ngVLA Memo # 25

Exploration of Suitable Mounts for a 15m Offset Antenna
Next Generation Very Large Array
NRC 15m Mount

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2017-09-29

Abstract

A design effort and analysis of several antenna mounts suitable for an offset low 15m antenna was undertaken. Antenna specifications revealed precision referenced pointing during 7 to 10 m/s winds was the most demanding requirement. A four point open truss structure wheel and track mount was selected as most viable. Analysis indicates deflections can be controlled to achieve <1.5 arc-sec pointing error. General issues related to wheel and track designs are also discussed as well as costing for the selected design. Future improvements to are also discussed.

Contents

Acronyms used in this document

ARA	Azimuth Rotating Assembly
ARS	Azimuth Rotating Structure
ERA	Elevation Rotating Assembly
ERS	Elevation Rotating Structure
NRC	National Research Council of Canada
DRAO	Dominion Radio Astrophysical Observatory
SKA	Square Kilometer Array
TDP	Technology Development Program (part of US SKA participation)
DVA-1	Dish Verification Antenna 1 (part of SKA project)
OH	Offset High optical arrangement (pointing at horizon secondary is high)
OL	Offset Low optical arrangement (point at horizon secondary is low)
CFRP	Carbon Fiber Reinforced Plastic
SRC	Single-piece Rim-supported Composite
VLBA	Very Long Baseline Array (10 antennas, 25m dia, symmetric, world wide)
GBT	Green Bank Telescope (100m dia, offset, 1.7 M lbs, Virginia)
LMT	Large Millimeter Telescope (50m dia, symmetric, Mexico)

1. Introduction

Minex Engineering was contracted by NRC to The purpose of this study is to examine several different mount concepts suitable for the 15m offset antenna reflector system being developed by NRC for the ngVLA[6]. The Single-piece Rim-supported Composite (SRC) reflector system and Elevation Rotating Assembly (ERA) was first explored with the SKA DVA-1 15m antenna and built at DRAO in 2015. This single piece primary reflector made from CFRP is an amazing surface and maintains excellent accuracy when supported by a stiffened rim. The Secondary and Feed platform structures also achieve excellent support and stiffness when mounted from the primary rim.

The ERA can be arranged with two optical configurations. When the ERA is mounted in an Offset High (OH) configuration, the feed arm and secondary are up high while observing near the horizon. When the ERA is mounted in an Offset Low (OL) configuration, the feed arm is low while observing near the horizon. With OH there are several mount options are reasonable to consider, including pedestal yoke type and pedestal turnhead type and wheel and track type mounts. However, with OL, the pedestal type mounts are at a mechanical disadvantage compared to a wheel & track type mount. Basically the OL configuration wants cut off the pedestal type mounts at the knees unless one extends the elevation axis a significant distance away from the azimuth axis. Alternatively, the Track type mounts can wrap around the ERA allowing elevation observation angles as low as 5°.

For the reasons discussed above we only examined Track type mounts for the NRC design ERA. We examined a 3 wheel shown in figure 1 and a 4 wheel design shown in figure 2 and we explored issues related to foundation design and wheel and track performance. We focused our work on the OL configuration 4 wheel design with elevation bearings providing guidance, see figures 3 through 5. In the course of our work we realized some very interesting opportunities for low mass ARA concepts can be envisioned for OH mounts using elevation drives based on a sector gear or direct drive. These are mentioned in the Conclusions Section.

