ngVLA Memo 27
Various Suitable Mounts for an 18m Antenna
2017-10-30 Rev 0

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Abstract

A design effort and analysis of several antenna mounts suitable for a proposed 18m NGVLA antenna was undertaken. Antenna specifications revealed precision referenced pointing near 3.0 arc-sec RMS was needed during 7 to 10 m/s winds. Of this we decided 1.0 arc-sec should be allocated to the mount potion of the antenna. With limited resources it was not be possible to do the several complete antenna designs one might desire. Never the less, it is useful to do an analysis of some basic candidate structures for comparison. Three mount designs including foundations were considered: a Pedestal type mount, an open truss three point wheel on track, and an open truss four point wheel on track type mount. For this report the Elevation Rotating Structure was kept the same in all applications. The loading applied to each structure was identical. In a more detailed design study, the load for each structure would be slightly different, especially for the pedestal. The four point structure wheel and track mount was selected as most viable for maximum performance, minimum mass and minimum cost. The three point structure did not do as well, especially when a moment about the azimuth axis is applied. The pedestal mount performed better than we initially expected. The changes needed to successfully apply a pedestal mount are discussed. It appears a pedestal mount could perform adequately, but at higher cost. The document contains an excellent discussion of general issues related to both wheel and track designs and pedestal type designs. The comparison section and conclusion, sections 10 & 11, have useful discussions of potential design and requirement changes and discussion of maintenance issues. An engineering estimate of the cost for each design is presented with details shown in appendix A. The absolute value of these cost estimates is useful, but the relative differences have greater value.

Contents

Acronyms used in this document

AUI	Associated Universities Incorporated
NRAO	National Radio Astronomy Observatory
NRC	National Research Council of Canada
SKA	Square Kilometer Array (international project)
TDP	Technology Development Program (part of US SKA participation, 2008)
DVA-1	Dish Verification Antenna 1 (part of SKA project, NRC & US TDP)
VLA	Very Large Array (27 antennas at 25m each, New Mexico)
NGVLA	Next Generation Very Large Array
VLBA	Very Long Baseline Array (10 antennas 25m each, world wide)
GBT	Green Bank Telescope (100m offset high, antenna)
LMT	Large Millimeter Telescope (50m antenna, Mexico)
BUS	Back Up Structure (supports primary reflector surface)
ARA	Azimuth Rotating Assembly
ARS	Azimuth Rotating Structure
ERA	Elevation Rotating Assembly
ERS	Elevation Rotating Structure
OH	Offset High optical arrangement (pointing at horizon secondary is high)
OL	Offset Low optical arrangement (point at horizon secondary is low)

1. Introduction

The purpose of this study is to examine several different azimuth rotating mount concepts suitable for an 18m offset antenna reflector system. With limited resources, it will not be possible to do the several complete antenna designs one might desire. Never the less, it is useful to investigate the azimuth structures for comparison of cost and performance. With an 18m diameter antenna, a Wheel & Track type mount is a viable design. It is also possible that a Pedestal type with an azimuth bearing is viable.

We have broken the antenna mechanical structures in 3 basic sections. The Elevation Rotating Assembly (ERA) contains the reflectors and feeds and is based on a framework called the Elevation Rotating Structure (ERS). It is held in position on two elevation bearings and an Elevation Drive. These components sit atop the Azimuth Rotating Assembly (ARA) which contains an azimuth drive and bearing or track. And the whole arrangement sits on a properly matched concrete Foundation.

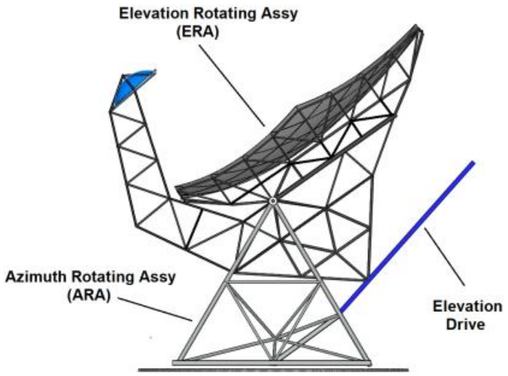

Figure 1.1a Antenna parts

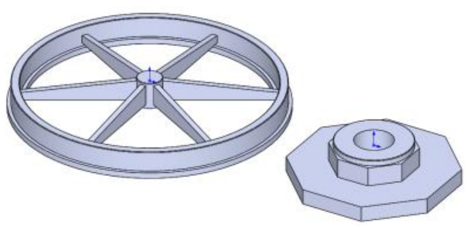

Figure 1.1b Foundations, 2 types

To proceed, we will define and characterize an Elevation Rotating Assy (ERA) and Elevation Drive that might be reasonable to share across all designs. From these, we will generate a set of properties and loads that we can consistently apply while exploring alternate designs for the Azimuth Rotating Assy (ARA) and Foundation.

Each ARA concept will require something slightly different from the ERA and Elevation Drive. We are unable to extend our design effort into these areas. So, for each design, we will discuss the likely changes needed and their effect on performance and cost. These design issues are important and will be presented in the Summary and Comparison, Section 10 of this document.

There is a community interest in the optics configured with the feed Offset Low (OL), that is with the feed and secondary low while looking at the horizon. In general, It is clear the wheel and track designs will adapt well to the OL arrangement and that is the reason for our keen interest. It is also clear OL configuration applied to a Pedestal mount will be more challenging. The lower edge of the primary and backing essentially cut the pedestal off at the knees.

We reviewed quite a few designs for this project and assigned identifying numbers to each one. The designs that were pursued sufficiently to present here are numbered as follows.

Design 1.1 Pedestal with 4.0m azimuth bearing.
Design 3.3 Wheel & Track with 3 wheels & 20m dia track.
Design 4,1 Wheel & Track with 4 wheels & 20m dia track.
These numbers will appear several places in the report to keep data organized.

For all designs, we maintained 11m between elevation bearings and an elevation axis height of 13.5 meters. The azimuth range of motion is +/- 270° and the elevation range of motion is from 12° to 90°. We targeted a natural frequency of 4 to 7 Hz for the antenna structure.

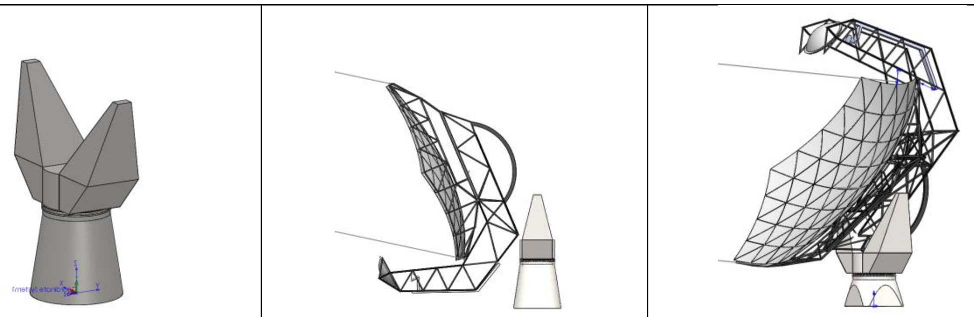
a) Pedestal ARS
b) Pedestal OL 12°
c) Pedestal OH 5°

Figure 1-3 Design 1.1 Pedestal mount

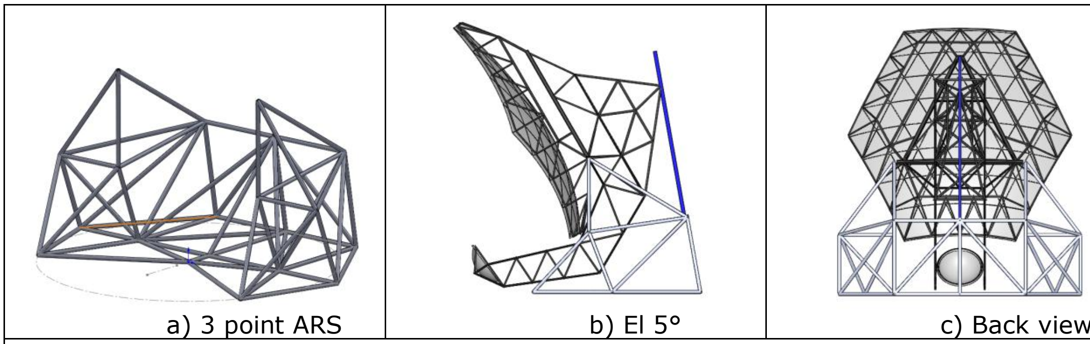
a) 3 point ARS
b) El 5°
c) Back view

Figure 1-4 Design 3.3 Offset Low, 3 point ARA

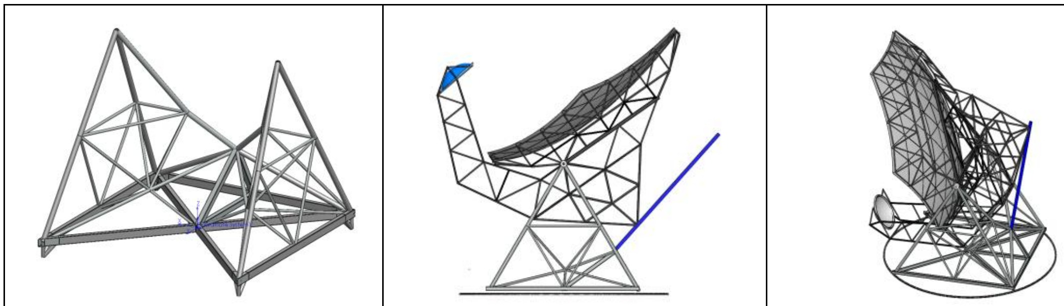
a) 4 point ARS
b) at El 90°
c) Pictorial

Figure 1-5 Design 4.1 Offset Low, 4 point ARA

2. Key Specifications, Loading and Design Drivers

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. Examination of the specifications showed the following items would be design drivers for the ARA: (most importantly items 5 & 6)

1) Aperture diameter 18m (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: 3.0 arc sec RMS (4 deg angle, 15 min time)
6) Pointing Secondary Operations: Day and Night, wind <= 10 m/s
   Referenced pointing: 4.7 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 will match ambient pretty quickly.

Pointing error performance for precision wind switching mode is used as the primary ARS design driver. Switching mode wind load requirement determines the azimuth rotating structure required stiffness. The specified pointing error (PE) requirement is 3 arc seconds. This mode of observation switches between a known strong signal source and a dark location that is within 4 degrees. This limited travel minimizes the gravity and dynamic operation pointing errors. Wind gust loading becomes the dominate deflection concern. Design for low speed winds of 7 m/s cause the structure to deflect from the desired pointing location. The design requirement is to limit the ARS PE to 1 arc second. The remaining 2 arc seconds is allotted to the elevation rotating structure. Nominal (average) wind loads and systematic errors are calibrated and removed using the ephemeris data from the known observed source. Deflection design uses the RMS gust wind load of the random wind gust loads.

We assumed that a characterized antenna with a recent calibration and pointing model could predicted and compensated for 60% of the pointing error. This would leave 40% of pointing error from a constant wind unpredicted. Then there is a gust component adding at about 40% above the average. So, for a 7.0 m/s wind we would use the following equation: Wind speed = $0.4 \cdot W_{avg}$ continuous + $0.4 \cdot W_{avg}$ gust = $0.8 \cdot 7$m/s = 5.6 m/s.

