ABSTRACT

The Array for Microwave Background Anisotropy (AMiBA) is a hexapod telescope for astronomy. The fully steerable platform can accommodate up to 19 dishes. We present the design, simulation, manufacturing and performance verification for the 0.6m Cassegrain antennae. The primary and secondary mirrors are carbon fiber sandwich structures, manufactured by CoTec Inc., in Taichung, Taiwan. They are aluminium coated with a final surface rms of 20-30 and 10 μm, respectively. Simulated load conditions for the mirrors show maximum rms surface errors of less than 10 μm. The measured antenna beam pattern confirms the expected performance.

1. INTRODUCTION

1.1. ASIAA and AMiBA

The Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) was established in 1993 after approval by the Academia Sinica Council. ASIAA currently has about 130 members, including research scientists, post-doctoral fellows, engineers, and technical and administrative staff. Research topics carried out at ASIAA range from solar system to cosmology, with the staff making use of many of the frontier ground-based and space observing facilities. ASIAA also sponsors international workshops and conferences on a regular basis.

AMiBA [1] is led, designed, constructed, and operated by ASIAA, with major collaborations with National Taiwan University, Institute of Astrophysics (NTU, IoAp), Electrical Engineering Department (NTUEE), and the Australian Telescope National Facility (ATNF). Contributions also came from the Carnegie Mellon University (CMU), and the National Radio Astronomy Observatory (NRAO). As a dual-channel 85-105 GHz interferometer array of up to 19 elements, AMiBa is designed to have full polarization capabilities, sampling structures greater than 2 arc minutes in size. AMiBA targets specifically the distribution of high red-shift clusters of galaxies via the Sunyaev-Zel'dovich Effect, as a means to probe the primordial and early structure of the universe. AMiBA will also measure properties of the Cosmic Microwave Background (CMB), which is sensitive to the ionization history of the universe and can be a potential probe for gravity waves. Fig. 1 shows AMiBA on Mauna Loa, Hawaii, at an elevation of 3,400m taking advantage of higher atmospheric transparency and minimum radio frequency interference. For the later expansion phase, we project a sensitivity of ~2 mJy in 1 hour with the 1.2 m antennas. This will allow us to detect and map 20-50 clusters of galaxies every year and investigate the CMB around l ~ 2000-3000.

Currently, 7 0.6 m antennae are being installed, aiming at first scientific results. Mechanical aspects of hexapod and platform, as well as the correlator and receiver system were introduced in recent papers [2,3,4].

Figure 1. AMiBA on Mauna Loa, Hawaii. 2 0.6 m antennae are installed. The optical telescope (in black) is used for pointing. 7 receivers and associated electronics are also installed.
1.2. Antenna Requirements

Antenna size and interferometric baselines are constrained by the window functions sampling the scales on the sky, which are relevant for the target science. Measuring the CMB (a 3°K background signal) requires a low-noise antenna with low side lobe levels. This is achieved through the feed horn’s parabolic illumination grading with a –10.5 dB edge taper. Free-space tapering for a focal ratio of 0.35 is 3.6 dB. For the 0.6 m antenna this projects about –20dB for the first side lobe and a 20 arcmin HPBW for the primary beam at 3 mm wavelength. Fig.2 compares the ideal parabolic illumination (without detailed coupling of the electric field to the feed horn and without secondary blockage) with the central scan of the far field beam pattern. The Cassegrain geometry (section 2.1) sets the feed phase center at the vertex of the primary with a feed-illumination angle of 14°. The corrugated feed horn is covering the 85 to 105 GHz bandwidth, with a center frequency of 95 GHz. Subreflector and feed positioning requirements are based on the Ruze formulae [5]. An axial and lateral secondary defocus of 0.1 \( \lambda \) and 0.45 \( \lambda \), respectively, keep the gain loss at less than 1%. (\( \lambda \approx 3\) mm at 90 GHz.) Similarly, a feed horn positioning within 1 \( \lambda \) gives a 99% gain. Random surface deviation on primary and secondary mirror will remove power from the main beam and distribute it in a scattered beam. A surface error requirement of 50 \( \mu \)m rms ensures a 95% gain.

The surface top layer is coated aluminium. Aiming at minimizing a possible emission from the underlying material and maximizing the reflection of the incoming signal, an aluminium layer attenuation of less than 1% is targeted. A 5 times skin depth leads to a (1/\( e \))^2=0.67% attenuation, which translates into about a 1.4 \( \mu \)m coating layer at the relevant frequency. By asking for at least 2.8\( \mu \)m coating we are ensuring a very low attenuation.

Having several antennae in a close-packed configuration on the platform can cause cross-talk problems. A baffle, seen in Fig. 3 and Fig. 6, with a characteristic curvature at the rim, aims at reducing this effect.

