1.2 m Shielded Cassegrain Antenna for Close-Packed Radio Interferometer

Patrick M. Koch, Philippe Raffin, Yau-De Huang, Ming-Tang Chen, Chih-Chang Han, Kai-Yang Lin, Pablo Altamirano, Christophe Granet, Paul T. P. Ho, Chih-Wei L. Huang, Michael Kesteven, Chao-Te Li, Yu-Wei Liao, Guo-Chin Liu, Hiroaki Nishioka, Ching-Long Ong, Peter Oshiro, Keiichi Uematsu, Fu-Cheng Wang, and Juin-Huei Protv Wu

ABSTRACT. Interferometric millimeter observations of the cosmic microwave background and clusters of galaxies with arcminute resolutions require antenna arrays with short spacings. Having all antennas co-mounted on a single steerable platform sets limits to the overall weight. A 25 kg lightweight novel carbon-fiber design for a 1.2 m diameter Cassegrain antenna is presented. The finite element analysis predicts excellent structural behavior under gravity, wind, and thermal load. The primary- and secondary-mirror surfaces are aluminum-coated with a thin TiO₂ top layer for protection. A low beam sidelobe level is achieved with a Gaussian feed-illumination pattern with edge taper, designed based on feed-horn antenna simulations and verified in a far-field beam-pattern measurement. A shielding baffle reduces interantenna coupling to below ~ – 135 dB. The overall antenna efficiency, including a series of efficiency factors, is estimated to be around 60%, with major losses coming from the feed spillover and secondary blocking. With this new antenna, a detection rate of about 50 clusters yr⁻¹ is anticipated in a 13-element array operation.

Online material: color figures

1. INTRODUCTION

The Array for Microwave Background Anisotropy (AMiBA) is a forefront radio interferometer for research in cosmology. This project is led, designed, constructed, and operated by the Academia Sinica, Institute of Astronomy and Astrophysics, Taiwan, with major collaborations with National Taiwan University, Physics Department, Electrical Engineering Department, and the Australian Telescope National Facility. Contributions also came from the Carnegie Mellon University, and the National Radio Astronomy Observatory. As a dual-channel 86–102 GHz interferometer array of up to 19 elements, AMiBA is designed to have full polarization capabilities, sampling structures on the sky greater than 2′ in size. The AMiBA target science is the distribution of high-red-shift clusters of galaxies via the Sunyaev-Zel’dovich effect, e.g., Sunyaev & Zel’dovich (1972), Birkhshaw (1999), and Carlstrom et al. (2002), and references therein, as a means to probe the primordial and early structure of the universe. AMiBA will also measure the cosmic microwave background (CMB), e.g., Spergel et al. (2007), Aghanim et al. (2008), and Larson et al. (2010), temperature anisotropies on scales, which are sensitive to structure-formation scenarios of the universe. AMiBA is sited on Mauna Loa in Hawaii, at an elevation of 3400 m to take advantage of higher atmospheric transparency and minimum radio-frequency interference.

After an initial phase with seven 0.6 m diameter antennas (Koch et al. 2006) in a compact configuration, the AMiBA is currently operating with 13 1.2 m diameter Cassegrain antennas (Fig. 1). This new antenna and its capabilities are described here. Section 2 lists the antenna requirements. In § 3 the mechanical and optical designs are detailed, including simulation results of the structure and the antenna feed-horn system. Section 4 is devoted to the antenna verification measurements. The factors composing the antenna efficiency are estimated in § 5. Section 6 discusses the improved design features of the 1.2 m antenna and the upgraded array operation. Our conclusion is given in § 7.

Previous AMiBA progress reports were given in Ho et al. (2004), Raffin et al. (2004), Li et al. (2006), and Raffin et al. (2006). A project overview is given in Ho et al. (2009). More details about the correlator and receiver can be found in Li et al. (2010) and Chen et al. (2009). The hexapod telescope mount is
introduced in Koch et al. (2009). Observing strategy, calibration scheme, and data analysis with quality checks are described in Lin et al. (2009), Wu et al. (2009), and Nishioka et al. (2009). The first AMiBA science results from the seven-element array are presented in Huang et al. (2009), Liao et al. (2010), Koch et al. (2010), Liu et al. (2010), Umetsu et al. (2009), and Wu et al. (2009). A possible science case utilizing the 1.2 m antenna array configuration is outlined in Molnar et al. (2010).

2. ANTENNA REQUIREMENTS

Antenna size and interferometric baselines are constrained by the required window functions sampling the scales on the sky, which are relevant for our target science. After the AMiBA initial phase with seven 0.6 m diameter antennas in close-packed configuration, 13 1.2 m diameter antennas are now installed, covering a baseline range from 1.4 m to about 6 m. This gives a synthesized beam resolution of about 2′ for a nominal central frequency of about 94 GHz. The collecting area of the 13-element array is increased by a factor of 7.4 upon the initiation with seven 0.6 m diameter antennas. This results from the antenna structure and antenna feed-horn cross talk and to reduce ground pickup and stray light. High sidelobes are suppressed with a −10.5 dB edge taper in the feed’s Gaussian illumination pattern (§ 3.3 and § 5). The antenna is shielded with a baffle to minimize the interantenna coupling (§ 3.4) and the ground pickup. Additional care is taken to send stray light back to the sky with triangular-roof-shaped quadripod legs (§ 3.5).

Due to the harsh volcanic environment, together with the large high-altitude temperature variations, we decided to add a TiO_{2} protection layer against abrasion on both the primary and secondary mirrors. Furthermore, visual and infrared sunlight is a potential hazard to burn our antennas. The 0.6 m diameter antennas were therefore additionally covered with a Gore-Tex layer on top of the shielding baffle in order to absorb the damaging radiation. At our observing microwave frequencies, the protection layer and the cover are designed to minimize the absorption loss and maximize the reflectivity and the transmission, respectively (§ 4.4). On the 1.2 m diameter antennas, no Gore-Tex cover is needed, because most of the visible and infrared light is not reflected by the TiO_{2}-coated surfaces.

