MMA Memo 263

A Hexapod 12 m Antenna Design Concept for the MMA

Jeffrey S. Kingsley[†] , Robert N. Martin[‡], Victor L. Gasho [†]

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[†] National Radio Astronomy Observatory, Tucson, AZ
[‡] Academia Sinica Institute of Astronomy and Astrophysics, Taipei, Taiwan

Abstract

We present an innovative antenna design concept for the MMA utilizing a hexapod mount. This design addresses several key limitations of conventional designs in meeting the demanding specifications of the MMA. The benefits of a hexapod design include accurate pointing under specified MMA load conditions, excellent dynamic performance, and low overall instrument cost. This hexapod design is lightweight and meets the key MMA specifications. A metrology system is directly integrated into the drive system of the antenna, in place of a conventional encoder scheme.

Introduction

The MMA antennas have several design goals that depart significantly from existing instruments for millimeter and submillimeter astronomy. The primary constraints of size (12 m diameter currently), surface accuracy (25 μm rms or better), and transportability are all within the realm of existing designs. However, there are several additional constraints which depart significantly from traditional design requirements. The wind pointing specification of 0.6 arcseconds (rss) in a 9 m/s wind is a difficult specification [1]. The fast switching between observed sky positions has not yet been realized on any existing telescope to the specified MMA design goal. The MMA will be located at a very high altitude site. This instrument will be remotely controlled and requires minimal maintenance and labor at the site (human operations at such altitude will always be less efficient than at sea level). And, the large number of antenna elements in the MMA requires an optimization of the design toward mass production so that the cost per element can be minimized.

Often, a significant departure in design goals requires a radical approach to a design. With that in mind, we have taken a fresh look at possible MMA design ideas. We present an outline of one new design in this memorandum. Our design uses a hexapod mount instead of the usual altitude-over - azimuth mount. We present two possible dish designs to use with this mount.

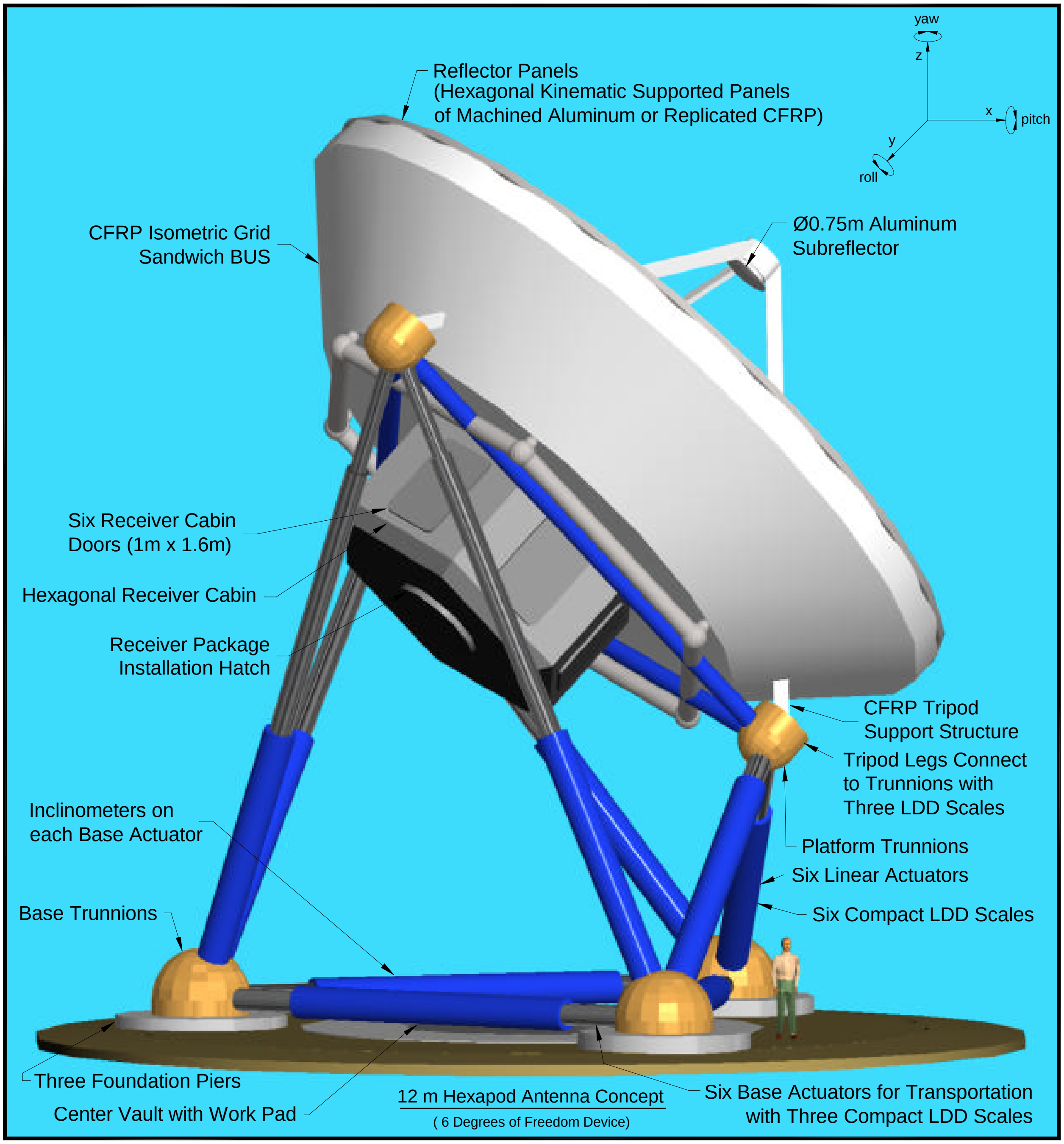

Figure 1. *12 m hexapod antenna descriptive side view.*

Hexapod Mount

The hexapod mount, or Stewart platform[2], is commonly used in flight simulators[3], ultra-precision machining centers[4], active vibration isolation[5], manipulators for surgery[6], and nanotech positioning devices [7]. It has recently been applied, also, to precision applications in optics. The GBT and Keck telescopes use the hexapod mount for their secondary mirrors and the MMT[8] and LBT are planning similar implementations.