We assume that both azimuth drive and the elevation drive deflections will be measured by the encoders, and we assume the servo system will adjust for the majority of these deflections. A stiff compliance will be important for a reasonably fast servo response for both axes. The elevation encoder's reference is assumed to be the upper portion of the arm supporting the elevation bearings. Our analysis further assumes a pair of elevation encoders, one at each elevation bearing. The defection and local tilting at 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.

For the 2 Truss Type Azimuth Rotating Structures an analysis was performed to determine the minimum track diameter needed for stability. Stability was analyzed for the 120 mph survival wind. Most antennas use a drive to stow wind speed to put the antenna in a more secure location with smaller motor power than the survival wind. This antenna uses a 15 m/s or 35 mph drive to stow wind. To prevent uplift a 20-meter diameter track is required for the stowed wind condition. The wheel housings are planned to have a hold down device that has a small clearance or movement but restrain uplift at the track. Traction is analyzed

for the 35 mph drive to stow condition. No loss of traction was determined for this design. Analysis wind loads were accomplished for the following wind load cases:
Case 1 - EL90 rear wind, Case 2 - EL35 front wind and Case 3 - EL35 120° wind. All truss concepts used the same foundations and elevation rotating structures except for the truss framing to the elevation drive beam connection. The ARS PE is determined as the difference between the antenna RF beam rotation deflection and the encoder read out. Two FEM nodes at the an elevation bearing, one on the El rotating structure El bearing tie beam and one on the ARS at the elevation bearing are used to define the EL PE.

For most of our calculations and Technical Memos, the PE deflections were determined using a 3.5 m/s wind load. When expressing PE deflections from 5.6 m/s we use a multiplier of 2.56 for the values.

3. Assumed Elevation Rotating Assembly (ERA)

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. See figure 3-1 for approximate configuration. The assembly weighs about 71,300 lbs or 32,340 kg. With an allocation of members as shown in Table 3-2

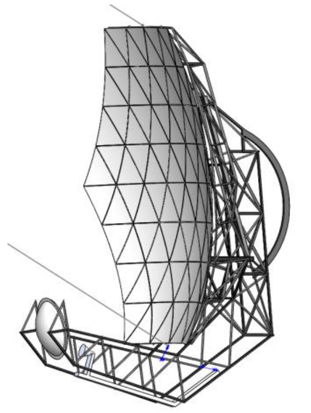

Figure 3-1a

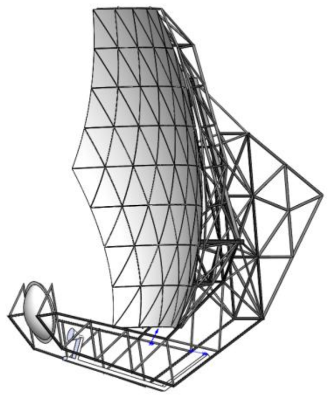

Figure 3-1b

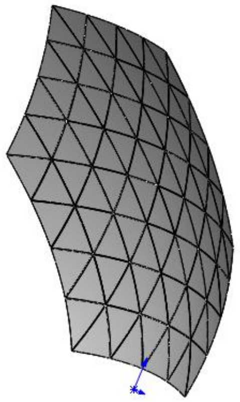

Figure 3-1c

Table 3-2 ERA estimated weight	(rate)(units)	(kips)
Primary Reflector:	(2.5 psf)(3757 sq-ft) =	9.4
Backup Structure (BUS):	(10 plf)(1901 ft) =	19.5
El Structure: Estimate total length:	(25 plf)(1200 ft) =	30.0
El Arm: Estimate total length:	(15 plf)(800 ft) =	12.0
Secondary Reflector:	4.0 psf)(108 sq-ft) =	0.4
El Rotating Subtotal =		71.3

The separation between elevation bearings is 11.0 m or 36 ft or 430”.

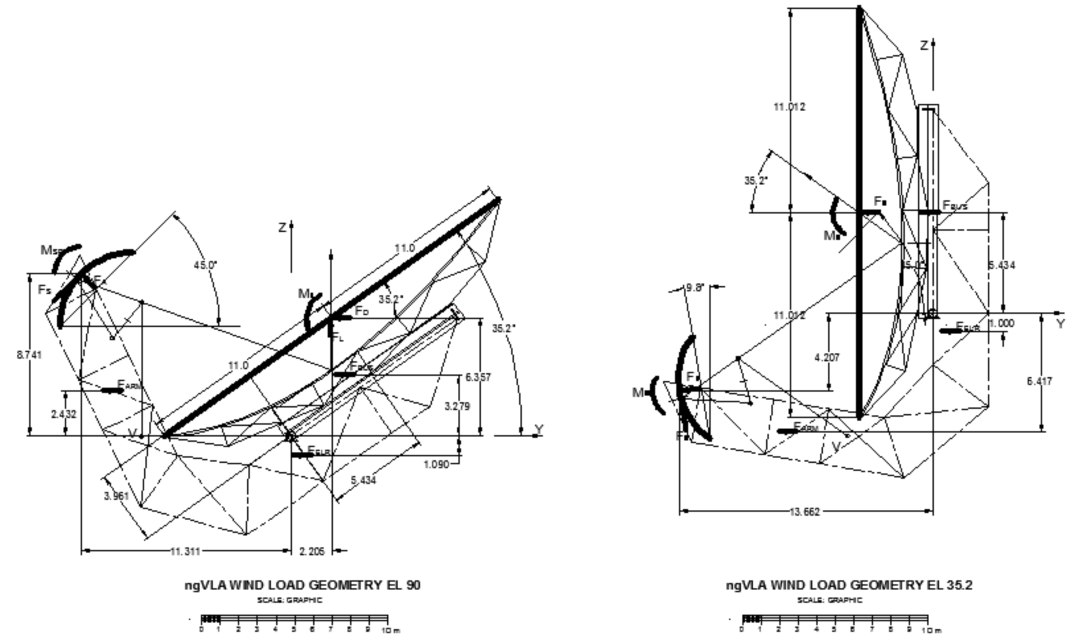

Figure 3-3a ERA Elevation Rotating Assembly

The final design may have a primary reflector from one single piece as done with DVA-1 or many panels deriving surface accuracy from the Back Up Structure (BUS). If metal panels are used we consider it likely that the maximum separation between adjusters will be in the neighborhood of 1.2 m due to gravitational deflection. If composite panels are used the spacing could be greater. In any panel type design where large volumes of panels are made, there is no reason to constrain panel shape to be pie shaped segments of the same profile. This is often done in order to reduce the number of expensive molds. Pie shaped panels impose an inefficient pattern of supports and BUS framework. The panel shapes should be optimized for deflection and manufacturing and chosen to match a structurally sensible framework. The number of panel molds needed should not drive the panel shape, because the cost of those molds will be amortized over so many parts.

We consider that triangular or rectangular panels are likely with an extensive parallel beam BUS or space frame BUS. In any case it is quite likely there will be a cantilevered arm to support the feed package and the secondary reflector. As mentioned the ERA will be allocated 2.0 arc-sec of the available 3.0 arc-sec of pointing error for a 7 m/s wind. The elevation bearing deflections are included in this ERA allocation.

The reflector, feed arm and elevation rotating structure positions locate the center of gravity near the elevation axis. This minimize the need for added counterweight to provide low elevation drive loads.

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4. Assumed Elevation Drive Unit

The Elevation Drive is an integral part of the antenna and has a range of 78° from 12° to 90° at zenith. Like the ERA some elevation drive concept with known properties is needed to achieve a predicted pointing error for the various mount structures under consideration. All of the structures entertained seemed to lend themselves to a single centered drive rather than a dual or parallel drive. Four drive types could be considered candidates.

1) Sector gear & pinion on elevation wheel.
2) Sector direct motor drive.
3) Rack & pinion beam.
4) Ball screw actuator.

With a requirement for exceptional stiffness and pointing accuracy over a long stroke the Ball Screw concept did not seem a good candidate, especially with regard to buckling. The sector direct motor drive is a very interesting candidate, but has traditionally been expensive and was not pursued here. The sector gear and pinion drive is well known and effective. It is also known to be rather expensive with regard to both parts and labor for alignment. The rack & pinion beam drive held our interest, as it can be easily made zero backlash and designed for long column lengths with structures that can resist buckling easily. It seems an attractive option for an offset on a Wheel & Track mount. It could also be applied to a pedestal yoke type mount, but with a desire to limit yoke arm lengths, it is likely a sector gear and pinion drive is a better match. In terms of pointing performance, both could be made to work. Our desire is not to confuse the comparison of structures with variation in the ERA or elevation drive, but it may be impossible. On the costing portion of the study we had to assume some additional cost associated with an elevation drive for a Pedestal and Yoke mount.

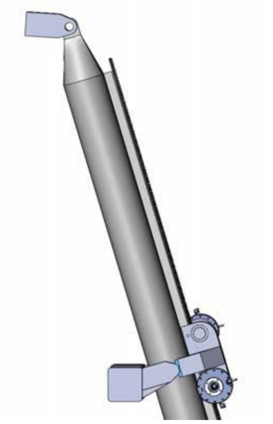


Figure 4-1a

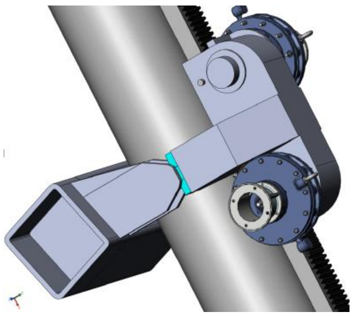


Figure 4-1b

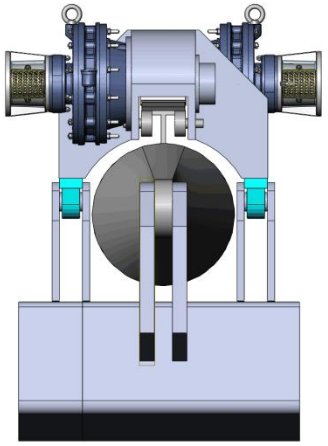


Figure 4-1c

Figure 4-1 shows some views of the elevation rack & pinion beam drive. The drive crawler and beam can be assembled in a factory setting and shipped as a unit for installation on the antenna. This has a good potential for lower cost compared with sector gear & pinion drives or sector direct motor drives.

5. Discussion of Pedestal Designs in general

Pedestal type mounts are based on an azimuth bearing of some diameter. This bearing must have very high stiffness. A properly supported slewing ring type configuration is very effective. This design is based on firm uniform support all around the perimeter of the bearing in line with the roller path. Usually a cylinder above and below the bearing is the best. The supporting structure should be a uniform direct structure with height > 0.5 x the bearing diameter. More is always better. The Turnhead from azimuth bearing to yoke saddle must also have a height > 0.5 x the bearing diameter backed by well aligned steel. This usually means the ERA backing structure members will have a height of at least 2 x the bearing diameter with yoke arms extending up from there. Usually this is not a problem.