Finally, minimizing any torque and possible tilting of the antennas when mounted on the receivers is crucial to reach a stable radio alignment. In addition, in order to keep the total weight below the acceptable limits of the hexapod telescope, a lightweight structure is needed, together with the desirable radio-frequency properties. Choosing carbon-fiber-reinforced plastic (CFRP) satisfies these conditions and keeps the weight of the antenna below 25 kg.

3. MECHANICAL AND OPTICAL DESIGN

Section 3.1 describes the basic Cassegrain antenna design. The results from the antenna structure and antenna feed-horn simulations are described in §§ 3.2 and 3.3. Sections 3.4 and 3.5 give more detail on the additional measures taken to control antenna cross talk and to reduce ground pickup and stray light.

3.1. Cassegrain Antenna Geometry

Based on requirements (§ 2), a shielded f/0.35 Cassegrain antenna was chosen. Tables 1 and 2 present the specifications

| Parameters | Values |
|------------|--------|
| Equation of primary mirror | $z = (x^2 + y^2)/(4F_p)$ |
| Equation of primary illumination angle | $\cot(\Theta_p/4) = 4F_p/D_p$ |
| Primary illumination angle | $\Theta_p = 142.151^\circ$ |
| Diameter of primary mirror | $D_p = 1182.000$ mm |
| Primary focal length | $F_p = 413.700$ mm |
| Depth of primary mirror | $H = 211.071$ mm |
| Primary f/ratio | $f/r = F_p/D_p = 0.35$ |
| Apex hole diameter | $W = 50$ mm |
for the primary paraboloid and the secondary hyperboloid mirrors. Figures 2 and 3 show a drawing and a photograph of the assembled antenna, respectively.

The Cassegrain geometry sets the feed phase center at the vertex of the primary. A parabolic illumination grading leads to about $-20$ dB for the first sidelobe and a $11'$ FWHM for the primary beam at a wavelength of $\lambda \sim 3.2$ mm ($\sim 94$ GHz). Subreflector and feed positioning requirements are based on the Ruze formulas (Ruze 1966). Axial and lateral secondary defocus values of 0.1$\lambda$ and 0.45$\lambda$, respectively, keep the gain loss at less than 1%. Similarly, a feed-horn positioning within 1$\lambda$ gives a 99% gain. Random surface deviations from a primary paraboloid and a secondary hyperboloid will remove power from the main beam and distribute it in a scattered beam. A surface error of less than 50 $\mu$m rms from the ideal geometry ensures a 95% gain.

### 3.2. Structure Simulations

Typical load cases on the AMiBA site include wind, low temperatures, and gravity load. Based on stiffness requirements and weight considerations, CFRP was chosen for the dish, the feed legs, and the baffle. The primary and secondary mirrors are sandwich composites. The baffle is made of two parts (Fig. 3): a structural baffle supporting the feed legs and a nonstructural (shielding) baffle fixed to the latter to prevent cross talk between antennas and to minimize ground pickup. Mass is an issue, as the AMiBA platform is designed to accommodate up to 19 identical antennas, but the hexapod drive system sets an overall weight limit. From an original 50 kg prototype antenna, the weight was reduced to about 25 kg with the help of a finite element analysis (FEA), while maintaining the overall structural behavior of the antenna. The main goal of the structural analysis is to ensure that the parabolic characteristics of the primary mirror are met for a minimized mass.

The simulation results presented in this section refer to the production antenna. Figure 4 shows the grid of the FEA model. The finite element model was analyzed with ANSYS version 11 with 15,400 nodes and 18,300 elements. In particular, 3D shell elements were used to model the CFRP primary-mirror skins, the baffle, the feed legs, and the subreflector coupling. Three-dimensional solid elements were adopted to model the

### TABLE 2

| Parameters                                | Values |
|-------------------------------------------|--------|
| Equation of secondary mirror              | $z = \sqrt{a^2 + (a^2/b^2)(x^2 + y^2)}$, $a = L(M - 1)/2$, $b^2 = L^2 M$, $c^2 = a^2 + b^2$, $L = 2c/(M + 1) = c - a$, $M = (c + a)/(c - a)$ |
| Final focal position                      | At vertex of primary |
| Distance between prime and secondary foci | $2c = F_p = 413.700$ mm |
| Final effective f/ratio                   | $f/ = 2.0361$ |
| Final illumination angle                  | $\theta_s = 28.000'$ |
| Secondary vertex to prime focus           | $M = 5.81739$ |
| Equation parameters                       | $L = 60.683$ mm |
| Secondary mirror diameter                 | $D_s = 2F_p/(\cot(\Theta_p/2) + \cot(\Theta_s/2)) = 190.048$ mm |

**Fig. 2.**—Drawing of the assembled antenna including the main components: primary and secondary mirrors, structure and shield baffle, quadripod support legs, and hexagonal bottom support plate. The units are in millimeters. See the electronic edition of the *PASP* for a color version of this figure.

**Fig. 3.**—AMiBA 1.2 m Cassegrain antenna. *Left:* Antenna with the structure baffle only. *Right:* Complete antenna with the shielding baffle. The secondary-mirror quadripod leg support is attached to the structure baffle.
core of the primary mirror, the structural baffle, and the hexagonal support-plate sandwich composites. Finally, 3D beam uniaxial elements served to model the subreflector and the inserts. Boundary conditions apply on the hexagonal support plate and are not symmetrical with respect to the antenna geometry. Therefore, structural behavior varies with the antenna orientation in its aperture plane. For each individual load case (gravity, wind load, and thermal load) the deformation (Fig. 5, left panels) is calculated from a displacement vector, which is the sum of the nodal components. The residual map from a best-fit paraboloid to the deformed primary mirror is shown in the right panels in Figure 5. Table 3 summarizes the results. For combined load cases the added surface deformations are within about 5μm over the entire elevation range. This only adds insignificantly to the manufacturing random errors (ϵ∥ < 30μm, § 5) and therefore does not further reduce the efficiency. Combined resulting tilts of the optical axis are within 1”, which is at the acceptable 10% level of the FWHM (~11”) around the operating frequency of 94 GHz. This is comparable with the achievable mechanical alignment between individual antennas on the platform, which then keeps the loss in amplitude for each antenna pair at the percent level.

