Design, and test of SubMillimeter Array (SMA) chopping subreflector

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1. ABSTRACT:

The Smithsonian Astrophysical Observatory (SAO) is constructing an array of antennas that is expected to be placed on Mauna Kea and operated at submillimeter wavelengths. To facilitate calibration work in single dish mode, each antenna is equipped with a subreflector that chops about its center of mass. In addition to chopping, the subreflector's position is controlled by three actuators permitting the mirror position to be corrected for the effects of temperature and pointing elevation. This paper discusses the specifications, design, fabrication and performance testing of the chopping subreflector system.

2. OVERVIEW:

The chopper system, shown in figure 1, consists of 4 distinct subsystems:

- the subreflector,
- the chopping stage,
- the linear stages' assembly, and
- the support structure and environmental enclosure.

The subreflector has two distinct sets of requirements placed on it, optical and structural. Its front surface shape is defined by the telescope optical requirements, the substrate material, and the difference between the fabrication and operating temperatures. The structural requirements stem from the need to maintain the mirror surface properties once it's mounted, and to be able to operate the chopper positioner with the required precision.

The chopping stage is required to move the mirror through an angle up to ±26armin at 10Hz, dwelling at either extreme for 80% of the time. To achieve this the resulting momentum must be balanced to reduce collateral force spikes below 5N, and torque spikes below 1Nm. The net zero momentum requirement stems from two issues, a need to keep from destroying the bearings in the systems that support the chopper stage, and a desire not to excite vibration in the support structure holding the subreflector assembly.

The linear stages, aligned in 3 mutually perpendicular axes, permit the subreflector to be positioned to offset initial alignment errors and deflections resulting from changes in temperature and pointing elevation.

The specifications governing the chopper and linear stages are given in table 1 below.

TABLE 1. Subreflector System Specifications

Axis	-Range	+Range	Resolution	Accuracy
Focus (z-axis)	-20 mm	+30 mm	2 μ	2 μ
Azimuth (x-axis)	-7 mm	+7 mm	50 μ	50 μ
Elevation(y-axis)	-7 mm	+7 mm	50 μ	50 μ
Chopping Axis	-12.8 arcmin	+12.8 arcmin	2arcsec	3 arcsec

The support structure enclosures the instrument, provides the housekeeping and required structural support. Included are heaters, temperature sensors, seals and the structural connection between the linear stages and the secondary support truss. These function to keep the working components warm and dry, and to keep grit out of rolling and sliding elements.

3. DESIGN:

3.1 Subreflector:

Aluminum was selected for the mirror material because it is light, inexpensive to purchase and fabricate, and because it can be diamond turned. A low mirror weight helps reduce elevation angle dependent mirror deflection. In addition, the chopping favors a stiff, low inertia mirror. Initial chopper system control models suggested that the first structural frequency had to be above 600Hz (see below). We decided on a mirror design that consists of a thin aluminum face sheet and a deep ribbed back-up structure as the best approach to balancing the stiffness requirement with those for a light weight and low inertia mirror. Once we decided on a ribbed structure we had to take the mirror cutting forces into account. The face sheet stiffness varys with its distance from the nearest rib, an effect that can result in "print through", replicating the mirror support onto its surface.

Before we could select the rib and face sheet thickness and rib spacing, we needed to design the whole chopper assembly; locating the motor mount, mirror position sensors, and mirror mounting points. A full solid model of the system was made using Structural Design Research Corp’s (SDRC) software, IDEAS. This permitted us to exchange geometric and structural modeling information quickly. IDEAS structural models were used to examine the effects of various face sheet thicknesses, rib thicknesses, rib widths, and rib spacings on the mirror stiffness, inertia, weight and deflection during manufacture (values shown in table). Thus we were able to select a mirror design that was predicted to meet the disparate requirements placed on it.

TABLE 2. Selected and Predicted Mirror Parameters

Face Sheet	**4mm**
Rib Width	**3.5mm**
Rib Depth	**53mm (max)**
Rib Spacing	**50mm**
Inertia	**0.013** Kgm^2
Weight	**2.3 Kg**
Deflection	**2 μ**

A number of approaches for fabricating the mirror blank were examined. We initially hoped to be able to cast or oven braze the blank before machining the final optical surface. We hoped that this would reduce the blank's expense. Casting was dropped because no aluminum alloy was found that could both be cast and diamond turned. This seemed to be an issue of silicon content: casting requires it to help fill the mold, while its presences creates hard inclusions that are impossible to diamond turn. We had trouble finding someone to oven braze the blank and once we did it turned out to be too expensive. We decided to machine the blank from a solid piece of 6061 aluminum, annealing the material as required to avoid warping and creep.