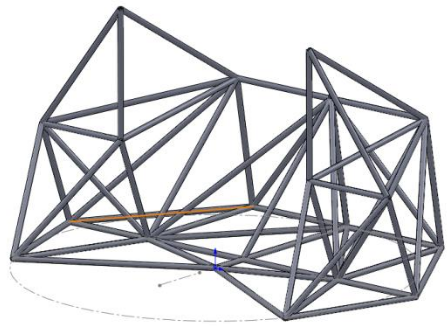

Figure 1
3 wheel ARS

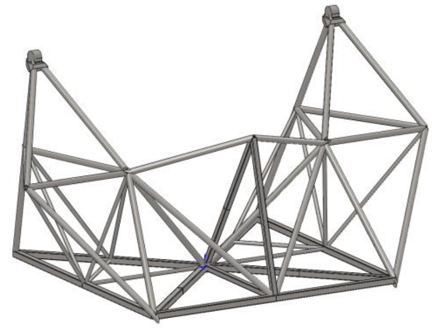

Figure 2
4 wheel ARS

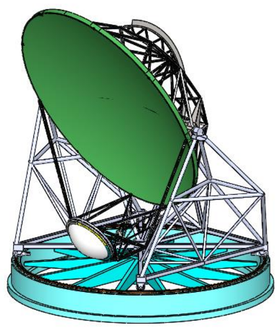

Figure 3
Elevation 12 deg, 4 wheel

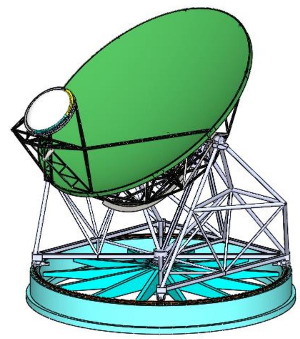

Figure 4
Elevation 90 deg, 4 wheel

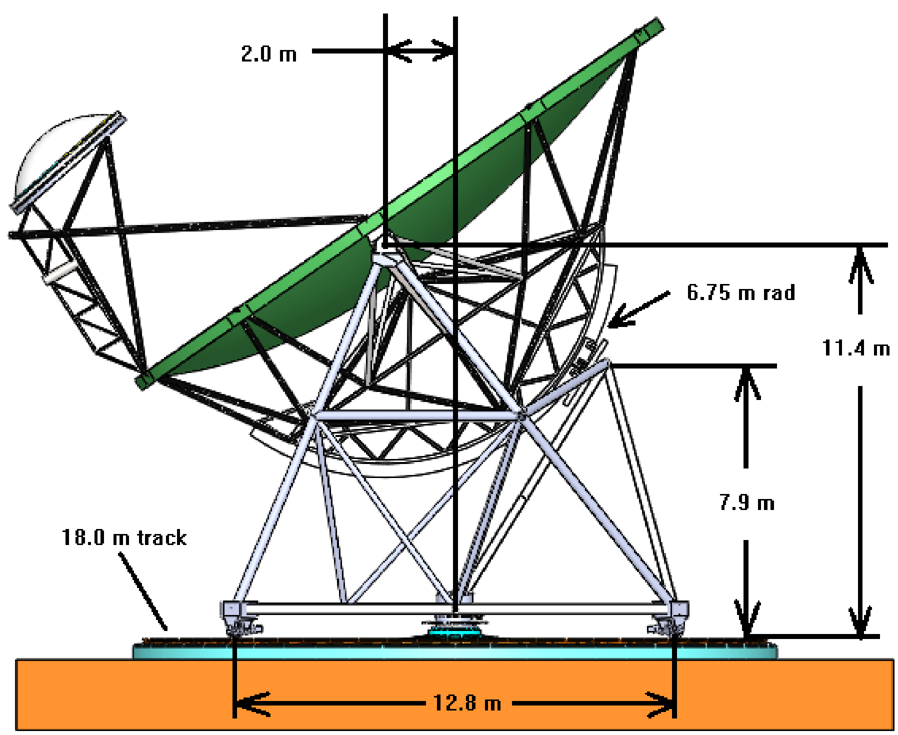

Figure 5
Basic dimensions, 4 wheel

2. Key Specifications and Impact on Design

The design team working on this project has been in close contact with Rob Selina of NRAO regarding the ngVLA Specifications document. We have been using information from: Preliminary Technical Specifications, Draft Ver 0.1, through the current, Draft Ver 0.8, 7/24/2017. Keep in mind that the specifications are for an 18 m dish and this analysis is for a 15m dish, so some appropriate adjustments were made to the pointing requirements. Examination of the specifications showed the following items would be design drivers for the ARA: (most importantly items 5 & 6)

1) Aperture diameter 15m (large wind loads)
2) Offset low optics (raises elevation axis and may force large el to az axis offset)
3) Elevation range 12° lower elevation limit. (same issues as above)
4) Frequency and surface accuracy, primary operations 160μ surface.
5) Pointing Primary Operations: Night only, wind <= 7 m/s
   Referenced pointing: 3.6 arc sec RMS (4 deg angle, 15 min time)
6) Pointing Secondary Operations: Day and Night, wind <= 10 m/s
   Referenced pointing: 5.6 arc sec RMS (4 deg angle, 15 min time)

Items 1 to 4 are reflected in the general geometry of structures we chose and items 5 & 6 have a lot to do with member cross sections and total mass required. Item 5 is less demanding because it does not include daytime thermal changes. Item 6 may be the most demanding because it has both higher wind and daytime thermal issues. Fortunately, a 15 minute time interval probably prevents thermal issues from dominating the pointing error in the ARA. It is also fortunate that when even a small breeze occurs an open truss structure well match ambient pretty quickly.

Our analysis assumed, for a 7 m/s wind, the ERA would consume 50 to 60% of the available 3.0 arc-sec pointing error budget, leaving 40 to 50% for the ARA or 1.2 to 1.5 arc-sec. Our analysis did not include an estimated error from thermal issues. We further assumed, the wind would have an average component at 7 m/s and an additional gust component of 30 to 40% of average. We also assumed that a characterized antenna would allow the average wind pointing error to be predicted and compensated for within 80 to 90%. This would leave a consistent wind at 10% of average plus a 40% gust equaling a variable loading of 50% of 7.0 m/s or 3.5 m/s. Our analysis further assumes a pair of elevation encoders, one at each elevation bearing. We assume that the elevation drive deflections will be measured by the encoders and the servo system will adjust for these deflections. So, the elevation drive compliance will not be extremely critical, although a reasonably fast servo response will be important. The elevation encoders reference is assumed to be the upper portion of the arm supporting the elevation bearings. The defection and local tilting of this area of the structure has the largest contribution to the elevation pointing error. With the azimuth encoder at the pintle, azimuth pointing errors will come from the entire structure above the wheels.

