A Measurement of the Coupling Between Close-Packed Shielded Cassegrain Antennas

Stephen Padin, *Member, IEEE*, John K. Cartwright, M. Joy, and J. C. Meitzler

***Abstract*—Design and performance details are given for a 0.9-m-diameter shielded cassegrain antenna, which will be used in a 13-element close-packed array. The array is designed to make images of brightness fluctuations in the cosmic microwave background radiation. Coupling between a pair of the shielded cassegrain antennas with a separation of 1 m is in the range −110 to −130 dB over the 26- to 36-GHz band.**

***Index Terms*—Multireflector antennas, mutual coupling.**

I. Introduction

THE Cosmic Background Imager (CBI) is a 13-element planar aperture synthesis array which will make images of the cosmic microwave background radiation (CMBR) on angular scales $\sim 5'$-1°, in the frequency range 26–36 GHz. Brightness fluctuations in the CMBR are at the level of just a few tens of μK [1]. To achieve the exceptional sensitivity required for CMBR observations, the CBI is a fairly close-packed array with cooled, low-noise ($\sim$20 K) receivers. Each receiver has a bandwidth of 10 GHz and signals from pairs of antennas are cross correlated in an analog correlator with ten 1-GHz bands.

The 13 antennas in the CBI are 0.9 m in diameter and these are mounted on a hexagonal platform $\sim$6.5 m in diameter. In such a sensitive close-packed array, coupling between the antennas becomes a serious problem. Noise emitted from the input of a receiver can couple into an adjacent antenna and cause a false signal at the correlator output, as shown in Fig. 1. The false signal limits the sensitivity of the instrument because it looks just like the CMBR signals we are trying to measure. In Fig. 1, receiver x has noise temperature T_r and emits from its input noise power pT_r that is correlated with the receiver noise. cpT_r is coupled into antenna y and this causes a false signal at the correlator output with maximum amplitude $T_r\sqrt{pc}$. Since the coupled noise arrives at the correlator with a delay error, the false signal is reduced by a factor $\mathrm{sinc}(\pi B\tau)$, where B is the bandwidth of the signals at the correlator inputs and τ is the delay error [3]. The false signal is then $s = T_r\sqrt{pc}\,\mathrm{sinc}(\pi B\tau)$ for noise coupling in one direction. If the receivers are identical, the signals for the two directions are complex conjugates, so the correlator output is always real but the amplitude can be anywhere in the range 0 to 2 s, depending on the coupling path length. In the CBI, $T_r \sim 20$ K, $\tau \sim 6$ ns and $B = 1$ GHz so the false signal could be as big as $4\sqrt{c}$ K. We can tolerate $\sim 1\ \mu$ K false signals, so the interantenna coupling should be $\lesssim 10^{-12}$. This is a very stringent requirement and is the key parameter driving the design of the antennas in the CBI.

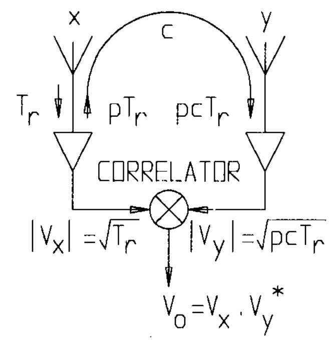

Fig. 1. Coupling between antennas in an array. T_r is the receiver noise, p is the correlation coefficient between the outgoing and receiver noises, pT_r is the outgoing receiver noise which is correlated with T_r and c is the coupling between the antennas. (If we transmit P_t from antenna x and receive P_r at antenna y, then $c = (P_r/P_t)$.) The correlator is a complex multiplier [2].

II. CBI Antennas

Low interantenna coupling requires antennas with very little scattering. Corrugated feedhorns are ideal, but a lens is required to reduce the horn length and loss in the lens degrades the sensitivity of the instrument. Offset reflectors are also an obvious choice but they are difficult to close-pack and access to the receivers is awkward. Because of these problems, we have pursued the shielded cassegrain design shown in Fig. 2. The 0.9-m-diameter primary is machined cast aluminum and all 13 primaries manufactured for the CBI have very small surface profile errors (110 μm rms for the first three mirrors manufactured, down to 30–40 μm rms for the last ten mirrors). The 0.155-m diameter secondary is made of carbon fiber epoxy [4] and weighs only $\sim$80 g. It is supported on four feedlegs made of expanded polystyrene. The feedlegs have a U cross section, hot-wire cut from 2 lb ft^{-3} expanded polystyrene stock. During assembly of the antenna, the secondary is supported on a fixture attached to the primary and the secondary and feedlegs are glued in place. The polystyrene feedlegs cause very little scattering and contribute only $\sim$0.5 K to the receiver noise.