Yoke arms are a source of considerable deflection as they are basically cantilevered beams with high moment forces at the connection to the yoke center. They are flexible to both front and back loads, contributing to elevation pointing errors. And they are particularly flexible with cross wind torsional loading contributing to azimuth pointing error. Once loads are resolved to the lower side of the yoke center the azimuth bearing is the next source of significant deflections. The type of load causing the most problematic deflection in a pedestal mount is call an overturning moment load. An Azimuth bearing must have zero clearance and requires a preloaded condition. Most importantly, it must have high stiffness in resisting overturning moment. Often this bearing is 20% of the pedestals contribution to elevation pointing error. The support column below the Azimuth bearing is exceptionally stiff for torsional deflection and contributes little to the azimuth pointing error. However, it is a beam in bending for overturning moment. It is often advantageous to use a cone for this portion of the mount with diameter increasing as load lever arm increases. Another source of deflection is at the interface area between the steel pedestal and the foundation. And finally the foundation itself and the soil make a small contribution to elevation pointing error. This is usually about 10% of the Pedestal typical deflection. A significant foundation will be needed for a pedestal mount to obtain the same stiffness offered by the large circular beam on a wheel and track foundation.

Figure 5-1a
VLA Az bearing & Yoke 25m 230 tons

Figure 5-1b
SKA DVA-1 15.0m OH

Figure 5-2a
MeerKAT 13.5m OL 42 tonnes

Figure 5-2b
MeerKAT El zenith

Pedestal type mounts are usually designed in nice sections that lend themselves to majority factory assembly with only a few large field assembled sections. This means more labor applied in a factory setting and less in the field when compared to a track type antenna. It is difficult to compare these costs. Another nice feature of the pedestal type mount is that it creates a housing for various components such as electrical systems and azimuth wraps. It might be that certain component maintenance activities are easier with the Pedestal type mount. This depends a lot on the individual design. As can be seen in figure 5-2 a pedestal design applied to an Offset Low ERS will require special considerations. These are discussed more in Section 11 Conclusions.

The break point between pedestal type and track type mounts usually is defined by the practicality of machining and shipping pedestal sections. The desired antenna size and pointing requirement will demand a pedestal of significant diameter. In general one wants to stay with structures less than 2.44 m or 8 ft wide for standard transportation. However pieces 4.26 m or 14 ft wide and less than 3.65 m or 12 ft tall are possible. These loads are considered oversize, but permitted with pilot cars on most highways. They are moderately more expensive than standard loads. Loads greater than 14 ft wide often require police escort, which is quite expensive. Taller items can be considered up to 15 ft, but higher than that should be avoided. Extra height means extra cost avoiding bridges and traffic signals.

There are few facilities that can properly stress relieve weldments and precisely machine them in the size range near 14 ft. Basically, the cost of machining parts greater than 8 ft cubes can get pretty high. There is an option to assemble sections on site and machine them in place with specially designed part mounted machines. The azimuth bearing itself will always be the limiting element. Machining the azimuth bearing mounting flanges to precise flatness is essential, and not easily accomplished on large welded parts.
Modern metrology and antenna control systems can characterize the deflections in the antenna mount if they are repeatable for each position. This is why the azimuth bearing is a source of so much discussion. Unrepeatable behavior and debilitating pointing problems can come from improperly manufactured or improperly assembled azimuth bearings and housings. High precision machining is necessary. Even the best machining practices are not likely to produce bearing mating surfaces flatter than about 0.004” on welded structures of this size. A robust bearing should be able to force housings into compliance, but at 4.0m diameter we are near the limit of reasonable expectations. It is important to note that wheel and track antennas do not experience the same issue. Their deflections are very repeatable based on position on the track. Wheel and track will have other less problematic conditions that result from wheel misalignment issues as discussed in the next section.

6. Discussion of Wheel & Track Designs in general

As pointed out an 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. See figure 6-1.


Figure 6-1
Woodbury, 3 point design

Figure 6-2
VLBA Antenna 25m, 240 tons, 4 point


Figure 6-3
GBT 100m dia, 8000 tons

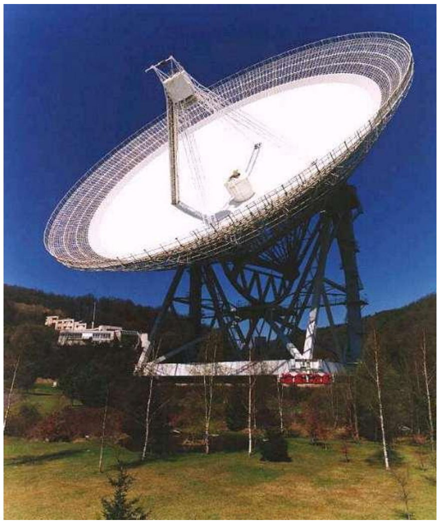


Figure 6-4
Efflesberg 100m, 3200 tonnes

Wheel and Track designs are always employed when a telescope becomes very large and an azimuth bearing is impractical. Very large telescopes such as GBT, LMT, Effelsberg are examples that have very little in common with what we are proposing for ngVLA. See figures 6-3 & 6-4. They have custom designed tracks 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. See figure 6-2. The VLBA antennas have had issues with track grout fracture, rail scuffing, axle troubles, rail joint and wheel alignment problems. These issues and 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 following issues that have given previous telescopes trouble, can be avoided with careful design.

1) The proposed antenna is not very heavy compared with many previous systems, axle loads and wheel contact pressures are relatively small.
2) Crane rail with a wide flat top flange and other favorable dimensions is readily available for our application.
3) It is now common to weld rail at joints and all the tooling and techniques are known and available. See figure 6-5.
4) 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.
5) Our design may require an uplift retention system for certain survival positions. We would use under the rail head retention structures similar to those used successfully on other projects.
6) Rail segments will need to be rolled to the correct radius. This might be possible at the on-site assembly area. In some cases it is necessary to Blanchard grind top and bottom flanges for parallelism. In that case rails would be delivered curved.

Once the rails are 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 may need to be ground by a custom designed grinding machine based on the pintle bearing and an active fast servo track guide system to generate a true planar surface. Figure 6-6a shows an arrangement where grouting will be used to finish rail installation. With special tooling rails can be positioned with all hardware attached and everything is incorporated in a final concrete pour without grouting. See figure 6-6b. In this arrangement errors in flatness of tie plate to rail connections are not an issue. The rail may or may not need a final finish grind. All these techniques need to be explored in several prototype experiments.


Figure 6-5a
Thermite weld


Figure 6-5b
Top side grind mobile tool

Figure 6-5c
Sole plate concept


Figure 6-6a
Multiple tie plates concept


Figure 6-6b
Rails, plates, anchors, supported on tooling

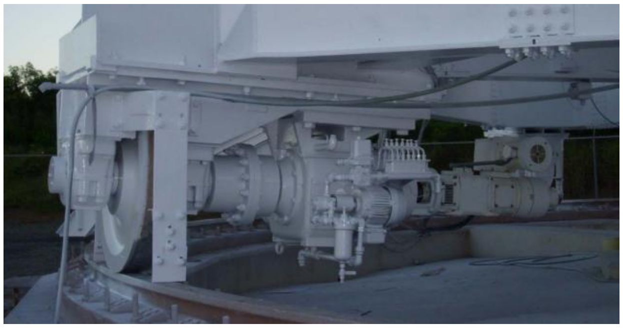


Figure 6-7a
VLBA antenna, driven wheel

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 axis on that plane. 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 on a 300” radius rail.(1) Keep in mind that VLBA antenna weight is about 450,000 lbs. It runs on 4 wheels at 36” diameter. Wheel loads are in a range that reaches 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 50,000 to 70,000 lbs. There are several good reasons to use oversized axles. Axle deflection and bearing longevity will be much better. We have also engaged in useful discussions with engineers at Gantrex and 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

Figure 6-8 shows some FEA work to characterize the various deflections associated with axle, wheel & track deformations. The analysis showed that all these deformations are small compared with the entire structure, perhaps at the 10% level.

As mentioned earlier, it is important to note that the ELA portion of this antenna is relatively light at perhaps 72,000 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. The antenna is almost always heavy enough that uplift on wheels does not occur. However, in very extreme conditions it is wise to have a retention bracket extending under the rail head and in some cases a clamping method. The rail tie down system appears to be adequate to transfer reasonable loads to the foundation. Further investigation is needed with exact antenna component weights and wind lift calculations.

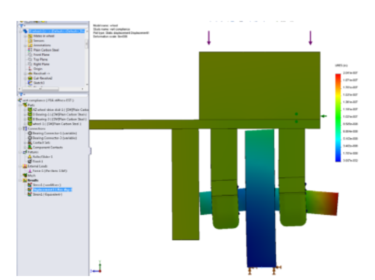


Figure 6-8a axle deflection

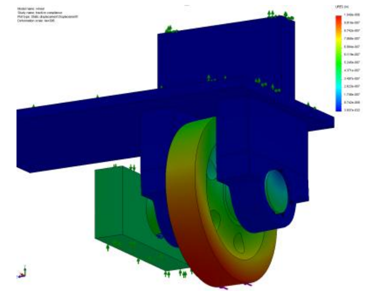


Figure 6-8b wheel deflection

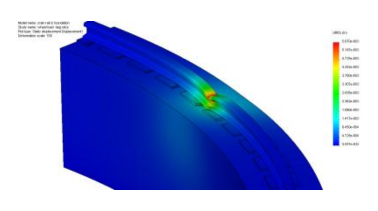


Figure 6-8c rail deflection

7. Pedestal Design Analysis (design 1.1)

As discussed in the Introduction the Pedestal and truss structures were analyzed with the same loading cases. The foundation was assumed to be a 30 ft octagon x 3′ thick, with a riser 20′ octagon x 5′ tall with a 10′ hallow at the center. See figure 7-1. The pedestal is designed around an azimuth bearing with a rolling element path at 4.0 m. This size was chosen because when it is mounted in housings and other support structures it will most likely be about 4.26m or 14 ft. This is basically the upper limit for transport at reasonable cost on most US roads. The plate structures in the base below the azimuth bearing are modeled from 25.4mm or 1″ steel plate. The plate structures of the yoke above the azimuth bearing are also modeled from 1″ steel plate. The basic dimensions of the structure are shown in figure xx. The structures estimated weight is 170,400 lbs with machinery added to that. The azimuth bearing is assumed to have a cross section of 9″ tall x 12″ wide. We assumed an overturning moment compliance of 3.26E-12 rad/in-lb. A single row crossed roller bearing can have up to 2 x the stiffness of a single row 4 point contact ball bearing. A crossed roller design also has higher turning torque and stick slip when compared to a 4 point contact ball bearing. The analysis shows the following Pointing Error for our 3 governing wind load cases.

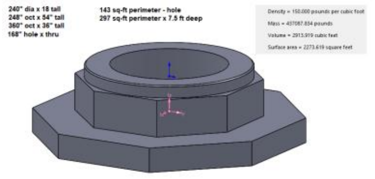


Figure 7-1a

Table 7-2	**1.1 Pedestal Mount Weights**	**(tons)**
Yoke Arms & Center Section	1.00″ plate walls, 2.5″ plate base.	32.5
Support Cone Section	1.00″ plate walls, 2.5″ flanges.	52.9
	Sub Total:	85.2
All other items	Az brg, Az drives, El brgs, El drives	20.5
	Total:	105.7
	more detail in Appendix A Table 1	

Table 7-3 Mount 1.1			
Wind Case & Pointing Error (PE)	EL	XEL (cross EL)	PE (total)
	(arc-sec)	(arc-sec)	(arc-sec)
El 90, Az 180 rear wind	-0.61	0.00	0.61
El 35, Az 0 front wind	1.08	0.00	1.08
El 35, Az 120 cross wind	-1.10	-0.13	1.10

As can be seen in figure 7-4b, a functional Pedestal will require modification of both the ARA yoke arms and the ERS. The elevation axis will have to be moved and most likely additional counterweight will be needed. More comments will be presented in Section 10 Summary and Comparison.