3. Elevation Rotating Assembly

The ERA consists of the primary reflector surface and support structure, the secondary and its support structure, the feed and its support structure, elevation drive connection point or sector gear and counterweight if needed. The ERA for this antenna is well defined by the team at NRC DRAO and our team was only required to coordinate elevation bearing points and elevation drive interface designs. The assembly weighs about 12,250 kg or 27,000 lbs.

4. Discussion of Pedestal Designs in general

A Pedestal type ARA design was not considered for this project. The NRC ERA is such an excellent match to an open truss Wheel & Track ARA, we only performed analysis on this type of structure. It might be possible to adapt a pedestal type mount for this application. If it were of interest the OH configuration would be the preferred approach with the OL configuration as a last choice from a mechanical standpoint. Of course other criteria might justify OL as a better choice.

5. Discussion of Wheel & Track Designs in general

As pointed out earlier, the NRC ERA in an OL configuration is an excellent match to an open truss structure for a Wheel and Track ARA. There are some general issues with wheel and track that we would like to discuss here. One important thing to note is many antennas of this type, especially in commercial ground station applications, have performed well for long periods.

Wheel and Track designs are always employed when a telescope becomes very large and an azimuth bearing is often employed for smaller antenna sizes. Very large telescopes such as GBT, LMT, Effelsberg are examples that have very little in common with what we are proposing for ngVLA. They are custom designs with extremely high loads and not very similar to conventional rail systems. Some of these telescopes have had troubles, but as mentioned they are so unique they do not provide useful lessons learned. The VLBA antennas are a bit closer to our proposed designs, and there are lessons to be learned. The VLBA antennas have had issues with track grout fracture, rail scuffing, axle troubles, rail joint and wheel alignment problems. These issues, discussions and repairs are nicely documented in the NRAO memo series(1).

Our team has consulted with some experienced engineers at companies that specialize in dock side container cranes, gantry cranes, and dynamic structures such as stadium roof systems. We have learned that some of the issues that have given previous telescopes trouble can be avoided with careful design. First of all, our antenna is not very heavy compared with many previous systems, axle loads and wheel contact pressures are relatively small. Second, crane rail with a wide flat top flange and other favorable dimensions is readily available for our application. Third, it is now common to weld rail at joints and all the tooling and techniques are known and available. Fourth, we have learned it is wise to use rail clip systems that allow small movements at the rail to tie plate interfaces which reduces stress buildup from the rolling wave in the rail and thermal effects of a welded hoop. The tie plates or sole plates for the rail are a critical part of the design. Fifth, our design will require an uplift retention system for survival positions. We would use under the rail head retention structures similar to those used successfully on other projects. Sixth, it is very likely the rail segments will need to be rolled for radius and then Blanchard ground to achieve top and bottom flange parallelism. Once installed, they would be carefully aligned to tie plates. Joints would be thermite welded and ground. And as a final step the top surface of the rail would be ground by a special grinding machine based on the pintle bearing arrangement.

Figure 6
Thermite weld

Figure 7
Top side grind mobile tool

Figure 8
Sole plate concept

Figure 9
Multiple tie plates concept

Figure 10
VLBA antenna, driven wheel

The Wheel and Track portion of the ARA in combination with the center pintle bearing, is equivalent to the Azimuth Bearing of a Pedestal type antenna. Concentricity of wheels, axles and bearings is critical so as not to introduce random pointing errors. Also wheel alignment is critical. The top of the track should be in a plane and the wheel should be conical toward the center pintle. No matter how well aligned, wheels will generate thrust loads along the axle equal to the coefficient of friction and the normal force on the wheel. This force along with drive torques will generate moments that attempt to distort the lower portion of the ARS. These distortions can be managed with careful consideration during the design process. NRAO has a VLBA memo series that is very useful to review. Jon Thunborg notes that the horizontal accuracy of the VLBA antenna wheel axles is critical to reduced bearing loads and for those antennas recommends axles at 93.44 +/- 0.01 degrees.(1) Keep in mind that VLBA antenna weight is about 450,000 lbs. It runs on 4 wheels at 36" diameter each with loads on a wheel in the neighborhood of 160,000 lbs. The 4 wheel design we are considering has similar wheel and track sizes, but will have wheel loads closer to 40,000 to 60,000 lbs. We have also engaged in useful discussions with engineers at Gantrex, Chip Miller of Molyneux Industries(2), Inc. and Ken Maurer of Morgan Engineering Systems(3), all of whom have experience with large rail mounted dynamic structures

As mentioned earlier, it is important to note that the ERA portion of this antenna is relatively light at 27,000 lbs. And with an offset low design the survival stow position will be either elevation 90° or more likely elevation 35° with the rim of the primary in a vertical orientation leaving the elevation drive with low loading. This generates higher overturning loads and possible uplift loads on azimuth wheels. This can be resisted with a retention bracket extending under the rail head. This will likely work well, but during very extreme winds there may be a damaging banging condition as the antenna is lifted against the retainer brackets. It may be necessary to actuate that bracket, or lift against it, in order to clamp the rail. Further investigation is needed with exact antenna component weights and wind lift calculations.