2. 0.6-M ANTENNA CONSTRUCTION

A feasibility study has been carried out to determine a material and a structural design suitable for the 0.6 m antennae for AMiBA. Carbon fiber reinforced plastics was proposed and chosen for the dish and for the feed legs to minimize weight and surface deformations. Typical load cases encountered on a high mountain site include wind, extreme temperatures, and gravity loads. When combining these loads, we obtain an antenna of less than 10 kg with a surface accuracy better than 8\( \mu \)m rms. To this error have to be added fabrication and measurement errors.

2.1. Design

Tab. 1 and Tab. 2 present the specifications for the primary paraboloid and secondary hyperboloid mirrors.

![Figure 2. Beam pattern comparison.](image-url)

<table>
<thead>
<tr>
<th>Equation of Primary Mirror</th>
<th>( z = r^2/4F_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation of primary illumination angle</td>
<td>( \cot(0/2) = 2(F_p/D-1/16(F_p/D)) )</td>
</tr>
<tr>
<td>Primary Illumination angle</td>
<td>( \theta_p = 142.157511^\circ )</td>
</tr>
<tr>
<td>Diameter of Primary Mirror</td>
<td>( D_p = 576.00 \text{ mm} )</td>
</tr>
<tr>
<td>Primary Focal Length</td>
<td>( F_p = 201.600 \text{ mm} )</td>
</tr>
<tr>
<td>Depth of Primary Mirror</td>
<td>( H = 102.857 \text{ mm} )</td>
</tr>
<tr>
<td>Primary ( f/ ) ratio</td>
<td>( f/ = F_p/D = 0.35 )</td>
</tr>
</tbody>
</table>

**Table 1. Primary mirror specifications**

<table>
<thead>
<tr>
<th>Secondary Mirror equations</th>
<th>((z + a)^2 = a^2 + (a/b^2) r^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a = L(M-1)/2 )</td>
<td>( b^2 = L^2 M )</td>
</tr>
<tr>
<td>( c^2 = a^2 + b^2 )</td>
<td>( L = 2c/(M+1) = c-a )</td>
</tr>
<tr>
<td>( M = (c+a)/(c-a) )</td>
<td>( e = c/a )</td>
</tr>
</tbody>
</table>

**Table 2. Secondary mirror specifications**

A shield, or baffle, surrounds the outside diameter of the dish and the sub-reflector system to guard against low
level radiation. The surface of the main dish and the sub-reflector shall both be better than 50 μm rms error. The primary mirror surface, sub-reflector surface, and the optics alignment must maintain the specifications when the system is tipped in all orientations. The optics must be aligned on assembly so that the sub-reflector is within 0.1 mm in x,y and 0.3 mm in z. The tilt must be less than 0.2 degrees. Fig. 3 shows all the parts constituting the dish assembly.

Figure 3. Exploded view of the parts of the 0.6 m dish for AMiBA.

2.2. Simulations

The antenna was designed using the finite element method (FEA), so that the whole structure meets specifications without any internal adjustment such as for the secondary mirror. Fig. 4 and Fig. 5 show the deformation of the primary mirror under typical loadcases.

2.3. Manufacturing Process

The primary mirror is a sandwich composite, made of carbon fiber skin and Nomex honeycomb. The following steps are necessary to manufacture the mirror:

- Form the honeycomb to its desired shape
- lay-up the lower skin to its design thickness on the mold
- put on the formed honeycomb core
- lay-up the upper skin to its design thickness
- cure the structure according to the defined curing cycle
- de-mold, clean and prepare for aluminum coating
- deposit aluminum on the reflective surface by evaporation under vacuum

For the secondary mirror the carbon fiber skins are preformed onto the formed core and cured in the mold. Then the baffle, secondary mirror support blades, the ring, and the interface plate of the secondary mirror are manufactured and assembled. The support blades, ring, and secondary mirror are bonded to the baffle. The primary mirror is set on the assembling table, taking the dish surface as reference. The baffle subassembly is attached to the primary dish. The secondary mirror is adjusted and aligned to the primary dish, with the help of an alignment fixture. The 0.6 m dish assembly is measured and the secondary mirror aligned again until the structure meets specifications.

Figure 4. Absolute deflections of primary mirror under gravity load, in horizon position. (Units=meter)

Figure 5. Absolute deflections of primary mirror at 60-degree elevation for a 10 m/s front wind. (Units=meter)

Figure 6. Assembled 0.6 m Unit for AMiBA
The mirrors are measured at the Center for Measurement Standards (CMS), founded by the Industrial Technology Research Institute (ITRI) in Taichung, Taiwan, using a ZEISS PRISMO 10 measuring machine. The accuracy of the measurements for the 0.6 m dish is 4.4 \( \mu \text{m} \). Fig. 7 shows the primary mirror on the measuring machine, undergoing surface measurements.