3.3. Feed-Horn Antenna Simulations

We designed a corrugated feed horn with a variable-depth mode converter to cover a full 20 GHz band from 85 to 105 GHz (Zhang 1993; Granet & James 2005). The center frequency is around 95 GHz. The geometry of the horn is shown in Figure 6. The feed horn has a semiflare illumination angle of 14° with a parabolic illumination grading with a −10.5 dB edge taper. Free-space tapering for f/0.35 is about 3.6 dB, which leads to about −20 dB for the first sidelobe and a 11’ FWHM for the primary beam at a wavelength of λ = 3.2 mm. The analysis of the horn is done using the well-proven mode-matching technique (James 1981). The resulting theoretical radiation pattern is shown in Figure 7. An aperture flange with an external radius of 11.86 mm is used in the calculations. The phase center of the horn is located 19 mm inside the horn, when measured from the aperture. The aperture of the horn is therefore located 19 mm above the vertex of the primary mirror.
TABLE 3
SUMMARY OF DEFORMATION FROM VARIOUS LOAD CASES

| Load                  | \( el \) (deg) | RMS (\( \mu m \)) | Tilt (\( ^{\circ} \)) | \( \Delta_{x} \) (\( \mu m \)) | \( \Delta_{y} \) (\( \mu m \)) | \( \Delta_{z} \) (\( \mu m \)) |
|-----------------------|----------------|-------------------|------------------------|-------------------------------|-------------------------------|-------------------------------|
| Gravity               | 90             | 1                 | 0                      | 0                             | 0                             | -9                             |
| Gravity               | 60             | 3                 | 40                     | -59                           | 0                             | -7                             |
| Gravity               | 30             | 3                 | 70                     | -102                          | 0                             | -4                             |
| Wind                  | 90             | 5                 | 63                     | -93                           | 0                             | 0                              |
| Wind                  | 30             | 2                 | -27                    | 39                            | 0                             | -2                             |
| Thermal, 20°C uniform | ...            | 1                 | ...                    | 0                             | 0                             | 0                              |
| Thermal, \( \Delta\theta_e = 2^{\circ} \) | ... | <1               | ...                    | <1                            | 0                             | 0                              |
| Thermal, \( \Delta\theta_e = 2^{\circ} \) | ... | <1               | <1                    | 0                             | 0                             | 0                              |
| Thermal, \( \Delta\theta_e = 2^{\circ} \) | ... | <1               | 0                     | 0                             | 0                             | 0                              |

Notes.—Antenna elevation position is \( el \), where \( el = 90 \) deg means pointing at zenith. The wind load is for a 10 m/s side wind. The thermal load is independent of elevation. \( \Delta\theta_e \) denotes a total temperature gradient in direction \( i \), linearly distributed over the entire length. The rms values refer to the residual maps after a best-fit paraboloid is subtracted from the deformed primary-mirror surface. Tilt values are different for \( x \) and \( y \) directions, due to the nonsymmetrical hexagonal mounting plate of the antenna, and therefore depend on the orientation of the antenna. Only the larger of the two cases is listed here. \( \Delta_{x} \) describes the shift in the primary apex in direction \( x \). The antenna focal axis is in the \( z \) direction. For combined load cases, the added surface deformations are within about 5 \( \mu m \) root of sum squares over the entire elevation range. Combined resulting tilts are within \( 1^{\circ} \).

3.4. Shielding Baffle

Having several antennas in a close-packed configuration on the platform can cause cross-talk problems that might affect CMB measurements (Padin et al. 2000). The total cross-talk signal \( C_{\text{tot}} \) for a single antenna is expected to be proportional to the number of neighboring antennas. This leads to a maximum cross-talk signal \( C_{\text{tot}} \sim 6C \) for the central antenna in a hexagonal compact configuration (Fig. 1), where \( C \) is the coupling strength on the shortest baseline. The Sunyaev-Zel’dovich effect signal from clusters is typically about 1 mK. The CMB temperature fluctuations are \( \sim 0.1 \) mK on cluster scales, and they decrease to \( \sim 10 \mu K \) or less on smaller scales. In comparison, the maximum false signal due to cross talk is \( T_{r} \sqrt{pC} \), where \( T_{r} \) is the receiver noise temperature and \( p \) is the correlation coefficient between the outgoing and receiver noises (Thompson & D’Addario 1982; Padin et al. 2000). Assuming \( p = 0.01 \) and \( T_{r} = 65 \) K for AMiBA (Chen et al. 2009), a maximum wrong signal of \( \sim 40 \sqrt{C} \) K might be present at the central antenna. Adopting a 10% tolerance of the weak CMB signal, 1 \( \mu K \), \( C \) should be reduced to about \( -127 \) dB.

Therefore, in order to ensure a low interantenna cross talk, it was decided to add a shielding baffle similar to the case of the Cosmic Background Imager (CBI). Baffle height and baffle rim curvature are the important parameters to determine. Our design is closely following the antennas built for the CBI (Padin et al. 2000). Generally, the approach is to eliminate sharp discontinuities that would diffract energy from the main lobe. Therefore, scattering from the baffle shield rim is minimized by rolling the rim with a radius \( \sim 5\lambda \approx 15 \) mm (Mather 1981).

Finally, when using a shielding baffle, its effect on the forward gain of the antenna needs to be considered. As an approximation in the antenna near field, the Fresnel diffraction integral for a circular aperture is adopted to calculate the propagating
electric field, \( E(x, y, z) \), above the aperture plane. The aperture field distribution, \( E(x, y, 0) \), is a Gaussian with a \(-10.5\) dB edge taper as a result of our feed-horn illumination. Evaluating \( E \) in the center and at the radius of the baffle location as a function of distance from the aperture plane shows a close-to-constant ratio between them. This finding is consistent with the expected beam broadening, 
\[
 w(z) = w_0\sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2},
\]
along the optical axis, which is less than 0.1\% up to a height \( z = 1 \) m for an initial beam waist \( w_0 \approx 0.545 \) m (for a Gaussian with a \(-10.5\) dB edge taper). Consequently, the power \( P = E^2 \) remains well confined, with a plane integrated loss of less than 1\% (at a height of 1 m), compared with a broadened beam without baffle. Therefore, the loss in forward gain does not set any stringent constraint in this case, due to the well-collimated beam. Eventually, it was decided to limit the baffle height to where the tangential plane at the edge of the secondary intercepts with the baffle. In the optical geometrical limit, rays scattered from the secondary are confined to this plane. This results in a total baffle height of about 630 mm above the aperture plane, which leaves the secondary mirror and feed legs about 360 mm inside the baffle (Fig. 2).