We contracted a company near Pittsburgh named II-VI to both machine the blank and diamond turn the final mirror. They specialize in manufacturing high power mirror substrate and fabricating it into mirrors. Recently they have branched out into diamond turning.

The mirror surface is given by the following hyperbola of revolution:

$$z=\frac{(Cr^{2})}{(1+(1-SC^{2}r^{2})^{.5})}$$

where:

$$S = -0.1275493$$
$$C = -0.003333265$$

This formula is adjusted to compensate for the fact that the mean observing temperature is lower than the diamond turning temperature.

3.2 Chopper stage:

The chopping stage is functionally based on a similar design built at the University of Washington by S. Radford, P. Boynton and F. Melchiorri and described in reference 1. It consists of two independent stages, one made up of the mirror and voice coils, the other of two linear motors and a support. Each stage rotates on its own set of flex-pivots. The linear motors are neodymium magnets containing an annulus in which the voice coil moves. A set of two Linear Varying Differential Transformers (LVDT) measure the linear position of two points on the mirror with respect to the stationary support. The calibration between the LVDT and a direct angular measurement is used in the mirror position control loop.

The stage operates by applying a pushing force with one of the motors and a pulling force with the other. This tips the mirror in one direction around its flex-pivot, while rotating the motor magnets in the other direction around their flex-pivots. The angles that each stage rotates through will depend on their relative flex-pivot spring constants and inertias, and the force applied by the two linear motors. The mirror positioning loop is closed around the mirror position as measured by the LVDT's, and the motors. The motor magnet stage position is uncontrolled. Achieving a zero net momentum system requires that the natural frequency of the mirror/flex-pivot system equal that of the motor magnet/flex-pivot system. If this were not true, there would still be zero net torque during the mirror movement, but while the mirror was held stationary, the motor magnet stage would oscillate, vibrating the support. When the positioner reacts external forces it does excite stage motion, especially when there is a cyclical component near the base natural frequency. This is particularly true with the wind, which contains all frequencies.

3.2.1 Modeling effort:

A model of the system dynamics, including a candidate pointing controller, was developed using MATLAB from MathWorks in Natick, MA. The model includes the mirror, base, both linear motors, flex-pivots and position sensors. A number of simulations were run to gage the effects of external forces and component imperfections, like mirror flexibility, on the pointing performance. The simulation showed two things. First there is an uncontrolled oscillation in the motor base under the influence of the wind. This results from wind gusts at the motor base natural frequency being reacted by the motors. The energy builds over time since there is little damping in the base. Second, assuming there is flexibility in the mirror between the linear motor and the LVDT attachment points, the control system can become unconditionally unstable. This problem dropped away when the first mirror mode was raised above 600Hz. If, however, we assumed that the mounting and measurement points were inflexibly attached, and the mirror were flexible elsewhere; the positioning loop was stable, though pointing precision was reduced. Either case demanded a stiff mirror. Thus we made the design stipulation that the first mirror mode come higher than 600Hz and the mounting points for the motor and the position sensors be structurally close together.

Two tactics were used to reduce problems related to the wind. First we took advantage of the fact that the energy in the wind goes down with increased frequency, and selected flex-pivots that set the base natural frequency to 10.7Hz. Next, since the flex-pivots have little internal damping, we potted the inside of those on the motor base with RTV to increase it enough to stop unbounded growth in base vibration.

There were numerous other approaches to these problems, most of them involved more complexity, added sensors, actuators, more sophisticated control logic, etc. We selected the described approaches for their simplicity, efficacy, and robustness.

3.2.2 Component selection:

Component selection is complicated by the fact that we are using linear components in a limited angle rotary application. There must be enough side clearance to permit the two stages to rotate as required. Both the linear motors' and the LVDTs' geometry have a cylinder riding within a cylinder and in both cases the efficiency of their operation depends on minimizing the side clearance. The component selection process involved balancing the need for light weight, small size, low power consumption and high resolution, with effective angular range.

The chopper position loop contains another significant component, the controller. In this case we selected the Delta Tau Data (DTD) Programmable Multi-Axis Control (PMAC) a single card computer that can independently control 8 functions simultaneously. This was selected to control the entire antenna because of the wide flexibility it permits. It provided us with the ability to implement compensation curves, thus programming axis calibration, on the fly control law adjustment, and commonality between two very distinct kinds of motion systems, the DC motor driven chopper and the stepper motor driven stages.