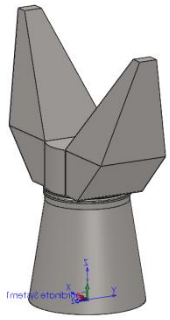


Figure 7-4a

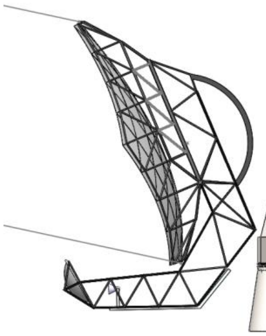


Figure 7-4b

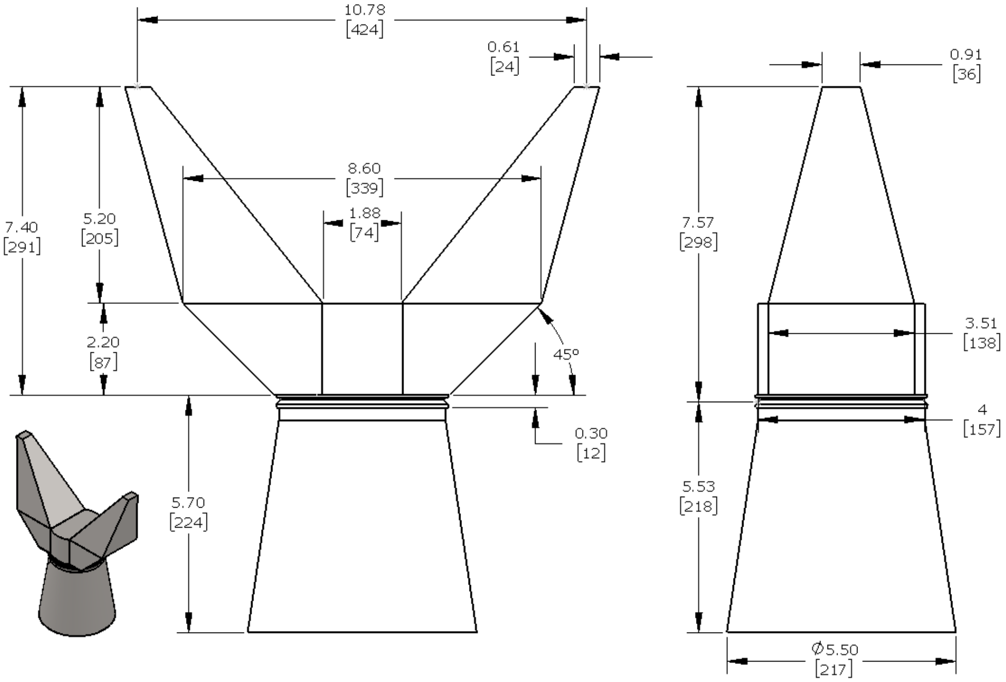


Figure 7-5
Basic dimensions

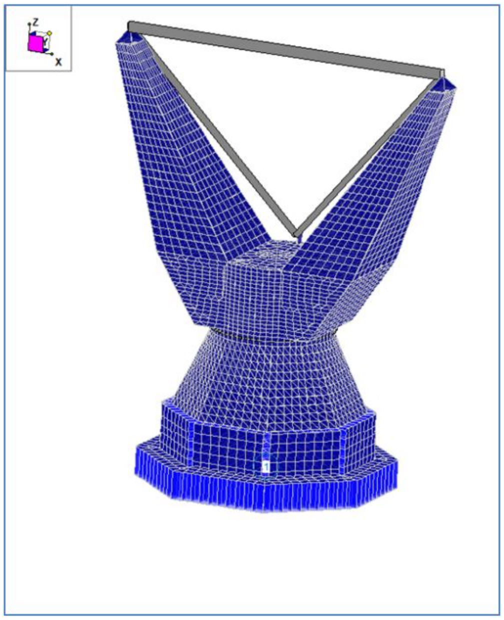


Figure 7-6a
FEA model for analysis

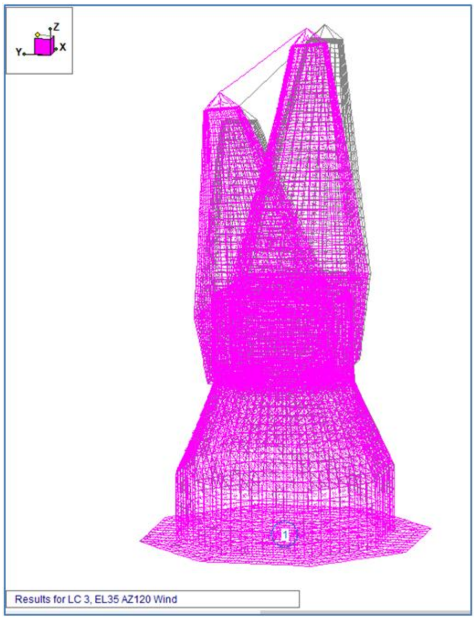


Figure 7-6b
FEA model load case 3 deflection

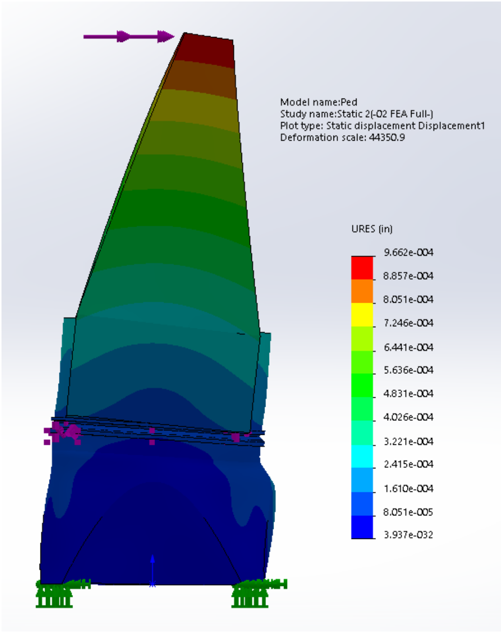


Figure 7-7a
Typical deflection for face load

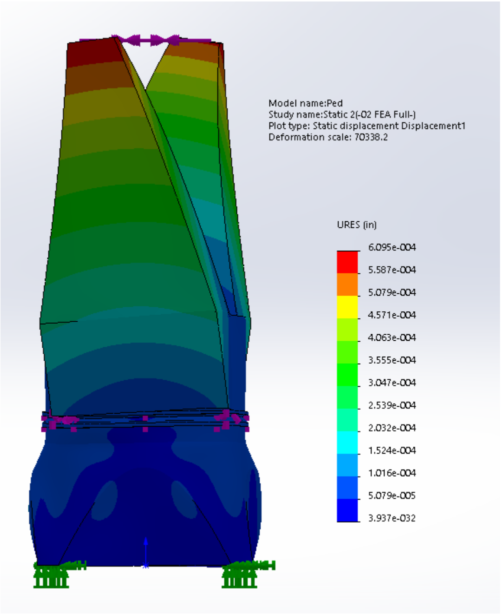


Figure 7-7b
Typical deflection for torsional load

8. Three Wheel Design Analysis (design 3.3)

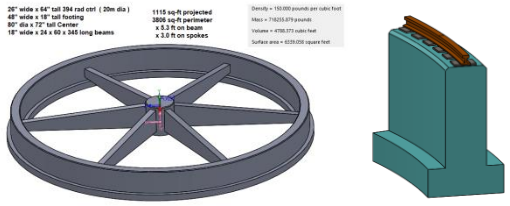


Figure 8-1

Both a three wheel and a four wheel ARA were designed and analyzed. Both use a 20m diameter track using 171 lb/yd crane rail. The foundation beam is 26" wide x 60 tall sitting on a footing 4' wide x 1.5' tall. The pintle foundation is 6.5' in diameter. In figure 8.1 the pintle foundation is shown stabilized by a spoke arrangement. A better design would likely have a simple shallow conical slab capturing the top of the pintle foundation. This would probably use less material and it would prevent rain water from entering the center foundation area.

A central pintle bearing is imagined to be a large diameter spherical roller bearing with a slip fit on a vertical axle. Cables are imagined to come up through the center to an area above for a cable wrap. Wheels are assumed at 36" diameter, however smaller will likely work. Axles and bearings are design oversize to ensure reduced maintenance.

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 corner points, it is statically determinate, assuming axial compliance at the radial pintle bearing. This design does well for wind loads either face on or from behind, at 0 or 180° azimuth, and this is true for all elevation angles. This is most likely true because the load path form the elevation drive goes very directly to the rear wheel. Unfortunately deflection from side wind loading is much more 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 pointing performance is lower than expected. Significant additional structure is required to resist the deflection around the azimuth axis. Indications are we should improve some of our geometry.

The structures estimated weight is 230,200 lbs with machinery added to that. The design we are considering has wheel loads in the range 70,000 to 90,000 lbs. The ARS portion of the antenna is comprised of the following members:

Table 8-2	**3.3 Wheel & Track Mount Weights**	**(tons)**
Main Load Members	22 x 22 square tube x 0.81 wall	83.0
Other Load Members	20 x 20 square tube x 0.38 wall	24.6
Bracing Members	8.63 tube x 0.500 wall	7.5
	Sub Total:	115.1
All other items	Az brg, Az drives, El brgs, El drives	22.5
	Total:	137.6
	more detail in Appendix A Table 2	

Table 8-3 Mount 3.3			
Wind Case & Pointing Error (PE)	EL	XEL (cross EL)	PE (total)
	(arc-sec)	(arc-sec)	(arc-sec)
El 90, Az 180 rear wind	-2.51	0.0	2.51
El 35, Az 0 front wind	-.26	0.0	0.26
El 35, Az 120 cross wind (0.25)	2.45	-5.25	5.79

Data from TM050117 Rev0 with modification to PE of case 3 by MCF 0.25.