The Astronomisches Institut of the Ruhr-Universität Bochum and Vertex GmbH have applied the hexapod mount to a 1.5-m optical telescope system[9][10] with an angular mechanical accuracy of 0.05 arcseconds. By taking advantage of the hexapod mount with its six degrees of freedom, the field rotation is corrected. A reduction in mass by a factor of 15 compared to a conventional optical telescope of this size is accomplished by the hexapod mount and lightweight primary mirror.

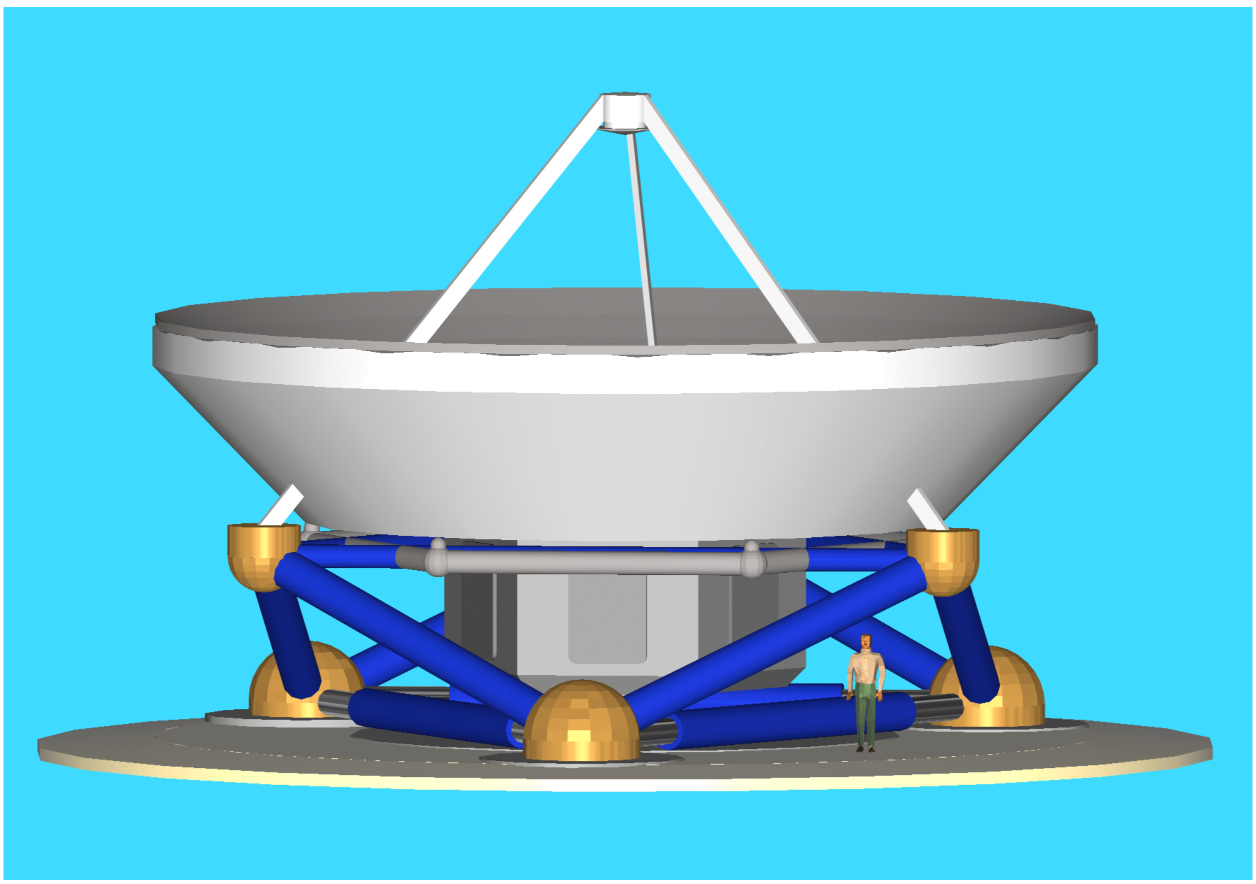

Figure 2. *12 m Antenna hexapod in lowest position (squat).*

The hexapod mount consists of six variable length struts which connect to 3 points on each of two planes. One plane is the fixed base, or ground. The other plane, the telescope itself, can then be moved in six degrees of freedom (three rotations, three translations) by changing the lengths of the six variable length struts.

The six struts can be either mechanical, ball-screw, planetary roller screw actuators [11] or hydraulic actuators [12]. Both types of actuators are commercially available and should be investigated further for best performance and cost characteristics. The joints where the actuators attach at their end points need to be carefully designed for variable load directions and extensive precision movement. However, they need not be designed for rapid rotation like normal bearings. Commonly used joints are universal joints (hook, u-joints, gimbals) or ball-and-socket joints.