### 3.5. Secondary-Mirror Feed Legs

In addition to minimizing the antenna cross talk, in order to further control the antenna sidelobe levels and scatter stray light back toward the sky, the geometrical shape of the secondary-mirror feed legs has been optimized. Two main concerns are related to the feed-leg shape: the antenna sidelobe level can increase due to diffraction from the legs, and the system temperature can increase due to reflected ground pickup. Satoh et al. (1984), Moreira et al. (1996), and Lawrence et al. (1994) have extensively studied the issue of ground spillover pickup and feed-leg shaping or baffling. One shaping technique is to attach
a triangular roof on the lower side of the feed leg (Lamb 1998). An optimized angle has been worked out for our Cassegrain geometry in order to keep scattered rays close to the pointing axis toward the cold sky and away from the secondary and primary mirrors. Using geometrical optics, the scattered rays are found to be within a cone with opening angle $\theta$ (Cheng & Mangum 1998):

$$\theta = \frac{\pi}{2} - 2 \arcsin(\sin(\beta) \sin(\alpha)),$$

(1)

where $\alpha$ is the half-angle of the triangular roof and $\beta$ is the angle between the lower side of the feed leg and the optical axis of the antenna. For our design, $\beta = 65^\circ$, which is close to half of the primary-mirror illumination angle, because the feed legs are attached close to the rim of the primary mirror (Fig. 2). With this resulting scattering angle ($\theta$), stray light is terminated to the cold sky. The angle $\theta$ is also well matched with the baffle height in order to avoid multiple scatterings from the baffle, which might occur if $\theta$ is too small and therefore intercepting with the upper parts of the shielding baffle. Since the height of the triangular roof increases with smaller $\alpha$, $\alpha \to 0^\circ$—which would ideally send scattered rays straight to the sky ($\theta \to 90^\circ$)—is not feasible in practice. Therefore, as a compromise, $\alpha \approx 15^\circ$ was chosen, which confines scattered rays to within $\theta \approx 65^\circ$ (Fig. 9) and keeps the height of the equilateral roof shape within about 20 mm. The two-dimensional antenna beam-pattern measurement in § 4.2 possibly demonstrates an improvement due to this triangular-shaped roof. Whereas for larger antennas an optimized leg design was able to reduce the system temperature of up to 10 K, in the case of our small antennas this might eventually be more a measure of precaution.

4. ANTENNA VERIFICATION

4.1. Surface and Alignment Measurements

The mirror surfaces are measured at the Center for Measurement Standards, founded by the Industrial Technology Research Institute in Taichung, Taiwan, using a ZEISS PRISMO 10 measuring machine with a 4.4 $\mu$m measurement accuracy. The surfaces are checked from a sample of data points: 885 and 276 uniformly distributed points are measured across the primary and secondary mirrors, respectively. This yields sets of $(x, y, z)$ coordinates for a two-dimensional fit for the primary
paraboloid and the secondary hyperboloid, respectively, using the following formulae:

For the primary,

\[ z = \frac{x^2 + y^2}{4F_p} + C_p, \] (2)

and for the secondary,

\[ z = \sqrt{\frac{a^2 + ab(x^2 + y^2)}{b^2}} + C_s, \] (3)

where \( F_p \) is the focal distance, \( C_p \) and \( C_s \) are offsets in the \( z \)-direction due to the measurement setup, and \( a \) and \( b \) determine the curvature of the hyperboloid with a resulting focal distance \( F_p = 2\sqrt{a^2 + b^2} \) (Tables 1 and 2). The primary and secondary mirrors typically have surface rms errors of about 30 \( \mu \text{m} \) and 15 \( \mu \text{m} \), respectively, as illustrated for one antenna in Figures 10 and 11. The resulting focal length \( F_p \) is found to be within 0.1 mm of the specifications. This reduces the dish surface efficiency by less than 2\%. After verification of the surface, the antenna is assembled and the secondary mirror is mechanically shimmed to meet the alignment criteria. The alignment is typically between 50 \( \mu \text{m} \) and 100 \( \mu \text{m} \) in the \( x \), \( y \), and \( z \) translation directions. The aperture efficiency (§ 5) is therefore reduced by only less than 1\%.

4.2. Antenna Beam Pattern

For precision cosmology an accurately measured antenna beam pattern is essential. The beam convolution effect reduces the information of the observed signal on small angular scales, which is of particular importance for the CMB power in the multipole space. Furthermore, defects in the beam pattern, such as an increase in the sidelobes or a circular asymmetry, can affect the sensitivity limits (Wu et al. 2001). In addition to confirming the theoretical expectations, the detailed measurement and characterization of the antenna beam pattern make it possible to use the exact beam response in the later science data analysis, if this should be needed.

Fig. 9.—Scattered ray angle (θ) as a function of the triangular-roof half-angle (α). The scattering angle is measured with respect to the aperture plane. A positive angle means scattering toward the sky, and a negative angle means scattering down toward the primary mirror. A triangular roof half-angle of about 15° was chosen.

Fig. 10.—Contour plot of the fitting residuals from a best-fit parabolic primary mirror. The units are in millimeters. The surface accuracy is about 28 \( \mu \text{m} \) rms, with maximum deviations of 96 \( \mu \text{m} \) and –98 \( \mu \text{m} \), respectively, leading to a focal distance \( F_p = 413.66 \text{ mm} \). The systematic ringlike pattern in the residuals reveal an imperfect manufacturing process (likely resulting from an uneven support during the machining) at a level that is irrelevant for our frequency range of around 94 GHz. See the electronic edition of the PASP for a color version of this figure.