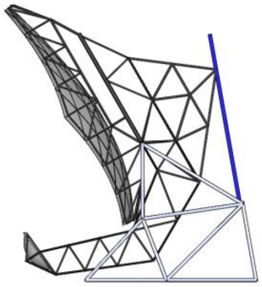


Figure 8-4a
3 wheel ARS, side view

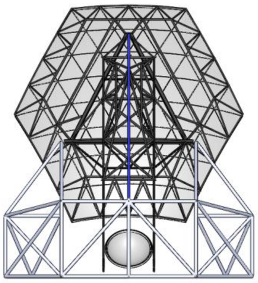


Figure 8-4b
3 wheel ARS, front view

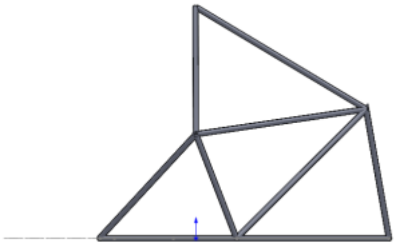


Figure 8-5a
3 wheel, structure only, side view

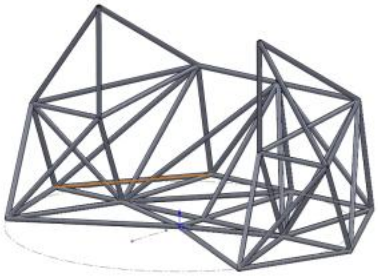


Figure 8-5b
3 wheel, structure only, pictorial

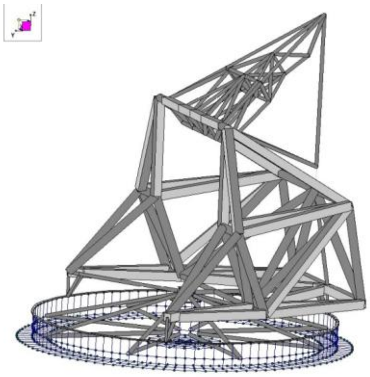


Figure 8-6a
3 wheel, El 90

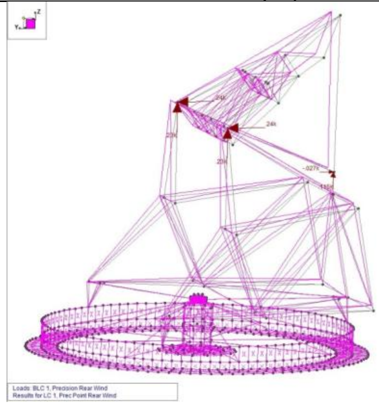


Figure 8-6b
3 wheel, deflected
El 90, Az wind on rear

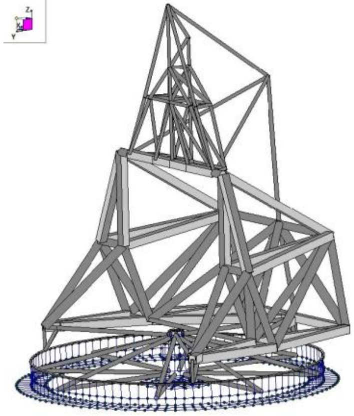


Figure 8-7a
3 wheel, El 35

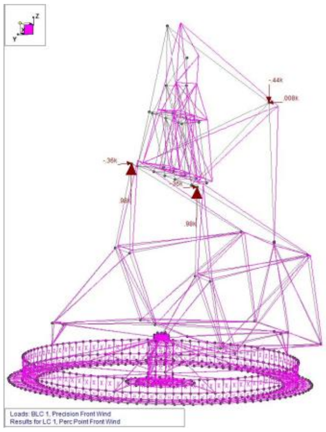


Figure 8-7b
3 wheel, El 35, Az 0 wind on face

9. Four Wheel Design Analysis (design 4.1)

The four wheel ARA uses the same foundation and wheel sizes as described for the 3 point design. It 4 wheels, 2 of which are driven and the same pintle bearing concept as described above. The 4 wheel design has better stability and better deflection performance than any other design for the same weight of material. In theory a structure supported at 4 points is statically indeterminate, however, a very flat track and the elastic behavior of steel will prevent high stresses in the structure. The deflection from wind at azimuth 0° front & 180° rear, are slightly worse than the 3 wheel arrangement because the elevation loads do not have a direct load path to 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 to nodding. The structure is very much better when a moment about the azimuth axis is applied, because of the wider stance offered with 4 support locations. The structure could probably be optimized further for lower mass and near similar deflections. The fabricated structure shown here has an estimated weight is 175,600 lbs with rails wheel and other machinery added to that. It has achieved about 0.89 arc-sec in a 7m/s wind. Wheel loads 55,000 to 75,000 lbs. Our deflection analysis for 3 key load cases is shown in table 9-3. Figure 9-6a shows tilting at top of elevation bearing area. Figure 9-6b shows typical bending in members.

Table 9-2	**4.1 Wheel & Track Mount Weights**	**(tons)**
Main Load Members	22 x 22 square tube x 0.81 wall	55.3
Other Load Members	10 x 10 square tube x 0.23 wall	4.4
Bracing Members	miscellaneous sizes	23.2
	Sub Total:	87.8
All other items	Az brg, Az drives, El brgs, El drives	25.0
	Total:	110.3
	more detail in Appendix A Table 3	

Table 9-3 Mount 4.1			
Wind Case & Pointing Error (PE)	EL	XEL (cross EL)	PE (total)
	(arc-sec)	(arc-sec)	(arc-sec)
El 90, Az 180 rear wind	-0.21	0.0	0.21
El 35, Az 0 front wind	-0.89	0.0	0.89
El 35, Az 120 cross wind	0.35	-0.74	0.82

Source TM050117 Rev 0 & Optimized 100217c

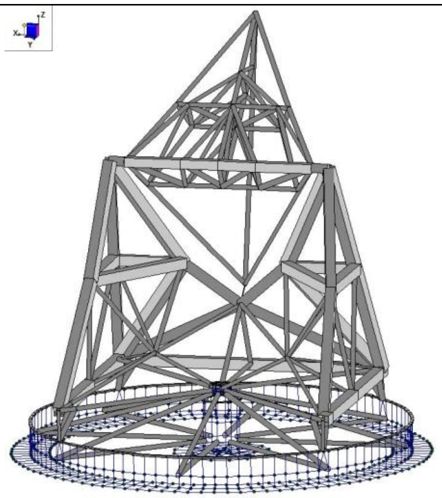


Figure 9-4a
4 wheel, El 90

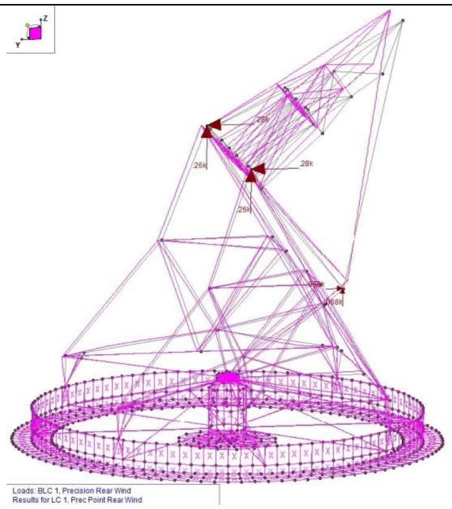


Figure 9-4b
4 wheel, El 90, Az wind on rear

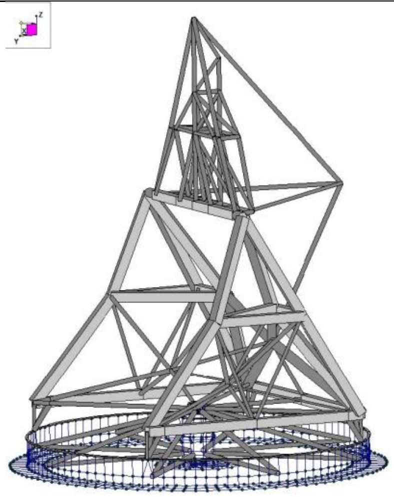


Figure 9-5a
4 wheel, El 35

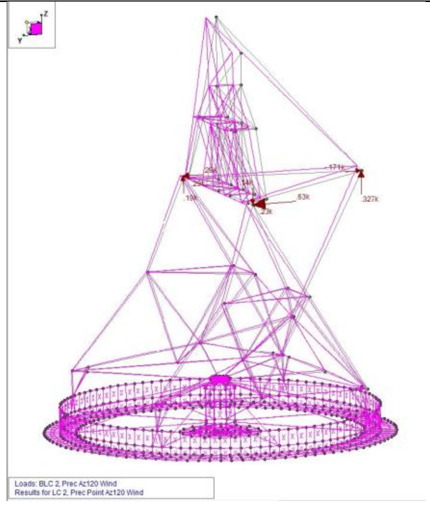


Figure 9-5b
4 wheel, El 35, Az 120 cross wind

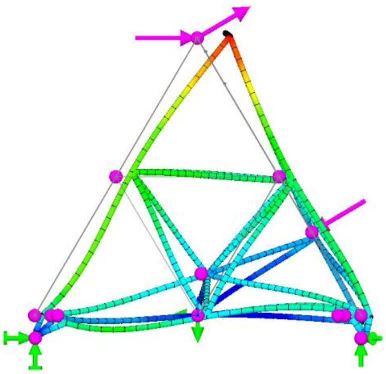


Figure 9-6a
Typical deflection
wind on face

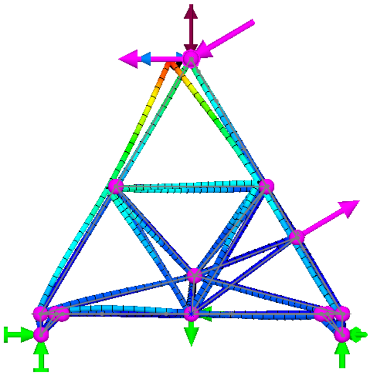


Figure 9-6b
Typical deflection
wind across at 120°

10. Summary Comparison of Performance and Cost

Below is a summary of estimated performance & weight & cost for 3 mount configurations as described in detail above. The cost estimates are generated from several sources. The primary source is data from the R. S. Means estimating system. Other sources were adjusted historical data from previous projects and recent experience. It is our opinion that a more thorough costing effort could produce a lower figures by as much as 20%. 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 the mechanical components section of the cost spreadsheet, since it is very analogous to the azimuth bearing in other mount designs.

The 3 point design does well for wind load cases 1 & 2 with either face on or from behind, at 0 or 180° azimuth, and this is true for various elevation angles. In fact the 3 point design does a little better than the four point design for these loadings, because of the direct line for elevation drive loads to the rear wheel. Unfortunately, deflection from side wind loading, case 3, is very difficult to control. 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.

The 4 point design does considerably better than the 3 point when all load cases are considered. An alternate statement would be that the 4 point design achieves similar or better pointing error than the 3 point design for less material and lower cost.

The pedestal design did better than we initially expected. We made an assumption that a 4.0m bearing would be needed and found that a structure primarily of 1" steel plate performed pretty well. Unfortunately, we cannot do an apples to apples comparison without a more detailed separate design. As can be seen in figure 7-4b, a functional Pedestal for an OL configuration will require yoke arms bent forward adding perhaps 10% to the structure cost. The ERS will require the elevation axis be moved further back, cantilevering the reflector set away a bit more and requiring additional counterweight. This would add perhaps 20% to the ERA cost. The elevation drive for this arrangement will not lend itself as well to the Gear Beam concept because the yoke saddle does not allow as large a radius for the drive to act on. The yoke design tends to favor an elevation wheel sector gear application. This is very likely 40% more expensive, as alignment of gear segments and setting pinion clearance is often an arduous expensive task, generally done in the field. The Az drive cost is also higher because higher torque and stiffness will be required since the machinery is working at a shorter mechanical advantage. This increased cost is associated with the ARA and is captured in the cost estimate presented for the Pedestal mount.

Table 10-1 Pointing Error	El PE	XEl PE	PE (arc-sec)
1.1 Pedestal	-1.10	-0.13	1.10
3.3 Three Point	2.45	-5.25	5.79
4.1 Four Point	0.35	-0.74	0.82

Source: TM050117 Rev 0 & TM092417 Rev 2, Load Case 3.