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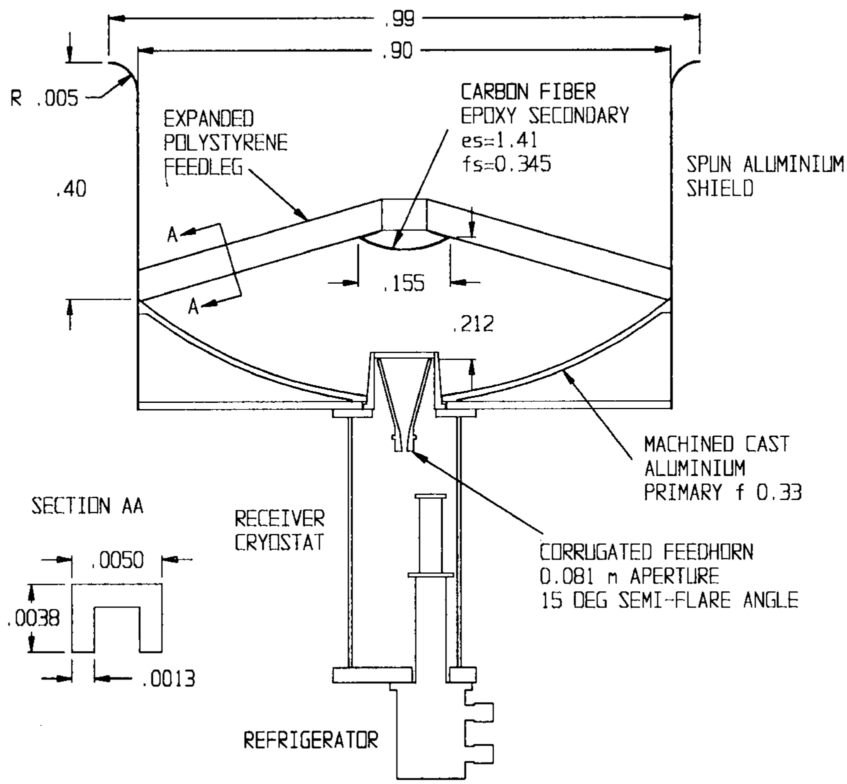

Fig. 2. Cross section of a CBI antenna. Dimensions are in meters; es and fs are the eccentricity and focal length of the secondary.

The cassegrain antenna sits in the bottom of a deep cylindrical shield which reduces coupling due to scattering from the secondary and the hole in the primary. Scattering from the shield rim is reduced by rolling the rim with a radius of $\sim 5\lambda$ [5]. The shield is made from a sheet of 1/16" aluminum welded into a cylinder and then spun to form the rolled rim [6]. The height of the shield is set so that the rim intercepts the beam where the electric field is about one tenth the on-axis field. This reduces the forward gain of the antenna by ~1%. Ohmic losses in the shield were measured using room temperature and liquid nitrogen loads in front of antennas fitted with 0.15 m and 0.40 m high shields. The 0.40-m shield contributes ~0.5 K to the receiver noise.

The antenna is fed by a wideband corrugated horn at the cassegrain focus, illuminating the secondary with a −11 dB edge taper. The horn has a semi-flare angle of 15° and an aperture diameter of 8.4λ at the band center. The −3-dB beamwidth of the horn varies by only ~1° over the CBI band so the efficiency of the antenna is essentially independent of frequency. A 15° semi-flare angle minimizes the horn aperture diameter for roughly constant beamwidth over the CBI band [7]. This in turn minimizes the diameter of the secondary, though the blockage is still rather high at ~2% of the area of the primary. The 2% aperture blockage degrades the efficiency of the antenna by ~4% [8]. The horn is mounted inside the receiver cryostat and is cooled to ~10 K along with the receiver electronics. Since the cryostat vacuum window determines the size of the hole in the primary, and hence the size of the secondary, the window is only 2 cm larger in diameter than the horn aperture.