Fig. 11.—Contour plot of the fitting residuals from a best-fit hyperbolic secondary mirror. The units are in millimeters. The surface accuracy is about 13 \( \mu \text{m} \) rms, with maximum deviations of 42 \( \mu \text{m} \) and –34 \( \mu \text{m} \), respectively, leading to a focal distance \( F_p = 413.59 \text{ mm} \). See the electronic edition of the PASP for a color version of this figure.
A measured IF frequency of 89.18 GHz is found, which is present in the RF. Such a MHz at the measured intermediate frequency (IF) of 84 GHz is related to the Gunn oscillator frequency of 84 GHz. The source is not in a thermally stable and cooled environment, some frequency drift (~1 GHz) in the RF is present. Such small variations are irrelevant, however, for the cross-talk measurements, and the source RF always remains in our observing band.

We measured the beam pattern with a computer-controlled equatorial mount, scanning a fixed 90 GHz thermally stabilized continuous-wave source at a distance of about 250–300 m. This is marginally in the far field (\(\sim D_p^2/\lambda \sim 480\) m). An example of a measured beam pattern from a two-dimensional scan is shown in the left panel in Figure 12. A crosslike feature likely resulting from the four legs of the secondary-mirror support structure becomes apparent, with an increase in power of 4 dB higher than expected. The detailed cause of this is unclear. One might speculate that this is due to a weaker feed illumination edge taper than was predicted and due to remaining stray light from the secondary-mirror support. The location and the level of the second sidelobe again agrees well with the simulation. From the measurement, a FWHM of about 11’ is found, with a first sidelobe peaking at about -16 to -18 dB.

The results are further analyzed following Wu et al. (2001), investigating azimuthally averaged beam profiles and \(\omega_l\), the indices of asymmetry: \(\omega_l = (\langle |B_{lm}|^2 \rangle - \langle |B_{lm}^*|^2 \rangle) / \langle |B_{lm}|^2 \rangle\). \(B_{lm}\) is the beam multipole expansion, with \(l\) being related to the corresponding angular scale. \(\langle |B_{lm}|^2 \rangle\) and \(\langle |B_{lm}^*|^2 \rangle\) are the mean of squares over \(m\) and the square of the mean over \(m\), respectively.

The preceding defined numerator is thus the variance of \(B_{lm}\) about its mean over \(m\), with a perfectly symmetric beam giving \(\omega_l = 0\). Calculating the indices of asymmetry further requires the beam data to be pixelized. As a result, the index of asymmetry is always below 0.2 within the FWHM, indicating a good symmetry of the antennas.

4.3. Antenna Cross Talk

Low cross-talk signals were verified on the operating 13-element array on the AMiBA site. As a measurement setup, one antenna served as an emitter and was outfitted with a 10 dBm narrowband polarized source (Gunn oscillator with a bandwidth of 2–3 MHz at the measured intermediate frequency [IF] of 5.56 GHz). In different adjacent antennas (dual linear polarization receivers) the weak cross-talk signal was then detected with a spectrum analyzer connected to the output at the end of the first section in the IF chain. Various amplifiers along the IF chain (from the receiving feed horn to the end of the first section) give rise to a gain of about 70 dB (Chen et al. 2009; Li et al. 2010). Subtracting that and taking into account the source power, the original cross-talk signal scattered into the feed horn is derived.

\(^{8}\)A measured IF frequency of 5.56 GHz corresponds roughly to an original source radio frequency (RF) of 84 + 5.56 = 89.56 GHz, with the receiver local oscillator frequency of 84 GHz. Since the source is not in a thermally stable and cooled environment, some frequency drift (~1 GHz) in the RF is present. Such small variations are irrelevant, however, for the cross-talk measurements, and the source RF always remains in our observing band.
The coupling between two 1.2 m antennas was measured for 1.4 m and 2.8 m baselines. In order to quantify the influence of the shielding baffle (Fig. 3), the measurements were done with and without baffle. Figure 13 summarizes the results. For comparison, also shown are the measured coupling strengths for the 60 cm antennas for 0.6 m, 0.69 m, and 1.38 m baselines. (No removable baffles were constructed for those antennas.) Solid and dotted lines are for maximally and minimally aligned polarizations, respectively. The down-arrow for the longest baseline with shielding baffle indicates an upper limit. Error bars include instrument noise and variations in the sky conditions. For better display, measurements for the 1.4 m baseline are slightly shifted horizontally. See the electronic edition of the PASP for a color version of this figure.

4.4. Material Properties

Both the antenna structure and shielding baffle are made of CFRP. The material has been measured with a vector network analyzer (VNA). For a 0.72 mm thick CFRP test sample an insertion (throughput) loss (S21 parameter) of about $-62$ dB or less is measured in the frequency range of 85–105 GHz, which is comparable with the 0.88 mm aluminum sample that shows an insertion loss at around $-60$ dB (Fig. 14, upper panel). The values are upper limits because they are at the noise level of the VNA. The return loss (S11 parameter) averages at around $-11$ dB in the observed frequency range, compared with about $-5$ dB for the aluminum sample (Fig. 14, lower panel). From this we conclude that very little radiation goes through the baffle and the deficiency in return loss (reflection) is absorbed in the material, which makes CFRP an ideal and lightweight shielding material. Similar VNA tests have also shown that a possible Gore-Tex cover to protect the antenna additionally against visible and UV light has a transmission loss of less than 0.1 dB.

The surface top layers of the primary and secondary mirrors are aluminum-coated in the vacuum. The reflectivity of aluminum is close to 100% as soon as there are only a few layers of atoms. Further aiming at minimizing a possible emission from the underlying material, an aluminum-layer attenuation to at
least 1% is targeted. A five times skin depth leads to a reduction in amplitude by a factor of $(1/e)\approx 0.67\%$. This sets the coating layer to $\delta = 5 \times \sqrt{2/(2\pi\nu\mu_0\sigma)} \approx 1.4 \mu m$ at a frequency of $\nu = 94$ GHz. The electrical conductivity $\sigma$ for aluminum and the free-space magnetic permeability $\mu_0$ are ($\sigma \approx 3.6 \times 10^7 \Omega^{-1} m^{-1}$ and $\mu_0 = 1.2566 \times 10^{-6}$ Vs A$^{-1}$ m$^{-1}$). The typical aluminum layer—measured at various positions across the primary mirror—is about 2 $\mu m$.