Table 10-2 Weights	Structure (tons)	Mech (tons)	Total (tons)
1.1 Pedestal	85.2	20.5	105.3
3.3 Three Point	115.1	22.5	137.6
4.1 Four Point	87.8	25.0	110.3

Sourrce: Appendix A sheet 1 – 4, Weight in US tons 2,000 lbs.

Table 10-3 Cost	Foundation (k$)	Structure (k$)	Mech (k$)	Site (k$)	Total (k$ USD)
1.1 Pedestal (partial)	91.7	853.4	285.4	92.8	1,324
3.3 Three Point	116.3	593.9	385.1	96.8	1,152
4.1 Four Point	116.3	447.5	379.0	96.8	1,040

Source: Appendix A sheet 1 – 4.

11. Conclusions & Recommendations

In conclusion we find the 4 point Wheel and Track mount very attractive for cost and performance. We initially imagined that the wheel and track designs would clearly out perform a pedestal type mount, but were surprised to find that a 4.0m pedestal performed pretty well. If the pedestal mount ARA was applied to an ERA configured for Offset High (OH) optics, we would have a near comparable situation. However, the Offset Low (OL) configuration will require that both the pedestal mount and the connected ERA would have to be modified.

For the pedestal mount with the ERA arranged OL, the elevation axis position relative to the primary may have to be moved to a less favorable location and the yoke arms may have to be extended forward significantly. Both changes increase drive loads and deflection values. Figure 11-2 shows how the MeerKAT project dealt with this issue. The pedestal in extended but still held in close to the primary. This is wise because it reduces counterweight requirements. The majority of accommodation comes from the channel on the lower side of the BUS. This channel creates a structural challenge due to loss of rigidity and a torsional compliance during wind load or accelerations in the side to side direction of the feed arm. Effectively this lowers the natural frequency of the structure. This is most likely an sensible compromise for a lower frequency antenna. The final pedestal design may require the array spacing to exceed the 30m spacing requirement for the array to provide clearance. The truss wheel and track design just fits the 30m spaced array specification.

For all the mounts considered here, it is 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 VLBA antenna azimuth drive wheel Figure 6-7a and Figure 11-1a. 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.

The presented wheel and track designs has wheels with no flanges and will most likely work well with relatively low normal forces. All axial loads on wheels will be transmitted to the pintle bearings. 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. See figures 11-1a & 1b. 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. Or a better solution is, a single pour of reinforced concrete up the base of the track, which has been used on other designs and has shown long life without grout or concrete failure. The MMT rotating building has lasted over 40+ years with very high wheel line loads (kips per inch) compared with other failed designs.

Whether the ERA is applied OL or OH, Almost all equipment serviced on this antenna will be too heavy for a single person to lift. Activities more than a few feet off the ground will require special access equipment or vehicles such as trucks lift beds and personnel buckets. We strongly recommend self removing equipment packages. See figure 11-3b. Equipment packages should be made to detach and lower to a service level rather than force maintenance activities at difficult to reach locations.

Just to show that it is hard to have a new idea in a field full of clever people, take a look at Figures 11-4. The equipment package is lowered to ground level for servicing. The good ideas are the same, the materials and labor ratios over time are what change the balance from one design to another. Another influence is the number of antennas in the system and the opportunity to amortize the cost of special tools over many antennas.

We are would like to remind the reader that from a structural standpoint Offset High (OH) configuration significantly reduces loads and deflections on the mount. The GBT is the ultimate surrender to this truth. Figure 11-3 is an illustration of OH configuration. There may be compelling performance reasons, such as reduced spillover, that favor OL in spite of the structural reasons. If Offset Low OL configurations are chosen, the performance improvement justification should be strong. Maintenance and access to equipment should not be a strong factor, as equipment packages requiring frequent maintenance should be self installing from a easy service level. With all this said, there are two additional points to understand. For the ERA, the primary surface probably has less gravitational deformation in the OL application, because the majority of the structure is in a more vertical orientation rather than cantilevered out as is the case for bird bath position. This is somewhat dependent on the aspect ratio of the dish and backing, but for a fairly flat offset primary it is something to keep in mind. The preferred stow position and water collection is another factor that enters the OL and OH tradeoff comparison.

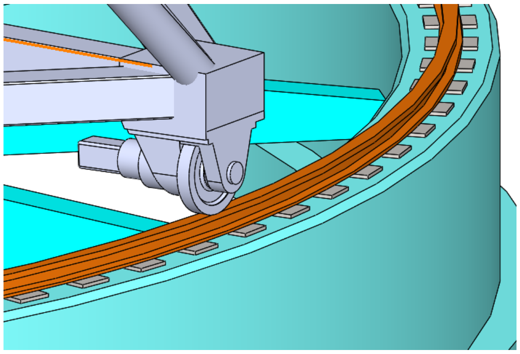
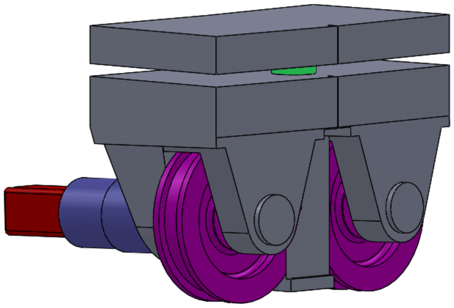
 Figure 11-1a	 Figure 11-1b

Figure 11-2a MeerKAT OL El 15°

Figure 11-2b MeerKAT BUS channel

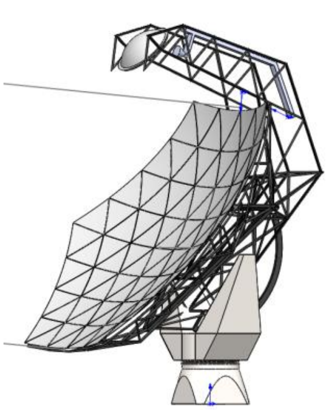


Figure 11-3a Pedestal OH El 5°

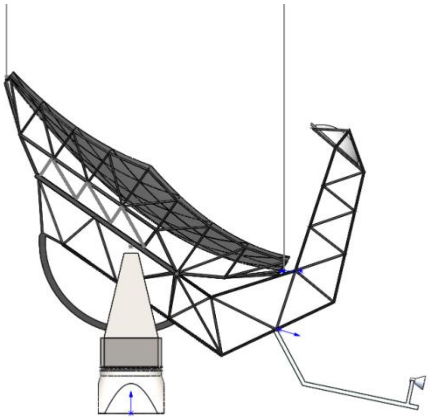


Figure 11-3b Feed equipment lowered.

Figure 11-4a SRI Dish Stanford

Figure 11-4b Feed equipment lowered.

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),
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Direct Fixation Track Design, 2005-May, Laurence E. Daniels Railroad Consulting Engineer & Bill Moorhead owner TRAMMCO, LLC

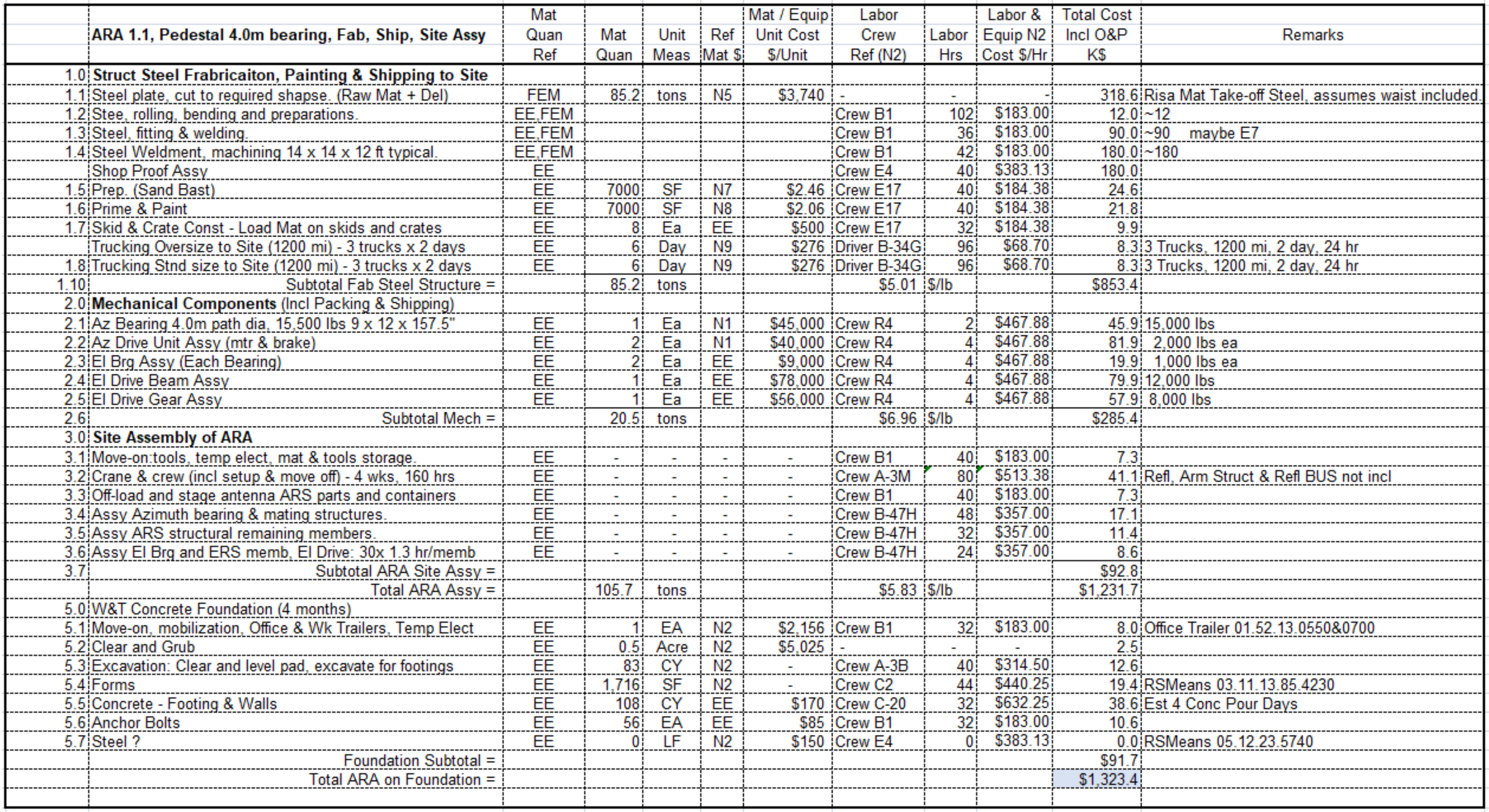
3) L. B. Forester Co.
Rails & Accessories.