Figure 1 illustrates the concept of a hexapod mount with a reflector and receiver cabin at the center of the mount. One of the principal advantages of a hexapod mount is that it eliminates an extensive amount of mass associated with a normal altitude-azimuth mount.

The base of the hexapod mount consists of three stable foundation points on the ground. Horizontal members are used to define the separation of these points. To relocate the antenna for array reconfiguration, a transporter would lift the structure at or near the receiver cabin in the lowest antenna position, as shown in Figure 2. Then, the hexapod legs can be folded out (or in) during transport if the horizontal members are removed (or themselves are actuators which can change length). The antenna's lowest position permits easy servicing of the antenna from the ground. By using the 1.5m diameter hatch in the bottom of the receiver cabin, this position can also be used to install receiver package and other equipment. The six doors around the receiver cabin provide easy access and allow equipment racks to be serviced from the rear.

Cabling for power and signals would be routed along the hexapod actuator members. Variation in cabling lengths could be handled with either a helical cabling along the actuator strut or a cable wrap mechanism at the bottom of the actuator strut. The cryogenic compressor, HVAC, and other miscellaneous equipment can be mounted off the structure on a separate pad, thus reducing vibration and weight on the antenna.

By optimizing the actuator length and travel, the MMA antenna close packing elevation specifications could be met. The large circle at the base in Figure 3 is a 15 m diameter that corresponds to a 1.25D close packing envelope. An additional capability of this mount is large horizontal translations, as shown in case 11 and 12 (Figure 3). This motion exceeds the MMA close packing specification and would only be used in configurations not requiring close packing.

Early calculations show promise of a very stiff structure with a large servo bandwidth that will be necessary to meet the MMA fast switching and wind pointing specifications. Initial finite element analysis of the hexapod mount indicates that the mount has very high resonant frequencies. These initial models assume a mass on top of the mount of 11,500 kg to simulate the reflector, BUS, receiver cabin structure, apex structure, upper trunnions, and part of the actuators. Manufacturer's specifications were used for the stiffness of the six linear actuator struts. The true foundation stiffness is not considered and it is assumed infinitely stiff for this approximation. The resonant frequencies vary between zenith and low elevations with the lowest value greater than 20 Hz. See Figure 3 for results at different antenna orientations. A detailed design and analysis will determine these values more accurately and precisely.

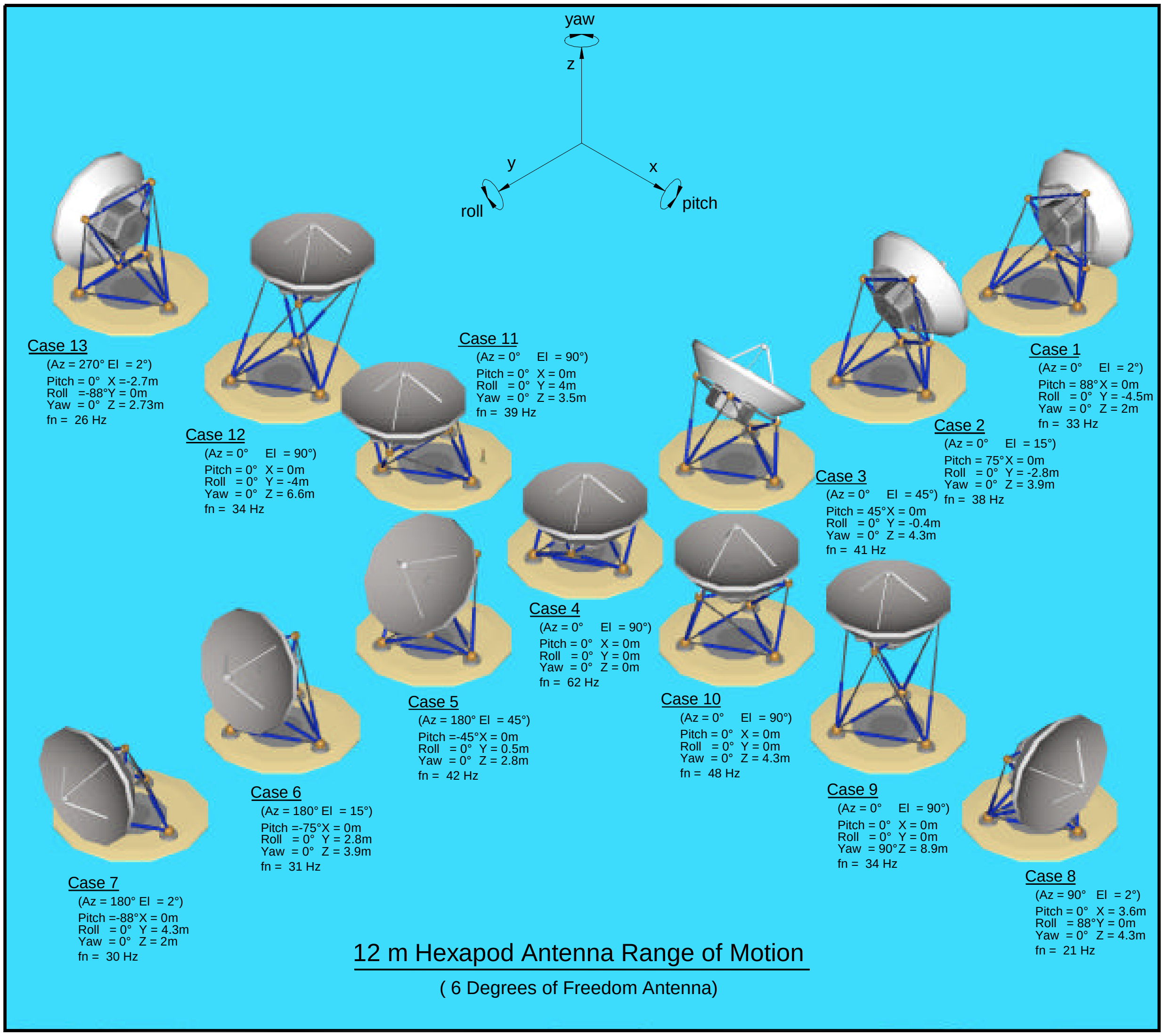

Figure 3. *12 m Antenna hexapod range of motion, degrees of freedom, and stiffness.*