Additionally, a thin top layer of TiO$_2$ is applied for protection from oxidation, abrasion, and peeling off and for thermal stability. Aiming for a thin layer of thickness $l (l \ll \lambda/\sqrt{\varepsilon})$, which is only very slightly lossy ($\sigma/(\omega\varepsilon) \leq 0.01$), we set $l \approx 0.3 \mu m$ (0.001 $\lambda/\sqrt{\varepsilon}$). In here, we have adopted $\varepsilon \approx 80$–170 As $V^{-1} m^{-1}$ and $\sigma \approx 10^6 \Omega^{-1} m^{-1}$ for the TiO$_2$ dielectric constant and electrical conductivity, respectively, at our operating wavelength $\lambda = 3.2$ mm. The criterion for a slightly lossy layer is easily met with $\sigma/(\omega\varepsilon) \sim 10^{-8}$. This criterion also ensures that no microwave depolarization arises from the thin top layer (Chu & Semplak 1976). The TiO$_2$ vacuum sputtering is done immediately after the Al sputtering. One sputtering run typically gives a layer of about 0.15 $\mu m$.

We note that this additional thin TiO$_2$ layer would even allow direct Sun observations. In tests where the antenna was directly pointed at the Sun, a maximum temperature of 46°C was measured after 20 minutes at the surface of the secondary mirror. The reflection of visible and infrared light is likely to be significantly reduced, due to multireflections in the TiO$_2$ layer. Consequently, only a small portion of heat is reflected to the secondary mirror and further to the feed horn. This small heat flux has also proven to be of no damage for the secondary-mirror support structure made from CFRP. For comparison, the initially used smaller 0.6 m diameter antennas (without TiO$_2$ coating) showed a temperature increase to 70°C within only 2 minutes.

![Graph](image)

**Fig. 14.—VNA measurement. Top:** Insertion loss (S21) for both CFRP and aluminum over the frequency range 85–105 GHz. **Bottom:** Return loss (S11). See the electronic edition of the *PASP* for a color version of this figure.

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$^7$For five specimens, four located at the outer radii and one in the center of the primary mirror, the thickness of the Al + TiO$_2$ layer was measured with an optical profilometer. From these test measurements, an average coating of $\sim 2 \mu m$ was derived, with slight variations probably resulting from different angles and distances to the sputtering source.

$^8$Thin films of deposited TiO$_2$ contain mainly two types of crystalline structures: anatase and rutile. The dielectric constant differs by about a factor of 2 (86 As $V^{-1} m^{-1}$ and 173 As $V^{-1} m^{-1}$) for parallel and perpendicular incoming waves (at 20°C and $\nu \sim 1$ MHz). No value for the conductivity $\sigma_{TiO_2}$ at our operating frequency $\nu \sim 94$ GHz was found in the literature. Since adding O$_2$ increases the conductivity $\sigma_{TiO_2}$, we use the available value, $\sigma_{TiO_2} \sim 10^9$, for a conservative estimation for $\sigma_{TiO_2}$. A measured very small loss ($\ll 1%)$ for $\nu \sim 1$–3 GHz for a 0.3 $\mu m$ TiO$_2$ layer (Haney 2006) is supporting this estimate.

5. **Antenna Efficiency**

In order to derive an overall system efficiency for AMiBA (Lin et al. 2009), we now analyze the antenna aperture efficiency $\eta_a$. Generally, $\eta_a$ can be written as the product of a number of independent efficiency components (e.g., Kraus 1982):

$$\eta_a = \eta_l \times \eta_b \times \eta_c \times \eta_f \times \eta_p \times \eta_c \times \eta_{misc},$$

where $\eta_l$ is the illumination efficiency of the aperture by the feed-horn taper function, $\eta_b$ is the blocking efficiency due to...
the secondary mirror and its quadripod leg support, $n_c$ is the surface efficiency due to small manufacturing random errors, $n_s$ is the spillover efficiency of the feed and the secondary mirror, $n_f$ is the focus error efficiency, $n_p$ is the cross-polarization efficiency of the feed-antenna combination, $n_e$ is the incoming radiation loss due to the absorption from the Gore-Tex cover, and $n_{misc}$ is the diffraction loss and reflector surface ohmic loss.

Part of the following analysis is based on the guidelines in Baars (2003). The illumination efficiency $\eta_i$ of the antenna is the ratio of the gain of the antenna to that of a uniformly illuminated aperture. An edge taper is applied to reduce the sidelobe levels. Our 1.2 m antenna has a Gaussian illumination pattern with a $-10.5$ dB edge taper. For a Gaussian distribution, $F(r) = \exp(-\alpha(r/r_0))$, where $r_0$ is the aperture radius and $\alpha = (T_e/20)\ln 10$, with $T_e$ being the edge taper in decibels, the illumination efficiency $\eta_i = (\int F(r) dA)/(\int F^2(r) dA)$ becomes

$$\eta_i = \frac{2(1 - \exp(-\alpha))^2}{\alpha(1 - \exp(-2\alpha))}. \quad (5)$$

For our antenna we derive $\eta_i \approx 90\%$.

The loss of gain due to the blockage, $\eta_b$, is given by

$$\eta_b = \left(1 - \frac{A_b}{A_p}\right)^2, \quad (6)$$

where $A_b$ and $A_p$ are the total blocked area and the aperture area, respectively. The double loss results from a decrease in the reflector area for the incoming plane wave front, and a reduction of the incoming energy (spherical wave) to the focus. $A_b$ is composed by the central obstruction due to the subreflector ($A_{bc}$), the plane wave shadow ($A_{bp}$), and the spherical wave shadow area. The spherical wave shadow (from the quadripod legs) is zero, since the legs are attached to the baffle and not the primary reflector (Fig. 3). Following Baars (2003) for the case of a tapered illumination with a $-10.5$ dB edge taper, we have

$$A_b = A_{bc} + A_{bp} = \pi R_s^2 + \frac{4W_s}{3} R_p^2 (3R_p^2 - R_s^2), \quad (7)$$

where $R_p$, $R_s$, and $W_s$ are the radii of the primary and secondary mirrors and the width of the leg, respectively. The aperture surface $A_i$ is reduced by the apex hole. For our antenna geometry (Tables 1 and 2) we derive $\eta_b \approx 92.3\%$.

