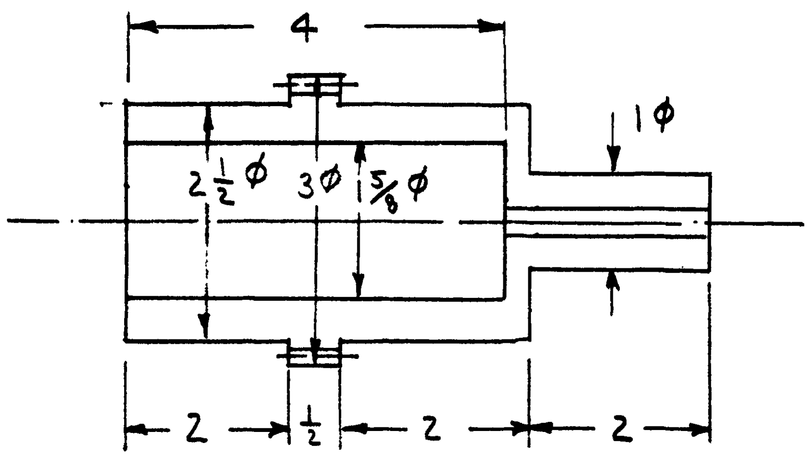
4.2.3 INERTIA OF AZIMUTH GEAR TRAIN

1.) INPUT SHAFT INERTA



$$I = \frac{MR^2}{2} = \frac{W}{2g} R^2 = \frac{1}{g} \frac{WR^2}{2}$$

ITEM	W (LBS)	R	R^2	$\frac{WR^2}{2}$	
1	5.55	1.25	1.56	4.35	+
2	1.00	1.50	2.25	1.12	+
3	.44	.50	.25	.06	+
4	2.35	.812	.66	.78	−
			Σ	4.75	

$$I_0 = \frac{4.75}{386} = .0123 \text{ IN-LBS-SEC}^2$$

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2.) INERTIA OF 1ST. STAGE:

P_D = 16.2 IN , F = .5 IN , P = 20
O.D = 16.3 IN

$$W = \frac{16.3^2 \pi}{4} (.50)\ .283 = \underline{28.3 \text{ LBS}}$$

$$\frac{WR^2}{2} = 28.3 \times \frac{(8.15)^2}{2} = \underline{940 \text{ LBS IN}^2}$$

$$I = \frac{940}{386} = \underline{2.44 \text{ IN-LBS-SEC}^2}$$

$$i = 5.4 : 1$$

$$I_{INPUT} = \frac{2.44}{(5.4)^2} = \underline{.084 \text{ IN LBS SEC}^2}$$

3) INERTIA OF 2nd. STAGE

P_D = 19.1 IN , F = 1.5 IN , P = 10
O.D = 19.3 IN

$$W = \frac{(19.3)^2 \pi}{4} \times 1.5 \times .263 = \underline{120 \text{ LBS}}$$

$$\frac{WR^2}{2} = 120 \frac{(9.65)^2}{2} = \underline{5550 \text{ LBS IN}^2}$$

$$I_{INPUT} = \frac{5550}{386\ (5.4 \times 7.65)^2} = \underline{.009 \text{ IN LBS SEC}^2}$$

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4.) INERTIA OF 3 rd. STAGE :

$P_D = 32.33$ IN , $F = 3.25$ $P = 6$

$OD = 32.67$ IN

$$W = \frac{(32.67)^2 \pi}{4} 3.25 \times .283 = \underline{775 \text{ LBS}}$$

$$\frac{WR^2}{2} = \frac{775\,(16.34)^2}{2} = \underline{103{,}000 \text{ LBS IN}^2}$$

WHEELS :

$W = 925$ LBS EACH

$$\frac{WR^2}{2} = \frac{1850\,(19)^2}{2} = \underline{333{,}000 \text{ LBS IN}^2}$$

AXLE :

$$W \approx \frac{8^2 \pi}{4} \times 89.25 \times .283 = \underline{1270 \text{ LBS}}$$

$$\frac{WR^2}{2} = \frac{1270 \times (4)^2}{2} \cong \underline{10{,}000 \text{ LBS-IN}^2}$$

$$I = \frac{103{,}000 + 333{,}000 + 10{,}000}{386} = \underline{1160 \text{ IN LBS SEC}^2}$$

$$i^2 = 444.62^2$$

$$I_{INPUT} = \frac{1160}{(444.62)^2} \cong \underline{.006 \text{ IN-LBS-SEC}^2}$$

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SUBJECT: GEAR TRAINS

5) TOTAL INERTIA @ INPUT SHAFT:

$$I_{INPUT} = .0123 + .084 + .009 + .006 = \underline{.1113 \text{ IN-LBS-SEC}^2}$$

USE $\underline{.125 \text{ IN-LBS-SEC}^2}$

6) LOCKED ROTOR RESONANCE OF GEARTRAIN:

INERTIA @ OUTPUT AXIS : $.125 \times (444.62)^2 = \underline{2.47 \times 10^4 \text{ IN-LBS-SEC}^2}$

$$K_{GT+AXLE} = 12.5 \times 10^6 \text{ \#/RAD} = \underline{15.0 \times 10^7 \text{ IN LBS/RAD}}$$

$$F_n = \frac{1}{2\pi}\sqrt{\frac{K}{I}} = \frac{1}{2\pi}\sqrt{\frac{15,000}{2.47}} = \frac{1}{2\pi}\sqrt{6100}$$

$$F_n = \underline{\underline{12.4 \text{ CPS}}} \quad \text{OK}$$

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PROJECT: 300 FT. DIA. HOMOLOGY TELESCOPE
SUBJECT: GEAR TRAINS

4.3 ELEVATION AXIS:

PITCH RADIUS OF ELEVATION GEAR : $92' = \underline{1104 \text{ IN}}$

PITCH DIA. OF PINION $= \underline{13.60 \text{ IN}}$ *

$$i_{\text{GEARTRAIN REQ'D}} = \frac{48,600}{1104/6.8} \cong \underline{300:1}$$

USE 4 - UNITS MODIFIED "WESTERN GEAR" # RTX-100*
(INPUT STAGE MODIFIED TO GET $i = 300:1$).

$K = 26.5 \times 10^6$ 1#/RAD. , WEIGHT = 12,000 LBS

$$I_{\text{INPUT, ESTD}} = \underline{40 \text{ IN LBS SEC}^2}$$

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{I}} = \frac{1}{2\pi}\sqrt{\frac{26.5 \times 10^6 (12)}{40 \times (300)^2}} = \frac{1}{2\pi}\sqrt{\frac{31.8}{3.6}}$$

$$f_n \cong \underline{1.5 \text{ CPS (OK)}}$$

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