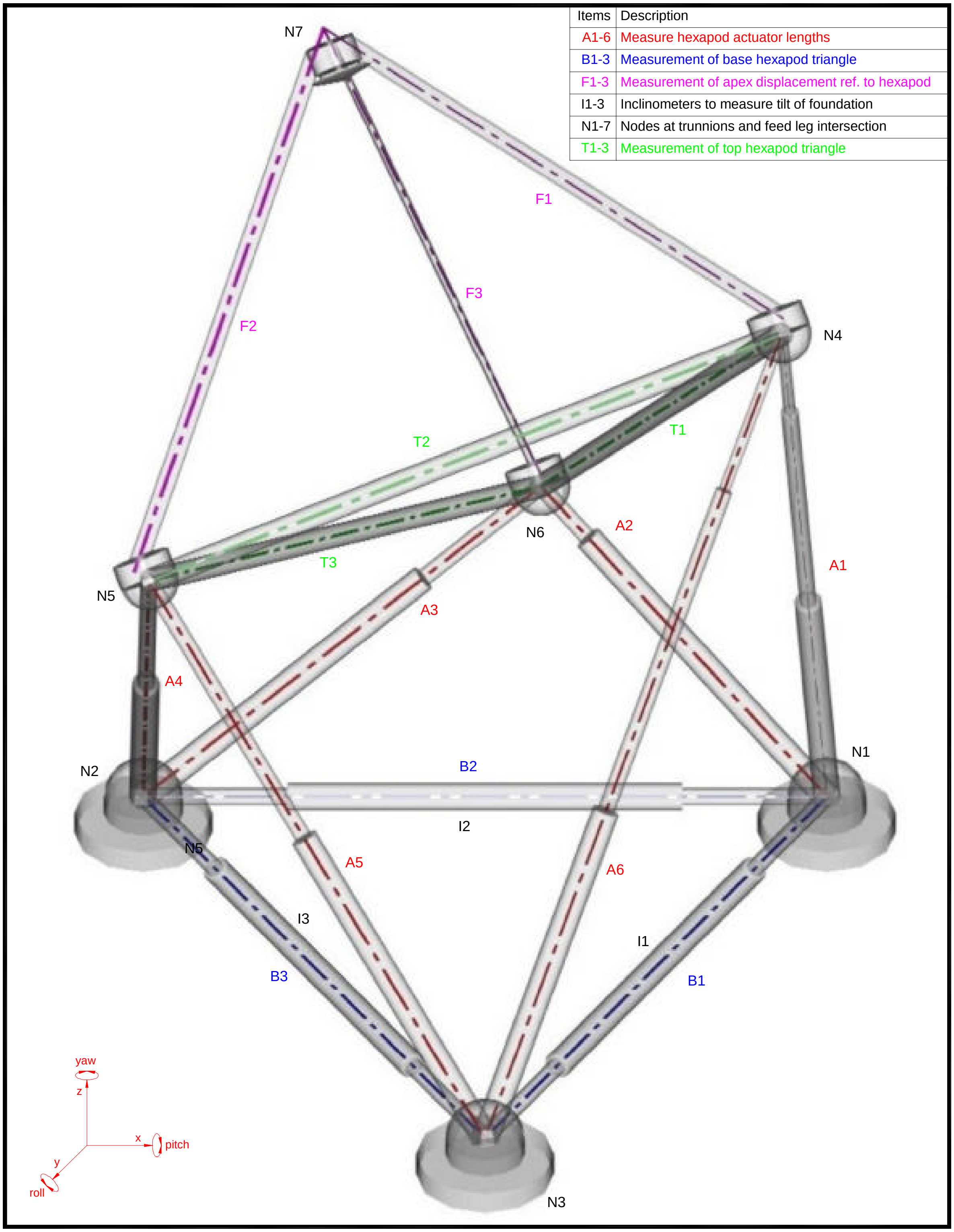

Figure 4. *Metrology system measurement diagram.*

Metrology and Drive

The linear actuator struts of the hexapod mount require an encoder system to monitor the length of each of the six actuators. We envision the center of the strut to be a long, variable length vacuum tube with a laser Doppler displacement system used to measure the absolute length of each of the six drive actuator struts from node to node as shown in Figures 4 and 5. Precision of greater than 2 μm is possible with a commercial Laser Doppler Displacement Meter (LDDM) system (e.g. Optodyn [13] or Renishaw [14]), as shown in Figure 6. These commercial units are relatively inexpensive, costing about $7,000 each including the electronics and retroreflector. For our implementation, the path of the laser beam is kept in a vacuum to minimize index of refraction errors caused by air temperature, pressure and humidity variations. The vacuum does not need to be of high quality in this case. This scheme results in angular precision of the reflector direction of better than 0.05 arcseconds. It is possible to economize on the number of laser systems needed by using a common laser for two path-length measurements of connecting hexapod legs.