The surface error efficiency $\eta_e$ caused by small manufacturing random errors is calculated following Ruze (1966):

$$\eta_e = \exp\left(-\left(\frac{4\pi\epsilon_\lambda}{\lambda}\right)^2\right), \quad (8)$$

where $\lambda$ and $\epsilon_\lambda$ are the observing wavelength and the rms surface deviation parallel to the antenna axis, respectively. The manufacturing errors in the $z$-direction with respect to the ideal geometrical surfaces are illustrated in Figures 10 and 11. They typically lead to $\eta_e \approx 97.5\%$, $\eta_e \approx 98.5\%$ and $\eta_e > 99\%$ for the primary and secondary mirrors, respectively, which is significantly better than the commonly accepted error $\epsilon_\parallel \approx \lambda/40$, which limits the gain loss to $10\%$.

The feed spillover efficiency $\eta_f$ measures the power radiated by the feed, which is intercepted by the subreflector with the subtended angle $\Theta_s$ (Table 2):

$$\eta_f = \frac{\int_0^{2\pi} \int_0^{\Theta_s} P_f(\theta, \phi) \sin \Theta d\Theta d\phi}{\int_0^{2\pi} \int_0^{\Theta_s} P_f(\theta, \phi) \sin \Theta d\Theta d\phi}, \quad (9)$$

where $P_f(\theta, \phi)$ is the power pattern of the feed. From the secondary-mirror illumination angle, $\Theta_s = 28$ deg, and the feed illumination pattern, Figure 7 at 93 GHz, we derive $\eta_f \approx 0.78$.

The focus error efficiency $\eta_f$ is conveniently analyzed separately for secondary mirror and feed and for axial and lateral defocusing. Following Baars (2003), the gain loss for the subreflector axial defocusing $\delta_z$ can be expressed in units of wavelength $\lambda$ for different feed illumination patterns. For $\delta_z/\lambda < 0.1$ (in our case, $\delta_z/\lambda \approx 0.03$ for $\delta_z \approx 0.1$ mm) the aperture efficiency is better than 99% independent of the illumination pattern. The axial defocus does not cause any change in the beam direction, and therefore there is no associated antenna pointing error. The placement of the feed in the secondary focus is less critical (Butler 2003) with $\delta_z/\lambda \sim \lambda$ still giving a 99% efficiency. We do not expect any efficiency loss here. Similarly, the lateral defocus tolerances were analyzed in Butler (2003): a positioning error of less than $0.45\lambda$ ensures a loss less than 1%. The measured alignment (§ 4.1) is well within this limit. The resulting pointing error is less than 1°. The sidelobe levels are unchanged, with no coma lobes.

The instrumental polarization or polarization cross talk is the ratio of the undesired orthogonal component to the desired one. The effect can be minimized with precision parts: no asymmetries in mirrors and feed horn, no squint feed, and no antenna distortion. Since the antenna reverses the polarization and since the primary and secondary surfaces have parabolic and hyperbolic curvatures with finite sizes, a parasitic cross-polarization component with the opposite polarization is introduced. The effect is curvature-dependent and grows for a deeper dish. We define the cross-polarization efficiency $\eta_p$ as

$$\eta_p = \frac{\int_0^{2\pi} \int_0^{\Theta_s} (P_C(\theta, \phi) + P_X(\theta, \phi)) \sin \Theta d\Theta d\phi}{\int_0^{2\pi} \int_0^{\Theta_s} P_C(\theta, \phi) \sin \Theta d\Theta d\phi}, \quad (10)$$

where $P_C$ and $P_X$ are the co- and cross-polar patterns, calculated in Figure 8. Assuming a negligible contribution from asymmetries in the surfaces and the feed, the level of cross-polarization $P_X$ is more than 40 dB lower than the copolarization within the main beam. The resulting efficiency loss (<0.01%) can therefore be neglected.

The finite subreflector size (based on a geometric optics design) produces diffraction, causing further phase errors, amplitude taper losses, and cross-polarization changes. All of these losses are summarized in a diffraction loss term. They have been
analyzed numerically and the loss terms are given in a tabulated form in Lee et al. (1979) and Milligan (2005). For our antenna parameters the diffraction loss is about 0.22 dB. The efficiency term due to ohmic losses is usually negligible. Thus, $\eta_{\text{misc}} \approx 0.95$.

Finally, the absorption from a possible antenna Gore-Tex cover is about 0.1 dB (§ 4.4), and hence the antenna cover efficiency $\eta_c \approx 0.98$. All the efficiency components with the resulting aperture efficiency $\eta_a$ are summarized in Table 5.

### 6. ADVANCEMENTS AND COMPARISON WITH PREVIOUS ARRAY OPERATION

#### 6.1. Antenna Design Novelty and Improvements

From the initial seven-element array operation with 0.6 m antennas, to the currently operating 13-element array with 1.2 m antennas, several improvements were made. Table 6 summarizes them with their resulting benefits. Structure-wise, a major reduction in weight per unit surface $-10$ kg for the 0.6 m antenna, $\leq 25$ kg for the four-times-larger collecting area of the 1.2 m antenna—without compromising on the antenna stiffness was achieved with detailed FEA modeling. This has been an important design requirement in order to keep the resulting torques on the receiver and bracket within acceptable limits. In this way, a stable radio alignment of $\sim 1'$ between antennas is achievable. Maintaining a mirror surface accuracy for the larger 1.2 m antennas to better than $\sim 30 \mu$m leaves the possibility open to operate the array up to 300 or 400 GHz with possible future modifications.

A significant improvement in the 1.2 m optical design was made possible with a higher shielding baffle without reducing the forward gain of the antenna. As a consequence, the inter-antenna coupling was reduced by more than one order of magnitude, as compared with the 0.6 m antennas, to $\leq -135$ dB. Given sufficient integration time, this will allow for deep CMB observations below the initial target level of 10 $\mu$K. Finally, a TiO$_2$ top layer was added on both primary and secondary mirrors as a protective measure. This makes the costly Gore-Tex cover redundant. At the same time, Sun observations for testing purposes are possible without damaging the mirrors.

