Broadband Amplitude Calibration of the ATA

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ABSTRACT

A planar equiangular spiral antenna can provide the calibration signal for the ATA antenna. The spiral antenna is located on the primary of the ATA antenna near its edge. It is fed by a broadband noise source whose spectrum yields a 1 K signal at every wavelength. The spiral radiates a circularly polarized signal which feeds the two linear polarizations of the ATA with identical calibration signals. To operate at the longest wavelength of the system, the planar spiral must be 60 cm in diameter, one wavelength. With this diameter, it is one tenth the diameter of the primary and 1% of its area. At the edge of the primary, the feed illumination is approximately 10 db tapered, and the spiral will have little influence on the main antenna system. This scheme satisfies the requirements for calibrating gain instabilities in the analog signal path, including those for polarimetric observations.

1. Introduction

The signal path of the ATA is expected to have instabilities on a wide range of timescales. To calibrate on the shortest of these, it will be impractical (or impossible) to observe nearby strong sources by moving the antennas. Meanwhile, the total flux density of sources within most fields will not be sufficient to perform self-calibration on the necessary timescales, especially when a narrow-band backend is in use.

In this memo we describe a scheme for amplitude calibration of the ATA that uses an equiangular spiral antenna located on the surface of the primary reflector of the ATA antenna to provide a calibration signal for both linear polarized channels of the antenna. The equiangular spiral is a member of the class of frequency independent antennas, as is the log periodic antenna which is the feed for this system. The spiral antenna produces a pure circularly polarized signal and thus an identical signal for both linear polarizations of the feed, except for a phase shift of 90 degrees between the two linear polarizations. Because the spiral is a broadband antenna, it can be made to provide a signal of approximately constant amplitude over the whole band-width of the system, 0.5–12 GHz. Both the spiral and the feed have approximately the same gains at all frequencies, and thus the coupling between them is proportional to the square of the wavelength. This wavelength dependence is easily corrected with an equalizer. The input signal to the spiral antenna will be a broad-band noise diode amplified by about 20 db by two wide-band amplifier chips. With an equalizer to compensate the frequency dependence of the coupling, the resulting calibrate signal will be about 1 K at every frequency. The signal can be turned on and off by a switch, so that calibration may be by either an occasional or periodically added one degree signal.

2. Amplitude of the Calibration Signal

The expected system temperature is about 50 K, and, relative to that, 1 K seems to be a reasonable calibrate signal. In the continuum with a band-width of 100 MHz, the RMS noise referred to the input, as usual, is 0.005 K in one second. For spectral line observations, for example for HI with a resolution of 1 km/sec, an observation of 1000 seconds duration of the calibration signal produces an uncertainty of about 0.02 K in each channel. These numbers seem reasonable. However, including the capability to temporarily increase the signal strength would facilitate special bandpass calibration observations.

3. The Equiangular Spiral Antenna

The theoretical paper discussing planar spiral antennas by Cheo, Rumsey, & Welch (1961) provides simple formulas for patterns and currents that agree well with measurements. It provides a simple basis for predicting the essential properties of these antennas. The important quantities are gain and necessary size for good operation over 0.5–12 GHz. The current distribution on this type of antenna scales with the wavelength, so that the overall size is dictated by the longest wavelength of operation, and the size of the input region is fixed by the shortest wavelength to be used. Beyond those restrictions, there is no limit to the range of wavelengths that can be accommodated. The model of Cheo et al idealizes the antenna as a metal sheet with infinitely many cuts parallel to the line of the spiral given by the formula: $r = e^{a\phi}$. The boundary condition becomes $E_r = aE_\phi$ everywhere on the antenna surface. The ϕ dependence is taken to be $e^{in\phi}$. $n = 1$ then corresponds approximately to the excitation of the two arm spiral. A simple field solution is found which satisfies the boundary conditions, and the patterns and current distributions are found in simple forms. For the $n = 1$ case, the theoretical patterns are very close to measured patterns for two arm spiral antennas. The magnitude of the amplitude pattern is given by:

$$A(\theta) = \frac{\cos(\theta)(\tan(\theta/2))^n e^{(n/a)\arctan(a\cos(\theta)}}{\sin(\theta)\sqrt{1 + a^2\cos(\theta)}} \tag{1}$$

The gain is greatest when a is small, and in this limit the amplitude pattern becomes:

$$A(\theta) = \frac{\cos(\theta)\tan(\theta/2)e^{n\cos(\theta)}}{\sin(\theta)} \tag{2}$$

For this case, the forward gain, for the two arm case $n = 1$, is found by integrating $(A(\theta))^2 \sin(\theta)$ over all solid angle. Half of the signal, corresponding to the underside of the antenna which is placed next to the primary reflector, must be terminated in an absorber, and the net gain normal to the topside is then about 1.85.