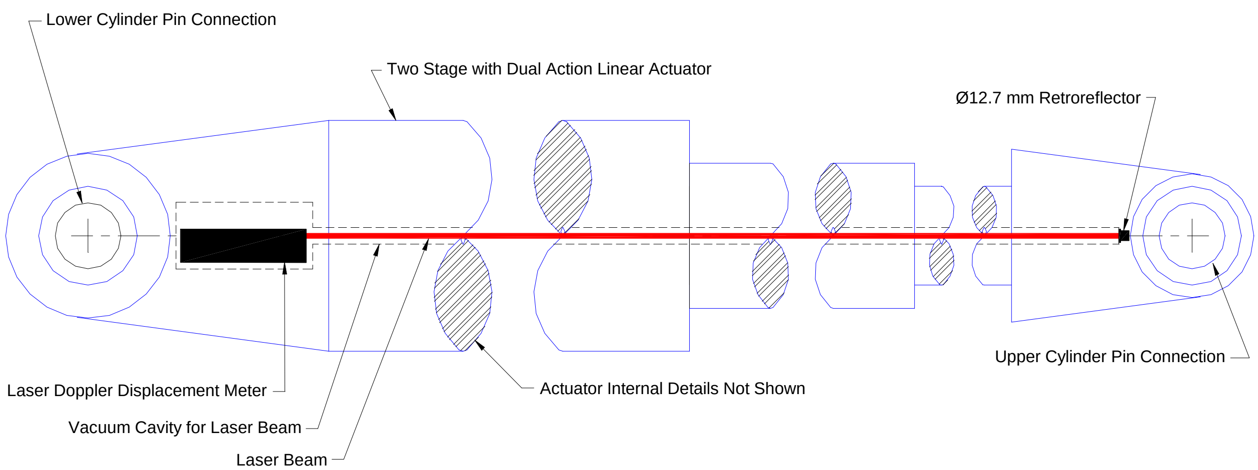

Figure 5. *Laser Doppler displacement system layout shown inside the linear actuator.*

Inclinometers will be mounted in the horizontal connecting struts that connect the base points of the hexapod mount. These will help define the base coordinate reference of the hexapod after transporting the antenna from one location to another and as measurement of the deflection of the foundation by wind or other movement.

Restricting the range of tilt angles improves the performance and reduces the cost of this hexapod mount. For normal astronomical observations, a restriction in zenith angle to 70-80 degrees is probably acceptable. The calibration of the dish structure with a terrestrial source requires an antenna position of about zero degrees elevation in a particular direction. To achieve this, one could build a couple of special pad locations that tilt toward such a source. It is not necessary for the entire array to point toward a low elevation holography source at the same time. To increase the astronomical source coverage, one would tilt the base mounting plane angle toward the north (for a Southern Hemisphere site). The optimal tilt angle would be equal to the site latitude. With such a tilted mounting base, full sky astronomical coverage would be achieved even with restricted tilt angles.

The servo system for tracking a source with the hexapod mount presents some interesting possibilities for radio interferometry. The antenna reflector can be driven in 6 degrees of freedom, not the usual 2 rotational degrees of an altitude-azimuth mount. It is possible with the third rotational degree of freedom to hold the reflector orientation at constant parallactic angle (like a polar mount), constant angle with respect to the gravity, or some other angle. The total range of angles is, of course, restricted. However, if greater than a 90-degree range is allowed, it is possible to switch the entire reflector-receiver system between polarizations. This would be extremely useful in checking for instrumental effects with sensitive polarization observations.

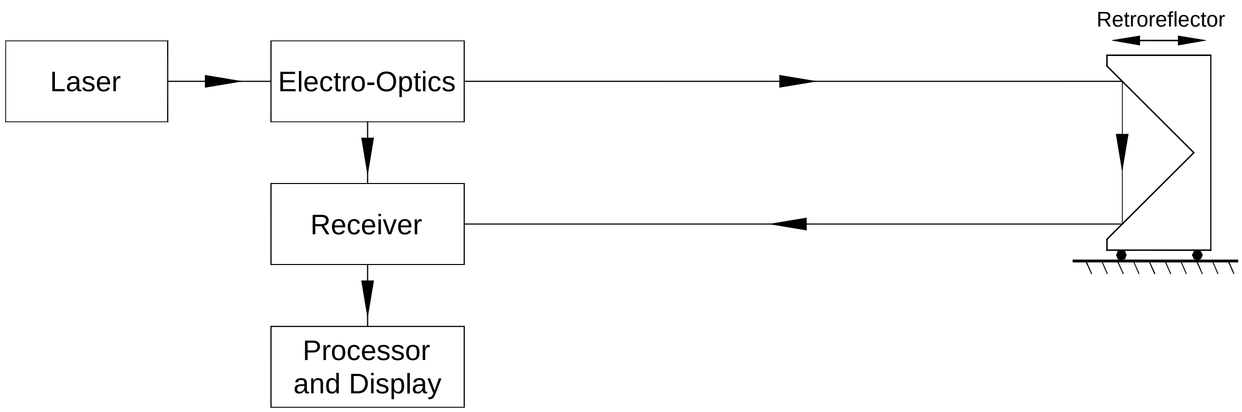

Figure 6. *Schematic of Laser Doppler Displacement Meter (LDDM).*

A new drive possibility with this mount is to move the reflector in 3 degrees of translation. It would then be possible to make limited corrections to the interferometric phase with the reflector location itself. This would be useful for engineering diagnostics but is not necessary for the standard array observations. Another interesting possibility is to dither the antenna position by a small amount at a fairly rapid rate. The phase and the baseline length between interferometric pairs could actually be modulated by moving the reflector locations rapidly. This could be useful for some astronomical experiments as well as engineering diagnostics. In addition, it is possible to move the antenna in x,y (horizontally) to optimize the antenna positions during close-packed configurations (to a limited extent).