6. Three Wheel Design Analysis

Both a three wheel and a four wheel ARA were designed and analyzed. A three wheel design has some nice properties. First it has one less wheel to pay for. It has two wheels forward allowing the Offset Low (OL) dish to nest between the elevation bearing support arms. With 3 points of contact, it is statically determinate, assuming axial compliance at the radial pintle bearing. It has the rear single wheel directly in line with the elevation drive loads, creating a very stiff arrangement. This design does well for wind loads either face-on or from behind, at 0 or 180° azimuth, and this is true for various elevation angles. In fact the 3 wheel design does a little better than the four wheel design for these loadings because of the direct line for elevation drive loads to the rear wheel. Unfortunately deflection from side wind loading is very difficult to control. In fact when the primary is pointed at 35° with the rim basically vertical and wind across the antenna is at 120° the performance is very poor. Significant additional structure must be added to resist the deflection around the azimuth axis. It turns out that 20 to 40% more steel is needed to achieve the same performance given by a 4 wheel design. In addition to the issues listed above the overall stability and resistance to overturning moment is lower which is important for lighter weight antennas. For this reason the 4 wheel will be preferred.

7. Four Wheel Design Analysis

The four wheel ARA has better stability and better deflection performance than any other design for the same weight of material. Although a structure supported at 4 points is statically indeterminate, a very flat track and the elastic behavior of steel will prevent high stresses in the structure. Four wheels may be driven or two wheels are driven and two are just load carriers. The desired natural frequency for the antenna would be 4 to 7 Hz. The deflection from 0 & 180° azimuth wind directions, front and rear are slightly worse than the 3 wheel arrangement because the elevation loads are not delivered directly in line with a wheel. The elevation drive load is delivered midway on a truss beam spanning between the two rear wheels. Most of this deflection will be detected by the elevation encoder but it does reduce the structures stiffness. The structure we analyzed is definitely on the light side for this application. It has achieved about 1.5 arc-sec in a 7m/s wind with a total weight of 87,675 lbs. Our deflection analysis for 3 key load cases is shown in table 1.

Table 1			
Wind Case & Pointing Error (PE)	EL	XEL (cross EL)	PE (total)
	(arc-sec)	(arc-sec)	(arc-sec)
El 90, Az 180 rear wind	-0.4	0.0	-0.4
El 35, Az 0 front wind	1.5	0.0	1.5
El 35, Az 120 cross wind	-0.6	-0.5	0.8

The structure described is made up of the following members:

Table 2

ARS Member Sizes		
Item	Name	Size
A	Base Frame	12" sqr x 0.50 wall
B	Drive Triangle	12" sqr x 0.50 wall
C	Side Frames	10" pipe x 0.50 wall
D	Braces	6" pipe x 0.43 wall

Table 3

ARS Az Rotating Structure	
Description	Weight (lbs)
El Bearing Set	4,136
El Drive	7,285
Tube Structure	62,070
Az Wheel Sets	10,280
Az Pintle Set	3,904
Total:	87,675