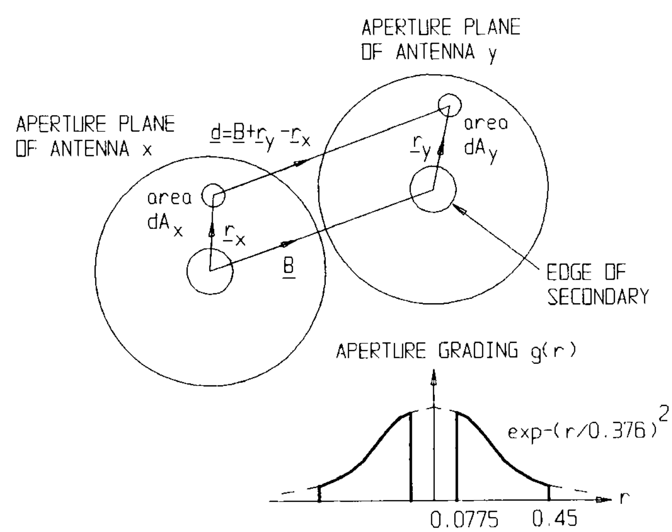

Fig. 3. Geometry for estimating the coupling between CBI antennas.

III. Interantenna Coupling

An accurate calculation of inter-antenna coupling involves computing the field surrounding a pair of antennas. This is quite time consuming, but we can make an estimate of the coupling using a simple scalar two-dimensional (2-D) calculation if we assume that the shield simply moves the aperture plane so that it lies at the shield rim. The calculation is further simplified by assuming that the edge of the secondary is also in the plane of the

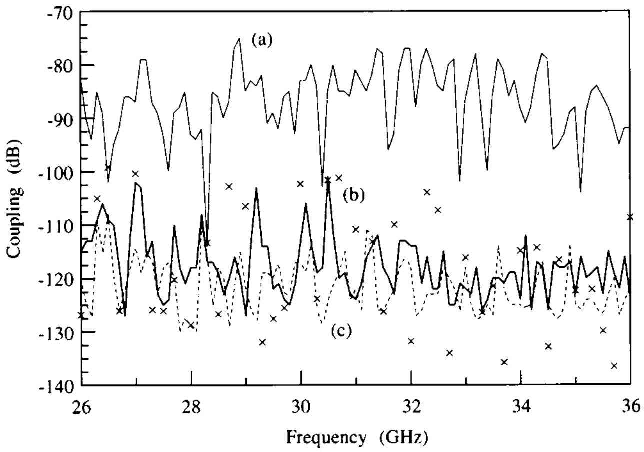

Fig. 4. Coupling between a pair of CBI antennas with 1-m spacing. (a) Without shields, polarizations → →. (b) With shields, polarizations → →. (c) With shields, polarizations ↑ ↑. The calculated coupling is shown by the crosses.

shield rim and the aperture grading is a Gaussian. Fig. 3 shows the geometry and the interantenna coupling is

$$c = \left[\frac{\displaystyle\int_y g_y(r_y) \int_x g_x(r_x) \frac{\exp\left(\dfrac{-i2\pi}{\lambda}|\underline{d}|\right)}{|\underline{d}|}\, dA_x\, dA_y}{\displaystyle\int_x g_x(r_x)\, dA_x} \right]^2$$

where the denominator is the power transmitted from antenna x when the amplitude distribution has a maximum value of unity, and the numerator is the corresponding power received by antenna y. The estimated coupling is shown in Fig. 4 along with measurements made using a pair of CBI antennas. The coupling was measured by transmitting a ~10 mW CW signal from one antenna and measuring the power received by the adjacent antenna. The receiver was a room-temperature HEMT amplifier and a spectrum analyzer. The measured and estimated coupling agree fairly well for the antennas with shields. If the shields are removed, the coupling increases by ~30 dB since signals can scatter from a secondary directly into the feedhorn of the adjacent antenna. The coupling decreases with increasing frequency because at higher frequencies the antennas are electrically larger and more widely spaced. Signals received by the CBI antennas are correlated in 10 1-GHz bands covering 26–36 GHz and in any one of these bands the average interantenna coupling is at most −110 dB. This could cause false signals at the $\sim 3\ \mu$K level, which is probably adequate for CBI observations.

IV. Summary

We have investigated the use of shielded cassegrain antennas for a close-packed imaging array which will make observations of the cosmic microwave background radiation. The sensitivity of this instrument is limited by coupling between adjacent antennas in the array. We have used cassegrain antennas because they can be close packed while still allowing easy access to the receivers, but we have added deep cylindrical shields to reduce the coupling between antennas due to scattering from the secondaries, the holes in the primaries and the feedlegs. The coupling between 0.9 m diameter antennas with 1-m spacing is in the range −110 dB to −130 dB over the 26–36 GHz band. This is ~30 dB better than for unshielded cassegrain antennas.

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