Reflector Structure

The design of the reflector that goes with this hexapod mount should keep the same triangular and hexagonal symmetry as the mount. Since the hexapod mount tips, tilts, and translates in 6 degrees of freedom, the gravity vector with respect to the reflector is not fixed. Thus, symmetry and stiffness of the structure is essential to minimize deflection and to maintain an accurate reflector surface. In a typical alt-az mount, the gravity vector is two-dimensional with respect to reflector and deflection effects can be reduced by implementing homology along with a rigging angle [15] or by tuning the surface. Our design emphasis for the reflector structure is (1) to support the structure at the optimal radius[16], (2) to make the structure very stiff, (3) to use a lightweight design, and (4) to support the secondary mirror system from the hexapod upper nodes.

The reflector panels would be hexagonal panels using optical kinematic mounts with adjustors. The large number of different hexagonal panel types in this antenna is not a cost concern since a large number of antennas will be built to use these panels. It is cost effective to optimize the reflector structure with many different part sizes rather than minimizing the number of different sizes. This would not be true for a production run of only a few antennas. The panels could be either machined aluminum, CFRP panels, or a large membrane surface [17]. The receiver cabin forms the central feature of the reflector backup structure. There are two potential reflector designs that we discuss.

The first reflector design would be a space frame structure of CFRP tubes and metal nodes. The structure would be optimized for stiffness and performance rather than for minimum number of tube types. The loads of the secondary feed support system would be taken almost directly to the hexapod mount points. A similar reflector structure was used successfully in the SMT 10 m antenna project [18],[19]. In the 12 m design concept here, the layout of the space frame would be optimized around hexagonal (rather than trapezoidal) panels.

The second reflector concept would be a departure from existing large radio reflectors. The reflector backup structure (BUS) would be made of quasi-isotropic CFRP sheets that form a core of isogrids. The core isogrid will be constructed of thin sheets that form triangular cells in the vertical plane (Figure 6). These panels will be notched, interlocked, and glued. Facing sheets of thicker material connect to the isogrid with mortise and tenon joints that are also glued (Figure 7). Figure 7 illustrates the connection joints for clear viewing; this geometry is not a true representation of the actual BUS. Hexagonal, honeycomb, egg-crate, and triangular-cell arrangements have been applied in other telescope panel and mirror projects[20]. The triangular cell arrangement we propose here is well suited to precut sheets that can be assembled and glued together along with a face sheet and backing sheet . This isogrid BUS could be manufactured in three or six sections and assembled on site. It could also be disassembled for transport. This structure results in high stiffness, low mass, and minimized deflections.