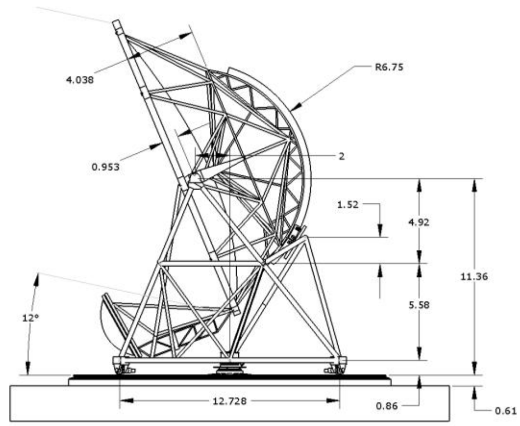

Figure 11

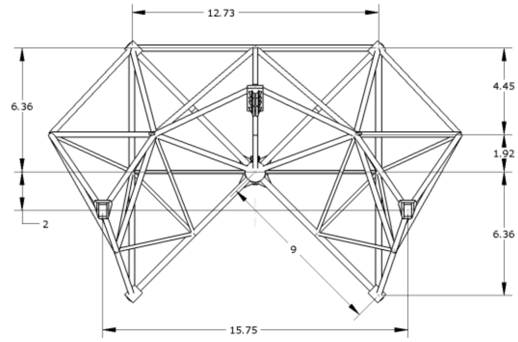

Figure 12

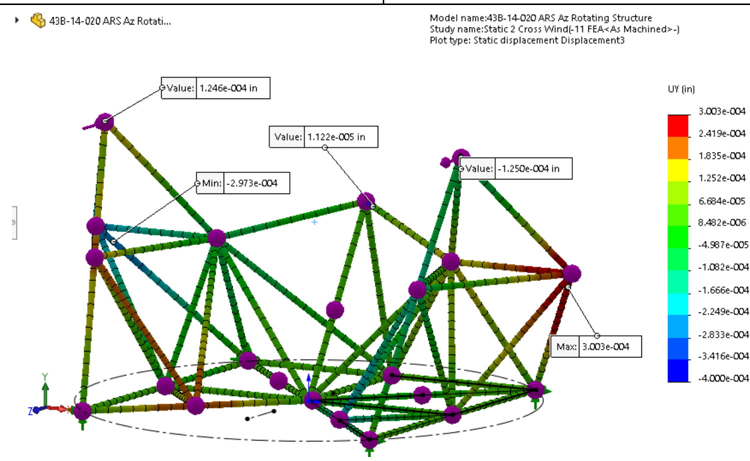

Figure 13
FEA model, 4 wheel ARS

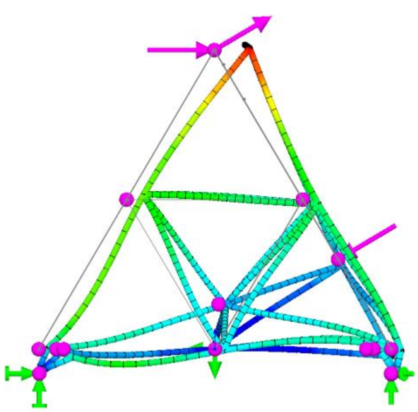

Figure 14
Typical deflection
front loading

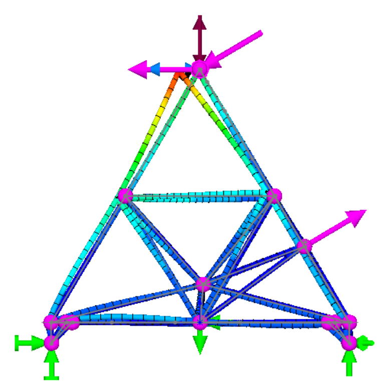

Figure 15
Typical deflection
azimuth moment loading

8. Summary Comparison of Performance and Cost

Below is an estimated cost for the 4 point wheel and track mount, including foundation. It is generated via costing from R. S. Means and we believe it is quite conservative. It is our opinion that a more thorough costing effort could indicate costing as much as 30% lower. The costing effort assumed several hundred units in production and significant tooling was made to keep up a high production rate of multiple antennas per week. The azimuth track and tie parts are included in section 2 with Mechanical components since it is very analogous to the azimuth bearing in other mount designs. The foundation has an 96" diameter, 96" tall pintle base with radial beams and an 18m diameter track support beam 26" thick and 60" tall on a pad 18" thick and 48" wide.

	Table 4 Cost Summary	K$
1.0	Struct Steel Fabrication, Painting & Shipping to Site	$252.1
2.0	Mechanical Components (Incl Packing & Shipping)	$412.1
3.0	Site Assembly of ARA	$117.9
5.0	Foundation Construction W& T	$140.2
	Total	$922.3

9. Conclusions & Recommendations

In conclusion we recommend the 4 point Wheel and Track mount. We consider it likely that further analysis will indicate that some members may need heavier wall thickness while other may be lightened. It will be worthwhile to consider design improvements that reduce local rotation of elevation bearing and encoder mounting regions of the structure. It may be useful to consider some elements of an independent reference structure for elevation encoders. We believe track, wheel, axle and gearbox designs can be arranged that will be reliable and low maintenance. It will be useful to integrate azimuth wheel drives to eliminate couplings and integrate bearings and to design it for easy maintenance. Compare Figure 10 and Figure 24. The use of a direct drive motor acting on a sector is very attractive for the elevation drive. The natural frequency of the telescope and the stiffness of the elevation axis will be greatly improved over any other concept. As noted is section 8, a more thorough costing effort could reveal costing improvement up to 30% lower.

During our analysis several interesting alternate configurations were conceived. If an Offset High (OH) configuration were acceptable some significant improvements might be possible. Figures 21, 22, 23 illustrate a comparison of some of these ideas.

A conventional no flange wheel design will most likely work well with reduced normal forces. However, it may be useful to investigate double flanged wheels and or double wheel bogies on a ball or pin joint at the bogie to frame interface. This could reduce alignment requirements significantly. These ideas could significantly reduce bending moment and loads into the ARS and reduce axial bearing loads at the wheel. Fig 24 & 25. Wheel flange wear and climb would be new issues introduced with these ideas and would have to be carefully evaluated. Another issue that is clearly troublesome on VLBA antennas is grout failure in the area under the rails. This can most likely be solved with higher quality epoxy type grouts.