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

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

5) D.Chalmers, G.Lacey, M Islam, M.Fleming L Baker, ngVLA Technical Study Morgan Offset Suitable Mounts for a 15m Offset Antenna, Oct 2017, ngVLA Memo #26

Appendix A 1 of 4



	ARA 1.1, Pedestal 4.0m bearing, Fab, Ship, Site Assy	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 plate, cut to required shapse. (Raw Mat + Del)	FEM	85.2	tons	N5	$3,740	-	-	-	318.6	Risa Mat Take-off Steel, assumes waist included.
1.2	Stee, rolling, bending and preparations.	EE,FEM					Crew B1	102	$183.00	12.0	~12
1.3	Steel, fitting & welding.	EE,FEM					Crew B1	36	$183.00	90.0	~90 maybe E7
1.4	Steel Weldment, machining 14 x 14 x 12 ft typical.	EE,FEM					Crew B1	42	$183.00	180.0	~180
	Shop Proof Assy	EE					Crew E4	40	$383.13	180.0	
1.5	Prep. (Sand Bast)	EE	7000	SF	N7	$2.46	Crew E17	40	$184.38	24.6	
1.6	Prime & Paint	EE	7000	SF	N8	$2.06	Crew E17	40	$184.38	21.8	
1.7	Skid & Crate Const - Load Mat on skids and crates	EE	8	Ea	EE	$500	Crew E17	32	$184.38	9.9	
	Trucking Oversize to Site (1200 mi) - 3 trucks x 2 days	EE	6	Day	N9	$276	Driver B-34G	96	$68.70	8.3	3 Trucks, 1200 mi, 2 day, 24 hr
1.8	Trucking Stnd size to Site (1200 mi) - 3 trucks x 2 days	EE	6	Day	N9	$276	Driver B-34G	96	$68.70	8.3	3 Trucks, 1200 mi, 2 day, 24 hr
1.10	Subtotal Fab Steel Structure =		85.2	tons			$5.01	$/lb		$853.4	
2.0	**Mechanical Components** (Incl Packing & Shipping)										
2.1	Az Bearing 4.0m path dia, 15,500 lbs 9 x 12 x 157.5"	EE	1	Ea	N1	$45,000	Crew R4	2	$467.88	45.9	15,000 lbs
2.2	Az Drive Unit Assy (mtr & brake)	EE	2	Ea	N1	$40,000	Crew R4	4	$467.88	81.9	2,000 lbs ea
2.3	El Brg Assy (Each Bearing)	EE	2	Ea	EE	$9,000	Crew R4	4	$467.88	19.9	1,000 lbs ea
2.4	El Drive Beam Assy	EE	1	Ea	EE	$78,000	Crew R4	4	$467.88	79.9	12,000 lbs
2.5	El Drive Gear Assy	EE	1	Ea	EE	$56,000	Crew R4	4	$467.88	57.9	8,000 lbs
2.6	Subtotal Mech =		20.5	tons			$6.96	$/lb		$285.4	
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	Assy Azimuth bearing & mating structures.	EE	-	-	-	-	Crew B-47H	48	$357.00	17.1	
3.5	Assy ARS structural remaining members.	EE	-	-	-	-	Crew B-47H	32	$357.00	11.4	
3.6	Assy El Brg and ERS memb, El Drive: 30x 1.3 hr/memb	EE	-	-	-	-	Crew B-47H	24	$357.00	8.6	
3.7	Subtotal ARA Site Assy =									$92.8	
	Total ARA Assy =		105.7	tons			$5.83	$/lb		$1,231.7	
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	83	CY	N2	-	Crew A-3B	40	$314.50	12.6	
5.4	Forms	EE	1,716	SF	N2	-	Crew C2	44	$440.25	19.4	RSMeans 03.11.13.85.4230
5.5	Concrete - Footing & Walls	EE	108	CY	EE	$170	Crew C-20	32	$632.25	38.6	Est 4 Conc Pour Days
5.6	Anchor Bolts	EE	56	EA	EE	$85	Crew B1	32	$183.00	10.6	
5.7	Steel ?	EE	0	LF	N2	$150	Crew E4	0	$383.13	0.0	RSMeans 05.12.23.5740
	Foundation Subtotal =									$91.7	
	Total ARA on Foundation =									$1,323.4	

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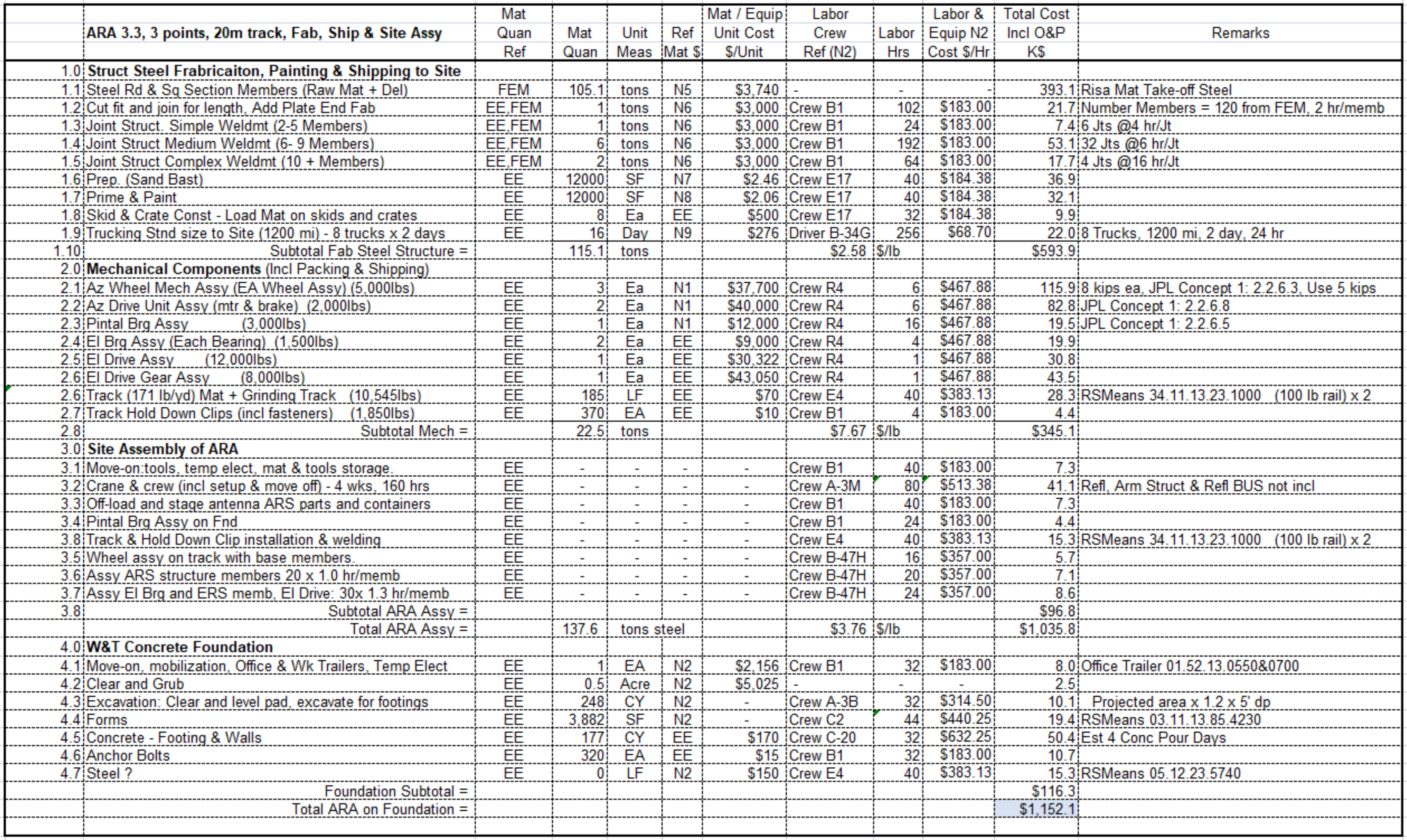

	ARA 3.3, 3 points, 20m track, Fab, Ship & Site Assy	Mat Quan Ref	Mat Quan	Unit Meas	Ref Mat $	Mat / Equip Unit Cost $/Unit	Labor Crew Ref (N2)	Labor Hrs	Labor & Equip N2 Cost $/Hr	Total Cost Incl O&P K$	Remarks
1.0	**Struct Steel Frabricaiton, Painting & Shipping to Site**										
1.1	Steel Rd & Sq Section Members (Raw Mat + Del)	FEM	105.1	tons	N5	$3,740	-	-	-	393.1	Risa Mat Take-off Steel
1.2	Cut fit and join for length, Add Plate End Fab	EE,FEM	1	tons	N6	$3,000	Crew B1	102	$183.00	21.7	Number Members = 120 from FEM, 2 hr/memb
1.3	Joint Struct. Simple Weldmt (2-5 Members)	EE,FEM	1	tons	N6	$3,000	Crew B1	24	$183.00	7.4	6 Jts @4 hr/Jt
1.4	Joint Struct Medium Weldmt (6- 9 Members)	EE,FEM	6	tons	N6	$3,000	Crew B1	192	$183.00	53.1	32 Jts @6 hr/Jt
1.5	Joint Struct Complex Weldmt (10 + Members)	EE,FEM	2	tons	N6	$3,000	Crew B1	64	$183.00	17.7	4 Jts @16 hr/Jt
1.6	Prep. (Sand Bast)	EE	12000	SF	N7	$2.46	Crew E17	40	$184.38	36.9	
1.7	Prime & Paint	EE	12000	SF	N8	$2.06	Crew E17	40	$184.38	32.1	
1.8	Skid & Crate Const - Load Mat on skids and crates	EE	8	Ea	EE	$500	Crew E17	32	$184.38	9.9	
1.9	Trucking Stnd size to Site (1200 mi) - 8 trucks x 2 days	EE	16	Day	N9	$276	Driver B-34G	256	$68.70	22.0	8 Trucks, 1200 mi, 2 day, 24 hr
1.10	Subtotal Fab Steel Structure =		115.1	tons			$2.58	$/lb		$593.9	
2.0	**Mechanical Components** (Incl Packing & Shipping)										
2.1	Az Wheel Mech Assy (EA Wheel Assy) (5,000lbs)	EE	3	Ea	N1	$37,700	Crew R4	6	$467.88	115.9	8 kips ea, JPL Concept 1: 2.2.6.3, Use 5 kips
2.2	Az Drive Unit Assy (mtr & brake) (2,000lbs)	EE	2	Ea	N1	$40,000	Crew R4	6	$467.88	82.8	JPL Concept 1: 2.2.6.8
2.3	Pintal Brg Assy (3,000lbs)	EE	1	Ea	N1	$12,000	Crew R4	16	$467.88	19.5	JPL Concept 1: 2.2.6.5
2.4	El Brg Assy (Each Bearing) (1,500lbs)	EE	2	Ea	EE	$9,000	Crew R4	4	$467.88	19.9	
2.5	El Drive Assy (12,000lbs)	EE	1	Ea	EE	$30,322	Crew R4	1	$467.88	30.8	
2.6	El Drive Gear Assy (8,000lbs)	EE	1	Ea	EE	$43,050	Crew R4	1	$467.88	43.5	
2.6	Track (171 lb/yd) Mat + Grinding Track (10,545lbs)	EE	185	LF	EE	$70	Crew E4	40	$383.13	28.3	RSMeans 34.11.13.23.1000 (100 lb rail) x 2
2.7	Track Hold Down Clips (incl fasteners) (1,850lbs)	EE	370	EA	EE	$10	Crew B1	4	$183.00	4.4	
2.8	Subtotal Mech =		22.5	tons			$7.67	$/lb		$345.1	
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	
3.8	Track & Hold Down Clip installation & welding	EE	-	-	-	-	Crew E4	40	$383.13	15.3	RSMeans 34.11.13.23.1000 (100 lb rail) x 2
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	
3.8	Subtotal ARA Assy =									$96.8	
	Total ARA Assy =		137.6	tons steel			$3.76	$/lb		$1,035.8	
4.0	**W&T Concrete Foundation**										
4.1	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
4.2	Clear and Grub	EE	0.5	Acre	N2	$5,025	-	-	-	2.5	
4.3	Excavation: Clear and level pad, excavate for footings	EE	248	CY	N2	-	Crew A-3B	32	$314.50	10.1	Projected area x 1.2 x 5' dp
4.4	Forms	EE	3,882	SF	N2	-	Crew C2	44	$440.25	19.4	RSMeans 03.11.13.85.4230
4.5	Concrete - Footing & Walls	EE	177	CY	EE	$170	Crew C-20	32	$632.25	50.4	Est 4 Conc Pour Days
4.6	Anchor Bolts	EE	320	EA	EE	$15	Crew B1	32	$183.00	10.7	
4.7	Steel ?	EE	0	LF	N2	$150	Crew E4	40	$383.13	15.3	RSMeans 05.12.23.5740
	Foundation Subtotal =									$116.3	
	Total ARA on Foundation =									$1,152.1	