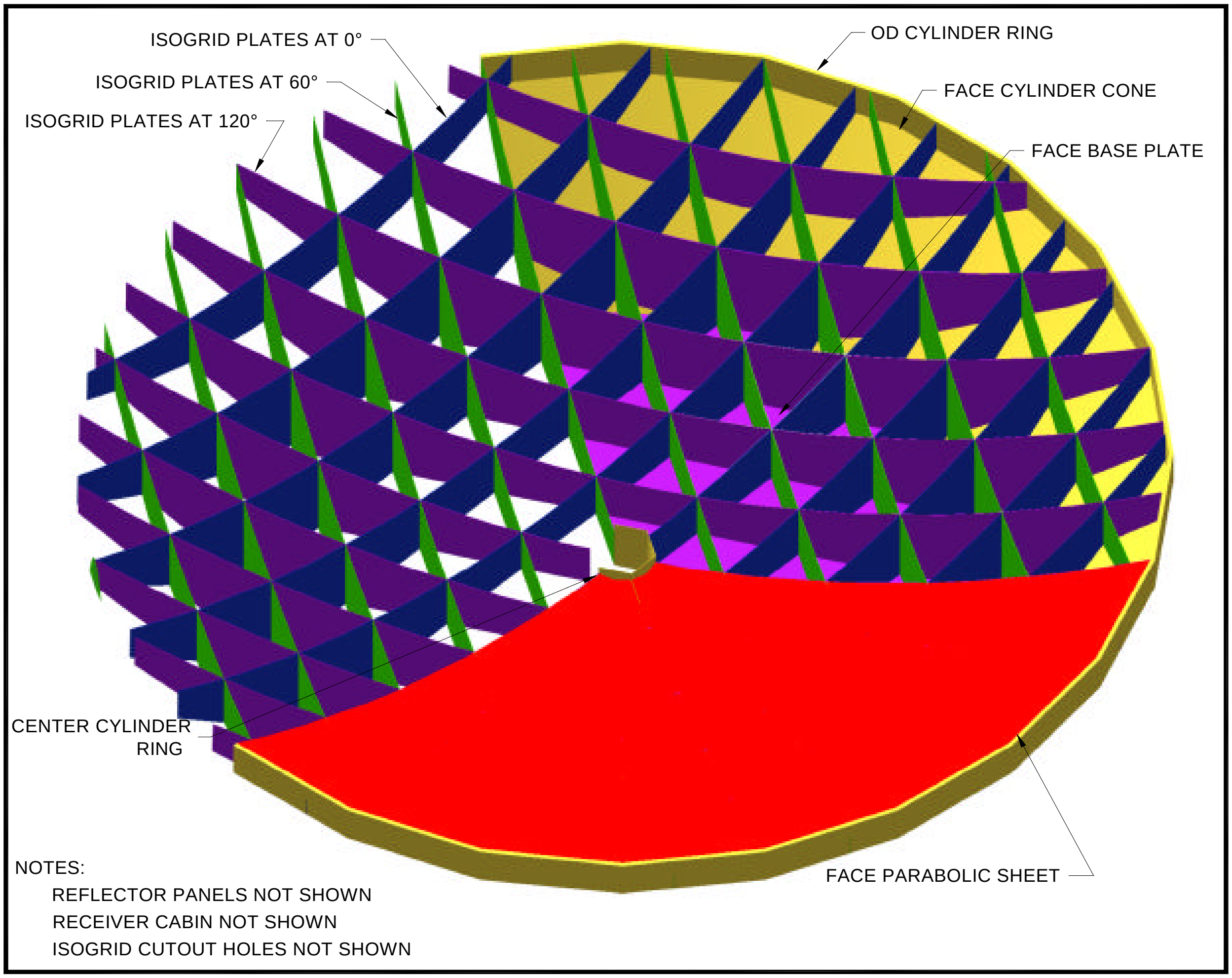

Figure 6. *Reflector BUS iso-grid design.*

For both reflector concepts, the secondary mirror would be supported by a tripod that rests directly on the upper hexapod mount nodes. This arrangement directs the loads of the secondary support system directly to the hexapod mount so that they don't distort the primary mirror. Secondary focusing and chopping (nutating) motions would be done with a motor system at the secondary mirror support.

An alternate system of supporting the secondary mirror would use a secondary support hexapod mount instead of a tripod. Again, the attachment of the secondary supports (6 struts) would be at the primary mirror upper hexapod nodes. The other end of these feed support struts would be to 3 nodes at the secondary mirror support. This secondary mirror support hexapod would have short range actuators at the base of each leg. This would allow for all the necessary focusing movements of the secondary. It may also be possible to use these hexapod secondary support actuators to provide rapid secondary chopping movement (nutation). Again, a laser system would be used to monitor the length of each secondary support leg. This hexapod secondary support arrangement would drastically reduce the weight of the secondary mirror package at the prime focus. However, this arrangement may result in extra blockage in front of the primary mirror. Further detailed study is needed to decide between the two possible secondary support systems.