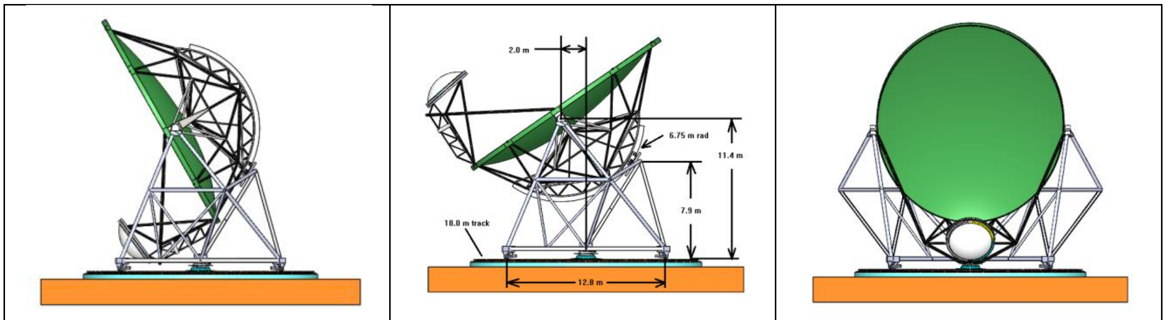

Figure 21: Offset Low, 4 wheel, Bearing guided, Elevation 5 to 12°

Figure 22: Offset High, 4 wheel, Bearing guided, Elevation 5°

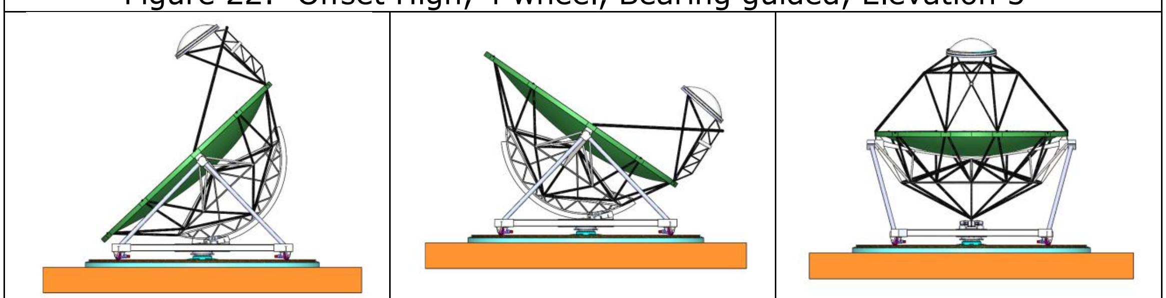

Figure 23: Offset High, 4 wheel, Sector guided, Elevation 12°

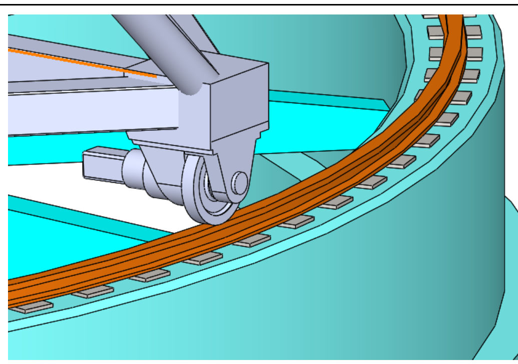

Figure 24

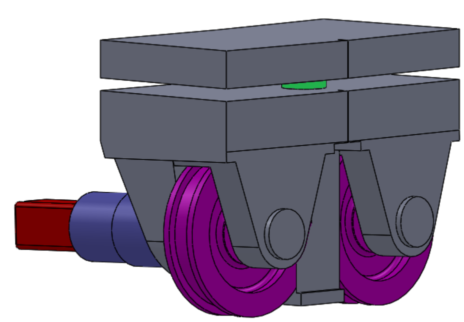

Figure 25

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References:

1. J. E. Thunborg, "VLBA Antenna Memo Series # 71, VLBA Wheel and Axle Design", July, 2014.   (see also memos 38,53,54, 83, 89)

2. Transportation Research Board (TRB), Transit Cooperative Research Program (TCRP), Report 71, Vol 6. Direct Fixation Track Design, 2005-May, Laurence E. Daniels Railroad Consulting Engineer & Bill Moorhead owner TRAMMCO, LLC

3. L. B. Forester Co.
   Rails & Accessories.

4. Molyneux Industries, Inc., Chip Miller.
   Rails & Accessories.

5. Morgan Engineering Systems, Ken Maurer.
   Specialists in rail mounted dynamic structures.

6. D.Chalmers, G.Lacey, M Islam, M.Fleming L Baker, ngVLA Technical Study Offset Gregorian Antenna, Oct 2017, ngVLA Memo #26

Engineering Cost Estimate, 4 wheel Mount, 15m Offset Low Antenna **2017-09-28** **Matt Fleming**