As a fundamental difference compared with earlier machined cast-aluminum antennas (CBI, Padin et al. (2000)) the AMiBA antennas are almost entirely made out of CFRP. The linear thermal expansion coefficient $\alpha$ is about an order of magnitude smaller than in the case of Al ($\alpha_{\text{CFRP}} \approx 1-2 \times 10^{-6}$ K$^{-1}$ and $\alpha_{\text{Al}} \approx 23 \times 10^{-6}$ K$^{-1}$). This reduces the thermal load ($\Delta T \approx 30$ K on the AMiBA site) and further ensures a very stable pointing of the antennas. The CFRP’s superior tensile strength ($\approx 5000$ MPa compared with about 500 MPa for aluminum) combined with its lower density ($\rho_{\text{CFRP}} \approx 1.2$ g/cm$^3$ and $\rho_{\text{Al}} \approx 2.7$ g/cm$^3$) make for a lightweight antenna ($\sim 25$ kg). This is crucial in order to keep the overall weight on the platform within the limits of the hexapod. For comparison, an equally stiff antenna made out of aluminum is estimated to be at least 35 kg.

#### 6.2. Upgraded Scientific Capabilities

A most immediate upgrade results from the significantly increased collecting area with the 1.2 m antennas. The original seven 0.6 m antennas were deployed in a close-packed hexagonal pattern on the AMiBA platform in order to utilize the shortest spacings (0.6 m) of the interferometer. This maximized the sensitivity for extended structures in clusters and primary CMB observations below the initial target level of 10 $\mu$K. Finally, a TiO$_2$ top layer was added on both primary and secondary mirrors as a protective measure. This makes the costly Gore-Tex cover redundant. At the same time, Sun observations for testing purposes are possible without damaging the mirrors.

As a fundamental difference compared with earlier machined cast-aluminum antennas (CBI, Padin et al. (2000)) the AMiBA antennas are almost entirely made out of CFRP. The linear thermal expansion coefficient $\alpha$ is about an order of magnitude smaller than in the case of Al ($\alpha_{\text{CFRP}} \approx 1-2 \times 10^{-6}$ K$^{-1}$ and $\alpha_{\text{Al}} \approx 23 \times 10^{-6}$ K$^{-1}$). This reduces the thermal load ($\Delta T \approx 30$ K on the AMiBA site) and further ensures a very stable pointing of the antennas. The CFRP’s superior tensile strength ($\approx 5000$ MPa compared with about 500 MPa for aluminum) combined with its lower density ($\rho_{\text{CFRP}} \approx 1.2$ g/cm$^3$ and $\rho_{\text{Al}} \approx 2.7$ g/cm$^3$) make for a lightweight antenna ($\sim 25$ kg). This is crucial in order to keep the overall weight on the platform within the limits of the hexapod. For comparison, an equally stiff antenna made out of aluminum is estimated to be at least 35 kg.

| Components | Efficiency |
|------------|------------|
| $\eta_l$ | 0.90 |
| $\eta_b$ | 0.923 |
| $\eta_c$ | $0.975^a$ |
| $\eta_e$ | <0.78 |
| $\eta_f$ | 0.99 |
| $\eta_p$ | $\approx 1$ |
| $\eta_t$ | 0.98 |
| $\eta_{\text{misc}}$ | <0.95 |
| $\eta_a$ (overall) | 0.58 |

*Notes.—* Since the feed power pattern is limited to the range of $\pm \pi/2$, $\eta_c < 0.78$ is a lower limit, and $\eta_{\text{misc}} < 0.95$ is a conservative limit accounting for possible miscellaneous components.

*Values are derived from measurements.*

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7. SUMMARY AND CONCLUSION

A 1.2 m f/0.35 Cassegrain antenna for a single-platform close-packed interferometer for astronomical radio observations is presented. Due to weight constraints, carbon-fiber-reinforced plastic (CFRP) is chosen as a lightweight material for the main antenna parts. With a detailed finite element analysis (FEA) it has been possible to keep the weight within 25 kg. The primary- and secondary-mirror sandwich composite structures show excellent behavior under thermal, wind, and gravity loads, leading to FEA-predicted surface rms deformation errors of less than 10 μm and maximum tilts in the optical axis of about 1′. The primary paraboloid and secondary hyperboloid mirrors’ manufactured surface rms errors are typically around 30 μm and 10 μm, respectively. The mechanical alignment after shimming and the resulting focal length are within ~0.1 mm of the specifications. The efficiency loss due to mechanical assembly and manufacturing is then within ~1%. For a good reflectivity, the mirrors are coated with a ~2 μm aluminum layer. Additionally, a thin TiO₂ layer (~0.15 μm) protects the antenna from the harsh high-altitude volcanic environment.

A corrugated feed horn with a parabolic illumination grading with a ~10.5 dB edge taper is used to achieve low sidelobe levels. The feed-horn antenna system is simulated and designed with the mode-matching technique. The results are verified in a far-field beam-pattern measurement. For the observing frequency around 94 GHz, the first sidelobe is around ~20 dB with a main lobe FWHM of about 11′. With the goal of sending more stray light to the sky, legs with a triangular-shaped roof are added to the secondary-mirror support structure. Despite this attempt, a weak remaining feature in the beam map at the level of ~1 dB around the secondary sidelobe is likely to be attributed to the secondary-mirror support structure. Measuring the weak CMB signals (~10 μK) poses a challenge for a close-packed array, due to interantenna coupling. A CFRP shielding baffle is therefore added, which extends to a height of ~300 mm above the secondary mirror. Insertion and return loss measurements show that CFRP is indeed an ideal lightweight shielding material. Without loss in the antenna forward gain, the antenna cross talk on the shortest separation of 1.4 m is measured to be ~ ~135 dB or less.

An overall antenna efficiency of about 60% is estimated from a series of efficiency factors. The dominating loss results from the feed spillover (efficiency ~0.78), followed by the illumination efficiency (~0.90) and the secondary-mirror blockage efficiency (~0.92).

In summary, based on the calculated and measured properties, the presented CFRP antenna is a lightweight, low-sidelobe-level, low-noise antenna. Thus, it is appropriate for the targeted astronomical observations (cosmic microwave background and galaxy cluster observations) in close-packed antenna array configurations. Currently, a 13-element compact array is used in daily routine observations.

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