3.3 Linear stages:

The linear stages provide the needed mirror position adjustment to overcome support deflection resulting from temperature and pointing changes. The positioning accuracy is therefore on the order of the overall telescope focus and alignment requirements. To meet these, linear bearings, ball screws and linear encoders are required on 2 of the axes, the Line-Of-Site (LOS), or Z axis, and the axis aligned with elevation motion or y axis. The third axis, that aligned with azimuth motion, is used only for initial alignment.

The linear stages themselves must deflect as little as possible under the changing relative gravity vector since this motion is unmeasured. We wanted to use purchased stages whose stiffness and positioning accuracy had been measured, and avoid a major development exercise. As an added consideration, all this hardware, including the housing has to fit within a smaller diameter than the mirror, 0.35m. We were unable to find a set of stages that met the space requirements, until we moved the telescope truss mounting points outside the subreflector obscuration and behind the quadrapod arms. This opened an additional 15mm inside the housing. Even with the additional space we only found one manufacturer, New England Affiliated Technologies (NEAT), that could deliver a small enough three axis assembly with the desired stiffness, range, and resolution.

The selected assembly consists of two separate catalog items, a single axis linear stage that is mounted in the LOS direction (called the z-stage), a two axis stage aligned normal to the optical axis (called the x-y stage), and a custom made mounting bracket. Each stage has crossed rollers, ball screw lead screw, and a stepper motor. The axes aligned in the focus and elevation directions have linear encoders, while the third axis has a rotary encoder. A mirror is bonded to the face of the x-y stage and is aligned with z-axis travel, permitting the stages to be aligned with the casing, chopper stage, and subreflector, and finally the whole assembly to be aligned to the telescope.

3.4 Support structure and environmental enclosure:

The required housekeeping functions for this assembly are:

- Structural Support,
- Temperature control,
- Dust protection,
- Extreme weather, and Rain Protection.

The structural support is an integral part of the casing, carrying the telescope truss stiffness from the mounting point down to the z-stage mounting surface. The wall thickness was selected to balance the housing's stiffness with the space and weight requirements.

The temperature control is provided by a set of heaters on the mirror and casing. These are programmed to keep the assembly 5°C above ambient or freezing, whichever is higher. This will avoid condensation and freezing.

The dust, rain and extreme weather protection was one of the hardest parts of the whole design to achieve. The most desirable method would be to seal from the mirror edge to the casing with a flexible membrane. However we were unable to make this work for two reasons: the membrane would interfere with chopping, especially at low temperatures; and maintaining membrane flexibility in the 3 linear axes, while keeping the seal within the subreflector shadow was impossible. Instead we divided the housing into two parts, one part containing the linear stages the other containing the chopper stage.

The linear stages have many rolling and sliding surfaces, and delicate electronics, while the chopper stage has none of these. The linear motors and LDVTs are non-contacting, the bearings work in flexure. We placed a sliding seal between the two sections, leaving the chopper side open to a small degree. There is a complete jacket around it, but there are small, tortuous passages into the stage. These paths permit the mirror to chop without touching anything, and the sliding seal to move approximately 1mm relative to this jacket. If there is heavy weather, the mirror can be retracted and the small clearances fully closed. As a final precaution, all the connectors are potted in RTV (Room Temperature Vulcanizing rubber) to stop short circuits and forestall oxidation of the contacts.

The linear stage chamber is always fully sealed. The sliding seal is on the chopper end and is pushed along by the z-stage. Since the sliding force effects the z-stage placement capabilities we designed a ±1.5mm deadband in the seal capture. We take advantage of this by overshooting a desired z-position and doubling back within that deadband. More importantly, the deadband encompasses the total range of projected mirror motion during normal operation.

4. PERFORMANCE TESTS:

4.1 Tests description:

A number of tests were run to verify the quality of the various system elements. The surface quality was measured to determine how closely it approximated the specified hyperbola. The linear stages were measured for positioning accuracy, angularity, straightness, and perpendicularity. The chopping axis was measured for linearity, repeatability, speed and range.

4.1.1 Subreflector:

The subreflector surface profile was measured using a high precision coordinate measurement machine by United Technologies Optical Systems (UTOS). A stylus was placed on the mirror surface at a number of locations along 3 radii and around a circumference. Errors related to the finite size of the instrument stylus and instrument signature were then removed. The resulting data was then compared to the desired hyperbola.