	Azimuth Rotating Structuer ARA 18m track Fab, Ship & Site As (Schedule 6 mo)	Mat Quan Ref	Mat Quan	Unit Meas	Ref Mat $	Mat / Equip Unit Cost $/Unit	Labor Crew Ref (N2)	Labor Hrs	Labor & Equip N2 Cost $/Hr	Total Cost Incl O&P K$	Remarks
1.0	**Struct Steel Frabricaiton, Painting & Shipping to Site**										
1.1	Steel Rd & Sq Section Members (Raw Mat + Del)	FEM	33	tons	N5	$3,400	-	-	-	112.2	Risa Mat Take-off Steel
1.2	Cut fit and join for length, Add Plate End Fab	EE,FEM	2	tons	N6	$3,000	Crew B1	102	$183.00	24.7	Number Members = 51 from FEM, 2 hr/memb
1.3	Joint Struct. Simple Weldmt (2-5 Members)	EE,FEM	2	tons	N6	$3,000	Crew B1	36	$183.00	12.6	9 Jts @4 hr/Jt
1.4	Joint Struct Medium Weldmt (6- 9 Members)	EE,FEM	2	tons	N6	$3,000	Crew B1	42	$183.00	13.7	7 Jts @8 hr/Jt
1.5	Joint Struct Complex Weldmt (10 + Members)	EE,FEM	2	tons	N6	$3,000	Crew B1	16	$183.00	8.9	1 Jts @16 hr/Jt
1.6	Prep. (Sand Bast)	EE	4000	SF	N7	$2.46	Crew E17	40	$184.38	17.2	
1.7	Prime & Paint	EE	4000	SF	N8	$2.06	Crew E17	40	$184.38	15.6	
1.8	Skid & Crate Const - Load Mat on skids and crates	EE	10	Ea	EE	$500	Crew E17	80	$184.38	19.8	
1.9	Trucking Shipmet to Site (1200 mi) - 6 trucks x 2 days	EE	12	Day	N9	$276	Driver B-34G	352	$68.70	27.5	6 Trucks, 1200 mi, 2 day, 24 hr
1.10	Subtotal Fab Steel Structure =		33.103	tons						$252.1	
2.0	**Mechanical Components** (Incl Packing & Shipping)										
2.1	Az Wheel Mech Assy (EA Wheel Assy)	EE	4	Ea	N1	$55,000	Crew R4	32	$467.88	235.0	8 kips ea, JPL Concept 1: 2.2.6.3, Use 5 kips
2.2	Az Drive Unit Assy (mtr & brake)	EE	2	Ea	N1	$18,000	Crew R4	16	$467.88	43.5	JPL Concept 1: 2.2.6.8
2.3	Pintal Brg Assy	EE	1	Ea	N1	$12,000	Crew R4	16	$467.88	19.5	JPL Concept 1: 2.2.6.5
2.4	El Drive Assy	EE	1	Ea	EE	$25,000	Crew R4	16	$467.88	32.5	
2.5	El Brg Assy (Each Bearing)	EE	2	Ea	EE	$9,000	Crew R4	16	$467.88	25.5	
2.6	El Drive Beam & El Gear Assy	EE	1	Ea	EE	$45,000	Crew R4	24	$467.88	56.2	
2.7	Subtotal Mech =		8.9485	tons						$412.1	
3.0	**Site Assembly of ARA**										
3.1	Move-on:tools, temp elect, mat & tools storage.	EE	-	-	-	-	Crew B1	40	$183.00	7.3	
3.2	Crane & crew (incl setup & move off) - 4 wks, 160 hrs	EE	-	-	-	-	Crew A-3M	80	$513.38	41.1	Refl, Arm Struct & Refl BUS not incl
3.3	Off-load and stage antenna ARS parts and containers	EE	-	-	-	-	Crew B1	40	$183.00	7.3	
3.4	Pintal Brg Assy on Fnd	EE	-	-	-	-	Crew B1	24	$183.00	4.4	
3.5	Wheel assy on track with base members.	EE	-	-	-	-	Crew B-47H	16	$357.00	5.7	
3.6	Assy ARS structure members 20 x 1.0 hr/memb	EE	-	-	-	-	Crew B-47H	20	$357.00	7.1	
3.7	Assy El Brg and ERS memb, El Drive: 30x 1.3 hr/memb	EE	-	-	-	-	Crew B-47H	24	$357.00	8.6	
5.8	Track (175 lb/yd) Mat + Grinding Track	EE	185	LF	EE	$70	Crew E4	40	$383.13	28.3	RSMeans 34.11.13.23.1000 (100 lb rail) x 2
5.9	Track Hold Down Clips (incl fasteners)	EE	370	EA	EE	$10	Crew B1	24	$183.00	8.1	
3.8	Subtotal ARS Assy =									$117.9	

Engineering Cost Estimate, 4 wheel Mount, 15m Offset Low Antenna 2017-09-28 Matt Fleming