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	ARA 4.1, 4 points, 20m track, Fab, Ship & Site Assy	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	77.75	tons	N5	$3,740	-	-	-	290.8	Risa Mat Take-off Steel
1.2	Cut fit and join for length, Add Plate End Fab	EE,FEM	1	tons	N6	$3,000	Crew B1	102	$183.00	21.7	Number Members = 51 from FEM, 2 hr/memb
1.3	Joint Struct. Simple Weldmt (2-5 Members)	EE,FEM	1	tons	N6	$3,000	Crew B1	36	$183.00	9.6	9 Jts @4 hr/Jt
1.4	Joint Struct Medium Weldmt (6- 9 Members)	EE,FEM	6	tons	N6	$3,000	Crew B1	42	$183.00	25.7	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	11000	SF	N7	$2.46	Crew E17	40	$184.38	34.4	
1.7	Prime & Paint	EE	11000	SF	N8	$2.06	Crew E17	40	$184.38	30.0	
1.8	Skid & Crate Const - Load Mat on skids and crates	EE	8	Ea	EE	$500	Crew E17	32	$184.38	9.9	
1.9	Trucking Stnd size to Site (1200 mi) - 6 trucks x 2 days	EE	12	Day	N9	$276	Driver B-34G	192	$68.70	16.5	8 Trucks, 1200 mi, 2 day, 24 hr
1.10	Subtotal Fab Steel Structure =		87.8	tons steel			$2.55	$/lb		$447.5	
2.0	**Mechanical Components** (Incl Packing & Shipping)										
2.1	Az Wheel Mech Assy (EA Wheel Assy) (5,000lbs)	EE	4	Ea	N1	$37,700	Crew R4	8	$467.88	154.5	8 kips ea, JPL Concept 1: 2.2.6.3, Use 5 kips
2.2	Az Drive Unit Assy (mtr & brake) (2,000lbs)	EE	2	Ea	N1	$40,000	Crew R4	4	$467.88	81.9	JPL Concept 1: 2.2.6.8
2.3	Pintal Brg Assy (3,000lbs)	EE	1	Ea	N1	$12,000	Crew R4	2	$467.88	12.9	JPL Concept 1: 2.2.6.5
2.4	El Brg Assy (Each Bearing) (1,500lbs)	EE	2	Ea	EE	$9,000	Crew R4	4	$467.88	19.9	
2.5	El Drive Assy (12,000lbs)	EE	1	Ea	EE	$30,322	Crew R4	4	$467.88	32.2	
2.6	El Drive Gear Assy (8,000lbs)	EE	1	Ea	EE	$43,050	Crew R4	4	$467.88	44.9	
2.6	Track (171 lb/yd) Mat + Grinding Track (10,545lbs)	EE	185	LF	EE	$70	Crew E4	40	$383.13	28.3	RSMeans 34.11.13.23.1000 (100 lb rail) x 2
2.7	Track Hold Down Clips (incl fasteners) (1,850lbs)	EE	370	EA	EE	$10	Crew B1	4	$183.00	4.4	
2.8	Subtotal Mech =		25.0	tons			$7.58	$/lb		$379.0	
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	Track & Hold Down Clip installation & welding	EE	-	-	-	-	Crew E4	40	$383.13	15.3	RSMeans 34.11.13.23.1000 (100 lb rail) x 2
3.6	Wheel assy on track with base members.	EE	-	-	-	-	Crew B-47H	16	$357.00	5.7	
3.7	Assy ARS structure members 20 x 1.0 hr/memb	EE	-	-	-	-	Crew B-47H	20	$357.00	7.1	
3.8	Assy El Brg and ERS memb, El Drive: 30x 1.3 hr/memb	EE	-	-	-	-	Crew B-47H	24	$357.00	8.6	
3.9	Subtotal ARA Assy =									$96.8	
	Total ARA Assy =		112.8	tons steel			$4.09	$/lb		$923.4	
4.0	**W&T Concrete Foundation**										
4.1	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
4.2	Clear and Grub	EE	0.5	Acre	N2	$5,025	-	-	-	2.5	
4.3	Excavation: Clear and level pad, excavate for footings	EE	248	CY	N2	-	Crew A-3B	32	$314.50	10.1	
4.4	Forms	EE	3,882	SF	N2	-	Crew C2	44	$440.25	19.4	RSMeans 03.11.13.85.4230
4.5	Concrete - Footing & Walls	EE	177	CY	EE	$170	Crew C-20	32	$632.25	50.4	Est 4 Conc Pour Days
4.6	Anchor Bolts	EE	320	EA	EE	$15	Crew B1	32	$183.00	10.7	
4.7	Steel ?	EE	0	LF	N2	$150	Crew E4	40	$383.13	15.3	RSMeans 05.12.23.5740
	Foundation Subtotal =									$116.3	
	Total ARA on Foundation =									$1,039.7	

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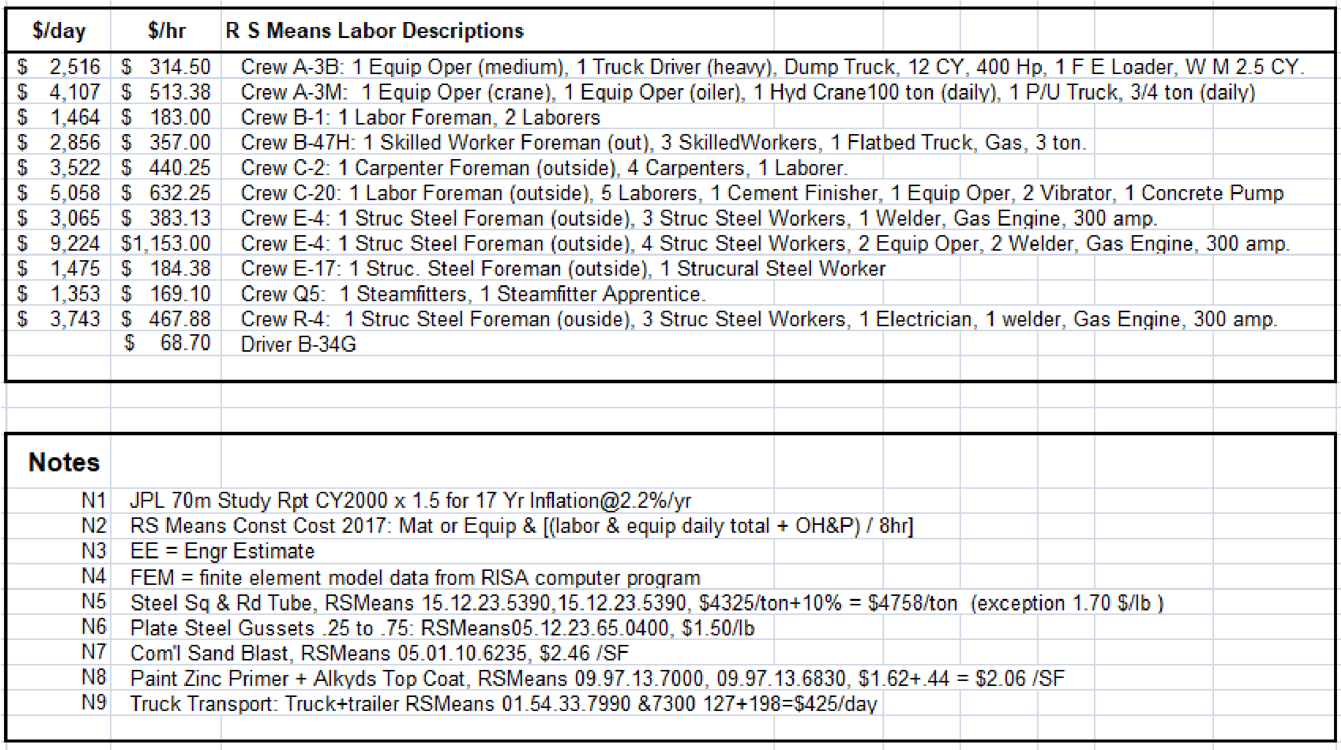

$/day	$/hr	R S Means Labor Descriptions
$ 2,516	$ 314.50	Crew A-3B: 1 Equip Oper (medium), 1 Truck Driver (heavy), Dump Truck, 12 CY, 400 Hp, 1 F E Loader, W M 2.5 CY.
$ 4,107	$ 513.38	Crew A-3M: 1 Equip Oper (crane), 1 Equip Oper (oiler), 1 Hyd Crane100 ton (daily), 1 P/U Truck, 3/4 ton (daily)
$ 1,464	$ 183.00	Crew B-1: 1 Labor Foreman, 2 Laborers
$ 2,856	$ 357.00	Crew B-47H: 1 Skilled Worker Foreman (out), 3 SkilledWorkers, 1 Flatbed Truck, Gas, 3 ton.
$ 3,522	$ 440.25	Crew C-2: 1 Carpenter Foreman (outside), 4 Carpenters, 1 Laborer.
$ 5,058	$ 632.25	Crew C-20: 1 Labor Foreman (outside), 5 Laborers, 1 Cement Finisher, 1 Equip Oper, 2 Vibrator, 1 Concrete Pump
$ 3,065	$ 383.13	Crew E-4: 1 Struc Steel Foreman (outside), 3 Struc Steel Workers, 1 Welder, Gas Engine, 300 amp.
$ 9,224	$1,153.00	Crew E-4: 1 Struc Steel Foreman (outside), 4 Struc Steel Workers, 2 Equip Oper, 2 Welder, Gas Engine, 300 amp.
$ 1,475	$ 184.38	Crew E-17: 1 Struc. Steel Foreman (outside), 1 Strucural Steel Worker
$ 1,353	$ 169.10	Crew Q5: 1 Steamfitters, 1 Steamfitter Apprentice.
$ 3,743	$ 467.88	Crew R-4: 1 Struc Steel Foreman (ouside), 3 Struc Steel Workers, 1 Electrician, 1 welder, Gas Engine, 300 amp.
	$ 68.70	Driver B-34G

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

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