4.1.2 Chopping stage:

The LVDT's were calibrated and their repeatability measured with the laser interferometer. This was done with the angle retroreflector mounted in the center of the subreflector. Again the controller was set to step through a set of positions from one edge of the range to the other. The chopping tests are too fast for our laser interferometer and have to be tested using the output of the LVDTs measured on an oscilloscope. It should be noted that the system response can be adjusted during operation with the controller that we are using. We can change control parameters and immediately view its effect on the wave form.

4.1.3 Linear stages:

The single axis tests, positioning, angularity, straightness were all performed with a Hewlett Packard laser interferometer. This is equipped with an automated data taking and reduction system. Using this and the programmable motion controller, the axes could be measured quickly, triggering the position directly from the axis encoder. The system was set to take many passes to determine the repeatability as well as the accuracy.

The perpendicularity measurements were made with a mechanical dial indicator on the surface of an appropriately aligned mirror. We used the z-axis reference mirror to determine the X-Z and Y-Z perpendicularity, and a separate mirror when we look at the X-Y mounting. The dial indicator was placed against the mirror and the stage moved. The dial indicator registered the motion into the axis perpendicular to the mirror surface. Since the mirror surface is aligned perpendicular to one of the other axes, we have an indication of the moving axis' perpendicularity to the aligned axis.

4.2 Measured performance:

4.2.1 Subreflector:

This testing is underway at this time and will be reported later.

4.2.2 Chopper stage:

The chopper stage positioning performance is presented in figures 6 and 7. Figure 6 shows the performance of the LVDT, translated into an angular measurement, without the LVDT's non-linearities being compensated. The characteristic sine wave non-linearity is apparent. Figure 7 shows the stages positioning performance once a compensation table has been placed in the controller. This easily meets the ±3 arcsec accuracy requirement.

4.2.3 Linear stages:

We present 4 tables outlining the stages' measured performance. Table 2 and 3 show a comparison between the specified values and those that were actually measured on the system. Table 2 shows the specifications that apply to placement of the carriage, that is, along the stage, while Table 3 ennumerates unintended motions. Table 4 shows the maximum values that were measured through the range of measurement and Table 5 shows the results of the perpendicularity measurements. It should be noted that the Z-X perpendicularity is clearly way out of specification. The X-Y stage was rotated when it was mounted to the Z-stage, this could have been adjusted but the Z stage reference mirror had already been permanently bonded to the face of the X-Y stage. In future build-ups we will have to make this measurement before bonding the mirror.

TABLE 3. Comparison Between Specified and Measured Performance, In Line

	Linear					
Axis	**Range**		**Resolution**		**Accuracy**	
	Spec	**Meas**	**Spec**	**Meas**	**Spec**	**Meas**
	mm	**mm**	µ	µ	µ	µ
X	±7	**±8**	50	**1**	±50	**±3**
Y	±7	**±8**	50	**2**	±50	**±5**
Z	-10 to +45	**Same**	2	**0.5**	±2	**±2**

TABLE 4. Comparison Between Specified and Measured Performance, Orthogonal

	Translation		Tilts	
Axis	**Limit**		**Limit**	
	Spec	**Meas**	**Spec**	**Meas**
	µ/µ	µ/µ	arcsec/mm	**arcsec/mm**
X	1/1200	**1/2000**	1/1.2	**1/4**
Y	1/1200	**1/2000**	1/1.2	**1/2**
Z	25/1200	**2/5000**	1/1.2	**1/10**

TABLE 5. Maximum Measured Deviations in each Measured Quantity

	Linear	Straightness		Pitch	Yaw
Axis	µ	µ	µ	**arcsec**	**arcsec**
X Axis	4	2 into Y	1 into Z	1	1
Y Axis	5	1 into Z	1 into X	2.5	4
Z Axis	4	7 into X	6 into Y	3	2

TABLE 6. Measured Perpendicularity

Axes	Perpendicularity
	arcsec
X-Y	30 ±20
Y-Z	30 ±10
Z-X	515 ±10 (0.14deg)

5. Acknowledgements:

I would like to acknowledge the efforts of the rest of the design team, Adrian Roy, who has done all the electronics, James Donaghey for much of the mechanical design and David Brown for all of the detailed design.

6. References:

1. S.J.E. Radford, P. Boynton, F.Melchiorri: Review of Scientific Instruments (March 1990) vol.61, no.3, p.953-9