The spiral antenna will be self-complimentary in its shape and will therefore have an input impedance of 189 ohms. Figure 1 shows a two arm spiral with the parameter $a = 1/3$. A circle is cut out of the inner part, and the balanced excitation is across the the inner edges of the two arms. The exciting signal will be brought in along one of the arms in a coaxial cable with the cable shield soldered to the arm. The shield will stop at one inner edge, and the inner cable will jump across to the other side. No balun is needed for the coaxial line to provide balanced excitation to the antenna. The coaxial cable will be brought up through the surface of the arm a few centimeters away from the central region, where it is attached to the driving source which is embedded in the absorber below.

The necessary dimensions of the antenna can be estimated from Figures 8 and 9 of Cheo et al. Figure 8 shows that for $a \sim 1/3$ the antenna current has dropped to about 10% of its input value when $2\pi r/\lambda$=3, where r is the radial variable. That corresponds to r=$\lambda/2$, or diameter equals one wavelength. For operation down to 500 MHz (60 cm), the antenna must be about 60 cm in diameter. The important part of the phase curve in Figure 9 is the flat part where most of the radiation must occur, although it begins at smaller radii as a backward wave, typical of frequency independent antennas. For $a \sim 1/3$, the antenna must begin within $2\pi r/\lambda \sim 1/4$, corresponding to an inner diameter of $\lambda/4\pi$. For a shortest operating wavelength of 25 mm, the inner diameter must be about 2 mm.

4. The Coupling to the Feed

The coupling between the spiral antenna and the feed is given by the general formula:

$$k = g_1 g_2 (\lambda/4\pi R)^2 \tag{3}$$

At the edge of the primary reflector where the calibration antenna will be located, the pattern angle is about 32°, and the gain of the feed antenna is about 3.0. The distance between the two antennas is approximately the focal length at the effective Gregorian focus, $F \times D$, where $F = 0.65$ and $D = 6.1$ m. This distance is $R = 3.97$ m. For a wavelength of 0.60 m, substitution of the two gains and the distance give a coupling of -31 db. At 2.5 cm wavelength, the coupling is -58.6 db. At this shorter wavelength, a signal of about 10^6 K is required to give a calibration signal of 1 K. This signal requires a gain of about 20 db following the 10^4K noise diode to provide an adequate calibration signal. Two of the NBB-300 chip amplifiers will supply this amount of gain. For the calibration signal to be about 1 K at all wavelengths, an equalizer providing about 6 db/octave of equalization (i.e., 6db/octave of attenuation at the longer wavelengths) will be needed. In addition, this equalizer must compensate for the 3 db roll-off at 10 GHz of each amplifier. The 6 db/octave of equalization can be provided by a series capacitor; the roll-off can be obtained with the use of an additional series inductor.

5. The Calibration Signal Drive Unit

The drive unit will consist of a Noisecom 3×10^5 K noise source, two amplifier chips, such as the NBB-300 from NITRO, and the equalizer. In addition, there will need to be a matching circuit between the 50 ohm output of the final drive chip with its 50 ohm output cable and the spiral antenna which has an impedance of 189 ohms. This unit, except for the matching circuit, will be made up on a circuit board and will be located in a box whose temperature can be regulated for stability of the calibration signal.

The simplest matching circuit consists of a resistor across the spiral antenna terminals that provides a total impedance of 50 ohms. A 68 ohm resistor in parallel with the 189 ohms of the feed should work. The effect of this resistor will be the loss of about 6 db of signal. However, this match will be much easier to build than a wide band filter, and the loss in signal can be compensated with one more amplifier stage.

6. Calibration Strategy

Since some of the instabilities on the intermediate to longer timescales will be due to the Low Noise Amplifier (LNA), it is desirable to calibrate with a signal introduced into the signal path before any active electronics. The expected fractional gain fluctuations of the LNA at the input are 40 parts per million in a one second integration with a $1/f$ spectrum for these fluctuations. This is approximately the same as the expected white noise thermal fluctuations in one second for the 100 MHz bandwidth of the first version of the array. For integrations longer than one second, the LNA gain fluctuations will dominate. On time scales of 100 seconds the LNA gain fluctuations will be of the order of 10^{-3}, which will be too large for polarization observations. There may also be gain fluctuations at this level in the long term gains of the optical fiber transmission systems on timescales of 1–100 seconds. These time scales are too short to be easily dealt with by moving the antennas to astronomical calibrators. Thus it may be necessary to switch on and off the calibration signal with a timescale of seconds. This should be taken into account in the design of the antenna and data acquisition control system.