### 3. QUALITY CHECK

#### 3.1. Geometry and Surface Checks

After the aluminium top layer coating, primary and secondary mirror surfaces are both individually measured (outlined in section 2.3) for their surface accuracy and optical geometry. The assembled system is later measured again to check the alignment. The primary paraboloid and the secondary hyperboloid surface data are fitted with their corresponding equations, Tab. 1 and Tab. 2. The fitting results, obtained from 240 and 96 measured points for primary and secondary, respectively, are summarized for one of the seven dishes in Tab. 3.

<table>
<thead>
<tr>
<th></th>
<th>( F_p ) [mm]</th>
<th>rms [( \mu \text{m} )]</th>
<th>min [( \mu \text{m} )]</th>
<th>max [( \mu \text{m} )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>201.55</td>
<td>31</td>
<td>-88</td>
<td>81</td>
</tr>
<tr>
<td>Secondary</td>
<td>201.52</td>
<td>7</td>
<td>-14</td>
<td>19</td>
</tr>
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</table>

*Table 3. Dish fitting results*

Looking at the contour plots of the fitting residuals reveals a slight saddle structure for the primary mirror, Fig. 8, whereas the secondary mirror residuals show a more random distribution in Fig. 9. The systematic increase of the residuals amplitude with radius is shown in Fig. 10. Despite these systematics, the 50 \( \mu \text{m} \) surface rms specifications are easily met.

#### 3.2. Beam Pattern Measurements

For precision cosmology, we need to get the beam patterns accurately measured. One reason is that its convolution effect will reduce the information of the observed signal on small angular scales. This effect is of particular importance for the case of measuring the CMB power in the multipole space. Another reason is
that some defects in the beam pattern, such as an increase in the side lobes or a circular asymmetry, may prevent us from reaching the designed sensitivity limits. In the following, we will first describe our ways of measuring the beam patterns, and then present the analysis results of some important investigations.

A typical approach for the beam pattern measurement is to observe astronomical sources such as the planets. However, to be able to pursue these tests while the AMiBA mount was still being assembled and commissioned, we adopted a new approach. Our setup includes an equatorial mount whose pointing can be accurately controlled, and an electronic system similar to the AMiBA design. The dishes can be mounted on one by one to scan a 90 GHz thermally stabilized CW source in the far field, \( \sim D_p^2/\lambda \approx 100 \) m. Fig. 11 shows the setup.

Figure 11. Our setup for measuring the beam patterns of the dishes.

Figure 12. Measured beam patterns in dB.

The measured beam patterns are shown in Fig. 12 (in dB) and 13 (in actual amplitudes). In Fig. 12, a clear four-arm structure is seen in all results, and we verified that they correspond exactly to the four spider arms of the secondary mirror for each dish. In Fig. 13, the contours have some jiggles, and we verified that this is due to the residual effect from the time constant of the receiver system. A more accurate deconvolution scheme along the scan should be able to remove this effect. The time constant is about 0.15 seconds.

We then perform some analysis to investigate a few important aspects that are strongly related to our science goals. Fig. 14 shows the azimuthally averaged beam profiles and the indices of asymmetry, \( \omega_l \), defined by

\[
\omega_l = (\langle |B_{lm}|^2 \rangle - \langle B_{lm} \rangle^2)/\langle |B_{lm}|^2 \rangle .
\]

\( B_{lm} \) is the beam multipole expansion, \( l \) being related to the corresponding angular scale. \( \langle |B_{lm}|^2 \rangle \) and \( \langle B_{lm} \rangle^2 \) are the mean of squares over \( m \) and the square of the mean over \( m \), respectively. The above defined numerator is thus the variance of \( B_{lm} \) about its mean over \( m \), a perfectly symmetric beam giving \( \omega_l = 0 \). Calculating the indices of asymmetry further requires the beam data to be pixelized [6].

Fig. 15 shows the volume fraction of the side lobes.

Figure 13. Iso-contours of the beam patterns in their actual amplitudes.

Figure 14. Beam profiles axially averaged from the beam patterns, and the indices of asymmetry.
The following summary can be drawn from these results:
1. Full Widths at Half Maximum (FWHM) are between 22 and 25 arcmin.
2. The peak value is about -16dB, higher than the first valley by about 20dB.
3. The first side lobe is higher than the first valley by about 1-4 dB.
4. The first side lobe volume fraction is about 10%.
5. The index of asymmetry is always below 0.2 within the FWHM and below 0.8 within the primary peak, showing good symmetry of the dishes [6].

We can therefore conclude that our dishes are of good quality, showing no obvious defects that may affect our science goals.

4. CONCLUSION

Choosing carbon fiber reinforced plastics allows us to build a 0.6 m Cassegrain antenna of less than 10 kg, still meeting all the stiffness requirements. Gravity and wind load simulations predict deflections of less than 10 \( \mu \text{m} \) rms for the primary mirror. The aluminium coated primary and secondary surface accuracies are better than 50 \( \mu \text{m} \). The measured beam pattern confirms the predicted FWHM of about 22 arcmin and a first side lobe peak at about –20 dB. The requirements are met by all 7 antennae for the initial AMiBA operation.

5. REFERENCES