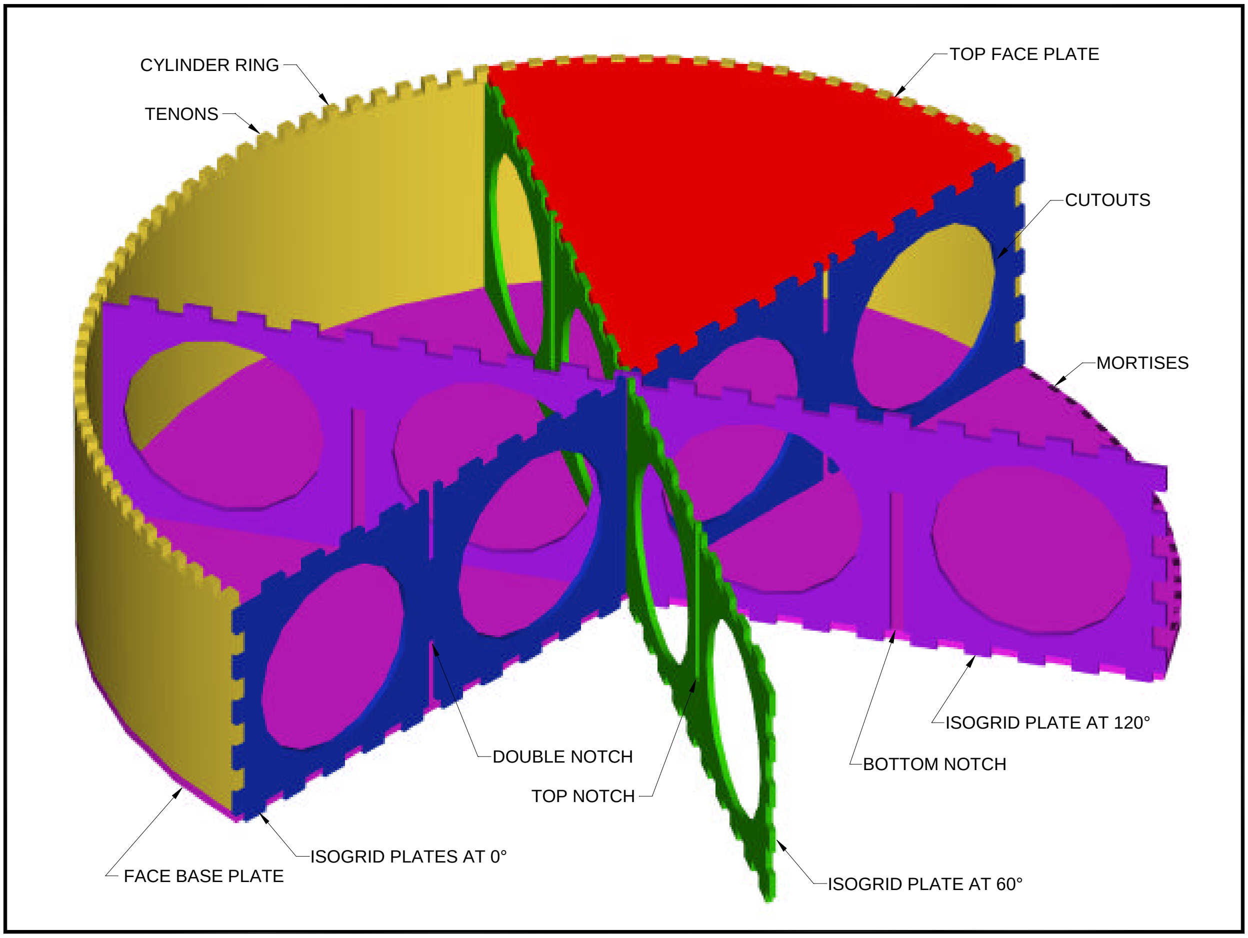

Figure 7. *Reflector BUS iso-grid connection detail illustrative example.*

Expected Performance

A more detailed design is necessary before we can accurately analyze the performance of this antenna design concept. However, we can already predict some of the design's characteristics.

We can estimate the weight from extrapolation of the weight for existing reflectors. The SMT backup structure is about 3000 kg with half the weight in the metal nodal points. Extrapolating to a 12 m diameter reflector, we can budget 4500 kg for a similar style structure. The triangular isogrid reflector design would save considerable weight by eliminating the heavy metal nodes. In that case, we estimate about 2500-3000 kg for the backup structure. The receiver cabin would contribute 600 kg. The secondary support and mirror systems adds about 150 kg. The reflector panels can be made with an areal density of 10-15 kg/m^2, leading to a contribution of less than 1700 kg. Thus, the total reflector plus receiver weight is 4950-5450 kg.

We estimate the total antenna mass to be about 26 metric tons. The total antenna weight for transport is considerably less than expected with a normal altitude-azimuth steel mount design. The design we discuss here is a lightweight, stiff structure. The mechanical resonant frequencies will be high and are expected to approach 20 Hz. Fast switching with a high bandwidth, high performance servo system will be possible. Full sky coverage with maximum acceleration and velocity is possible. This design even allows controlled tracking through the zenith (which is not possible with a conventional mount). It is only at very low elevation angles where there will be increased difficulty (and perhaps reduced drive performance). However, these lowest elevation angles are only important for holographic measurements with a terrestrial source.

ITEM	**TRUSS REFLECTOR STRUCTURE**	**ISOGRID REFLECTOR STRUCTURE**
Panels (~15 kg/m^2 & adjustors)	1,700 kg	1,700 kg
Apex (subreflector, legs, ect.)	150 kg	150 kg
BUS	4,500 kg	3,000 kg
Receiver Cabin	600 kg	600 kg
Cabin Equipment (Rx., racks & ect.)	1,400 kg	1,400 kg
Top Trunnions (3)	500 kg	500 kg
Total Reflector Mass	**8,850 kg**	**7,350 kg**
Drive Linear Actuators (6)	12,000 kg	12,000 kg
Base Trunnions (3)	2,000 kg	2,000 kg
Base Linear Actuators (3)	3,000 kg	3,000 kg
Total Hexapod Mount Mass	**17,000 kg**	**17,000 kg**
TOTAL ANTENNA MASS	**25,850 kg**	**24,350 kg**

Table 1. *Estimated mass of reflector structure and mount.*

The light structure and built-in metrology system will result in an accurate system of full sky pointing. The three point kinematic support is an advantage for control of the telescope optics. The hexapod mount does not have much exposed surface area to the wind, as compared to a conventional mount, so it will perform well under the specified wind loading conditions. The solar loading conditions are also easily controlled with this hexapod mount. Any changes in the actuator's length are measured directly with the metrology system. Special materials are not needed for the actuator construction.

The light antenna structure will also result in reduced power consumption during operation compared to conventional designs. We estimate a 20% reduction in power consumption. The drive system components are readily accessible for maintenance and could be easily removed and replaced for service. There is a single cable wrap that is easy to access for service. The cost savings in maintenance time (and cost) and in the operation costs due to power consumption are important considerations for astronomical facilities operated at remote locations.

We expect the construction cost of this design will be lower than for conventional designs. The foundation requires an efficient use of stable, small pillars or pads rather than a large massive base. The hexapod mount is much less massive than a conventional design. Generally, the cost is directly related to the amount of material used (when precision is held fixed). The reflector design is similar in concept and cost to other designs being considered. The receiver cabin is potentially a lower cost in this design, since it is an integral part of the reflector structure and does not need to be interfaced with the conventional mount.

Summary

We have presented an innovative design concept for the MMA antennas that is expected to meet the performance specifications. This design is a lower cost alternative to the conventional design concepts discussed elsewhere. The design is lightweight, potentially has extremely accurate pointing, and has excellent dynamic performance. Direct metrology is built into the design for improved pointing performance.

The hexapod design concept is new to radio astronomical applications. There will be some "learning curve" in understanding all of the characteristics of the mount. An initial prototype antenna will provide the necessary familiarity and experience.

We are currently working on a more detailed design to (a) optimize hexapod geometry, (b) design trunnions, (c) select an appropriate actuator, (d) study the proposed metrology in detail, and (e) fully analyze and optimize the structure with finite element analysis modeling. After these further studies, a preliminary bill of materials can be generated and a reasonable cost estimate can be produced. Then the true feasibility of this design can be evaluated.

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