	Foundation Construction W& T	Mat Quan Ref	Mat Quan	Unit Meas	Ref Mat $	Mat / Equip Unit Cost $/Unit	Labor Crew Ref (N2)	Labor Hrs	Labor & Equip N2 Cost $/Hr	Total Cost Incl O&P K$	Remarks
5.0	W&T Concrete Foundation (4 months)										
5.1	Move-on, mobilization, Office & Wk Trailers, Temp Elect	EE	1	EA	N2	$2,156	Crew B1	32	$183.00	8.0	Office Trailer 01.52.13.0550&0700
5.2	Clear and Grub	EE	0.5	Acre	N2	$5,025	-	-	-	2.5	
5.3	Excavation: Clear and level pad, excavate for footings	EE	12000	CY	N2	-	Crew A-3B	40	$314.50	12.6	
5.4	Forms	EE	3694	SF	N2	-	Crew C2	44	$440.25	19.4	RSMeans 03.11.13.85.4230
5.5	Concrete - Footing & Walls	EE	140	CY	EE	$170	Crew C-20	32	$632.25	44.0	Est 4 Conc Pour Days
5.6	Anchor Bolts	EE	320	EA	EE	$15	Crew B1	32	$183.00	10.7	
5.7	Steel ?	EE	185	LF	N2	$150	Crew E4	40	$383.13	43.1	RSMeans 05.12.23.5740
5.10	Foundation Subtotal =									$140.2	

	$/hr	
#	$ 314.50	Crew A-3B: 1 Equip Oper (medium), 1 Truck Driver (heavy), Dump Truck, 12 CY, 400 Hp, 1 F E Loader, W M 2.5 CY.
#	$ 513.38	Crew A-3M: 1 Equip Oper (crane), 1 Equip Oper (oiler), 1 Hyd Crane100 ton (daily), 1 P/U Truck, 3/4 ton (daily)
#	$ 183.00	Crew B-1: 1 Labor Foreman, 2 Laborers
#	$ 357.00	Crew B-47H: 1 Skilled Worker Foreman (out), 3 SkilledWorkers, 1 Flatbed Truck, Gas, 3 ton.
#	$ 440.25	Crew C-2: 1 Carpenter Foreman (outside), 4 Carpenters, 1 Laborer.
#	$ 632.25	Crew C-20: 1 Labor Foreman (outside), 5 Laborers, 1 Cement Finisher, 1 Equip Oper (medium), 2 Vibrator, Gas Engine, 1 Concrete Pump (small)
#	$ 383.13	Crew E-4: 1 Struc Steel Foreman (outside), 3 Struc Steel Workers, 1 Welder, Gas Engine, 300 amp.
#	$ 184.38	Crew E-17: 1 Struc. Steel Foreman (outside), 1 Strucural Steel Worker
#	$ 467.88	Crew R-4: 1 Struc Steel Foreman (ouside), 3 Struc Steel Workers, 1 Electrician, 1 welder, Gas Engine, 300 amp.

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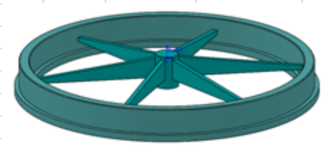

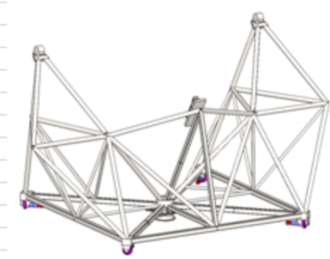

Notes

N1 JPL 70m Study Rpt CY2000 x 1.5 for 17 Yr Inflation@2.2%/yr
N2 RS Means Const Cost 2017: Mat or Equip & [(labor & equip daily total + OH&P) / 8hr]
N3 EE = Engr Estimate
N4 FEM = finite element model data from RISA computer program
N5 Steel Sq & Rd Tube, RSMeans 15.12.23.5390,15.12.23.5390, $4325/ton+10% = $4758/ton (exception 1.70 $/lb)
N6 Plate Steel Gussets .25 to .75: RSMeans05.12.23.65.0400, $1.50/lb
N7 Com'l Sand Blast, RSMeans 05.01.10.6235, $2.46 /SF
N8 Paint Zinc Primer + Alkyds Top Coat, RSMeans 09.97.13.7000, 09.97.13.6830, $1.62+.44 = $2.06 /SF
N9 Truck Transport: Truck+trailer RSMeans 01.54.33.7990 &7300 127+198=$425/day

ARS Az Rotating Structure

Description	Weight (lbs)
El Bearing Set	4,136
El Drive	7,285
Tube Structure	62,070
Az Wheel Sets	10,280
Az Pintle Set	3,904
Total:	87,675

ARS Member Sizes

Item	Name	Size
A	Base Frame	12" sqr x 0.50 wall
B	Drive Triangle	12" sqr x 0.50 wall
C	Side Frames	10" pipe x 0.50 wall
D	Braces	6" pipe x 0.43 wall

	Summary Table	K$
1.0	Struct Steel Frabricaiton, Painting & Shipping to Site	$252.1
2.0	Mechanical Components (Incl Packing & Shipping)	$412.1
3.0	Site Assembly of ARS	$117.9
5.0	Foundation Construction W& T	$140.2
	Total	$922.4

The National Radio Astronomy Observatory and Green Bank Observatory are facilities of the U.S. National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This work was supported by awards AST-2034328 (MSIP Prototype Antenna) and AST-2334267 (ngVLA Design Activities); NRAO related activities are funded under award AST-1647378 (NRAO Operations/Development).