6.1. Polarimetric calibration

Observations made with the ATA will in general require full polarimetric calibration. Although much emitted radiation of interest will not be intrinsically polarized, many lower-frequency observations will require the subtraction of a continuum polarized background. Furthermore, since RFI sources are polarized, many mitigation methods will require that the data be well-calibrated polarimetrically. This memo does not consider polarimetric calibration of the ATA in its entirety. Polarimetric calibration of interferometric arrays is discussed in detail by Sault et al. 1996; some further details and strategies for a system with linearly-polarized feeds are given in the earlier memo on AT polarimetric calibration (Sault et al. 1991). A memo relating these works to the ATA is forthcoming. However, one parameter which needs to be determined is the phase difference between the two orthogonal polarizations received by each antenna. An error in this parameter leads to a proportional corruption (for crossed linear feeds) of U into V and vice-versa. So measurements of linear polarization would be corrupted if circular polarization should be present, and measurements of circular polarization would be difficult in the presence of the ubiquitous linearly polarized emission at low frequencies. The necessary parameter can be determined from observations of three sources with strong polarization or from three observations of a single strongly polarized source distributed widely in parallactic angle. 3C286 and 3C138 are two well-known suitable sources. However, in general the phase difference between the polarizations can be expected to vary during an observation. So for many purposes this parameter will need to be calibrated instrumentally, rather than astronomically, since nearby or in-field sources will generally be only weakly polarized. The ATCA (which also has crossed linear feeds) has successfully used a common signal coupled to both polarizations to calibrate observations of polarized emission in this way. It is important that the relative delay of the signal to each channel remains constant. Since our scheme emits a circularly polarized calibration signal that is radiatively coupled to the feed, it should be possible to rely on the stable telescope geometry to maintain the calibration between observations of the primary polarization calibration sources.

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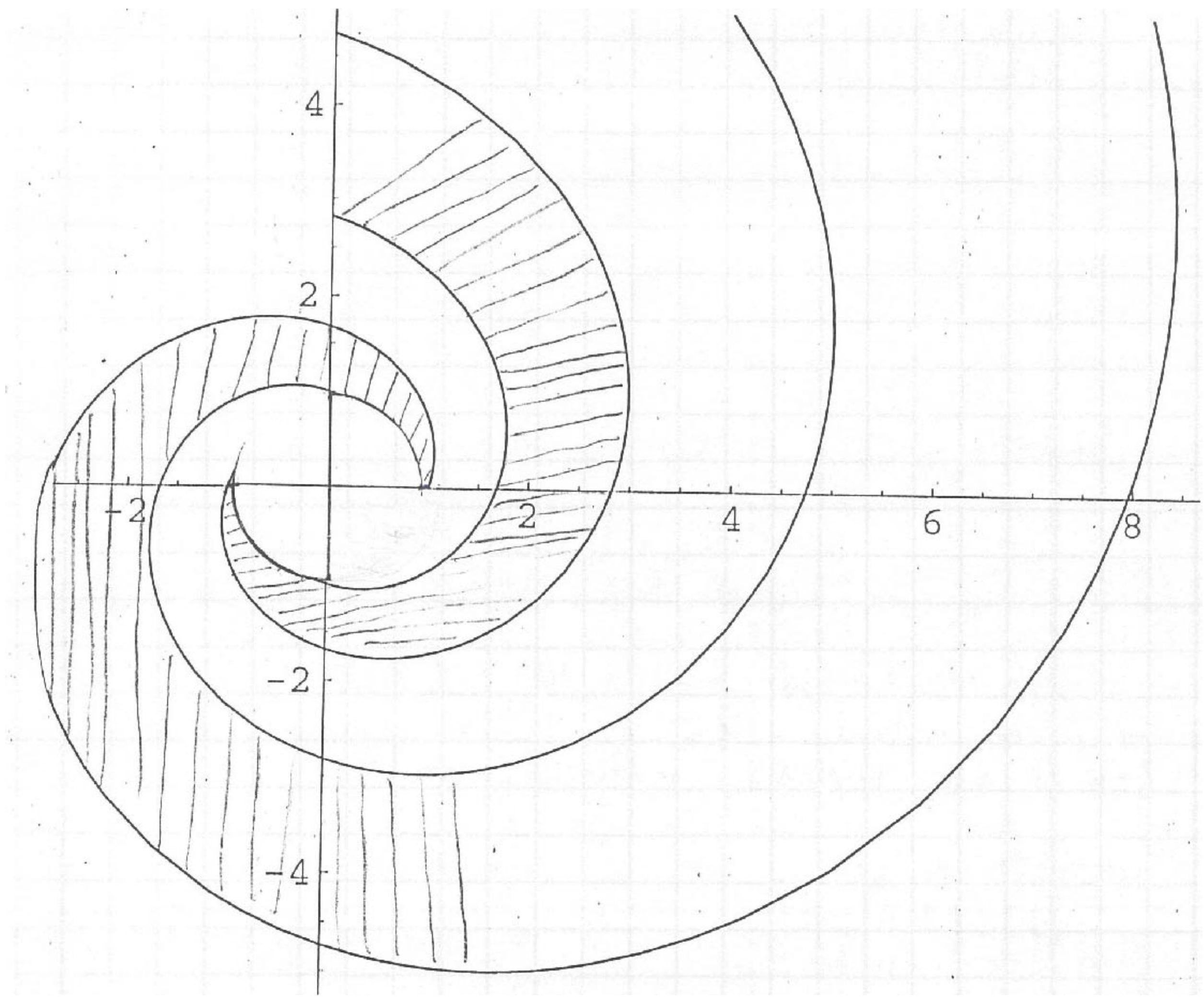

Fig. 1.— A self-complementary two arm spiral antenna with $a = 1/3$. The input terminals are in the center.

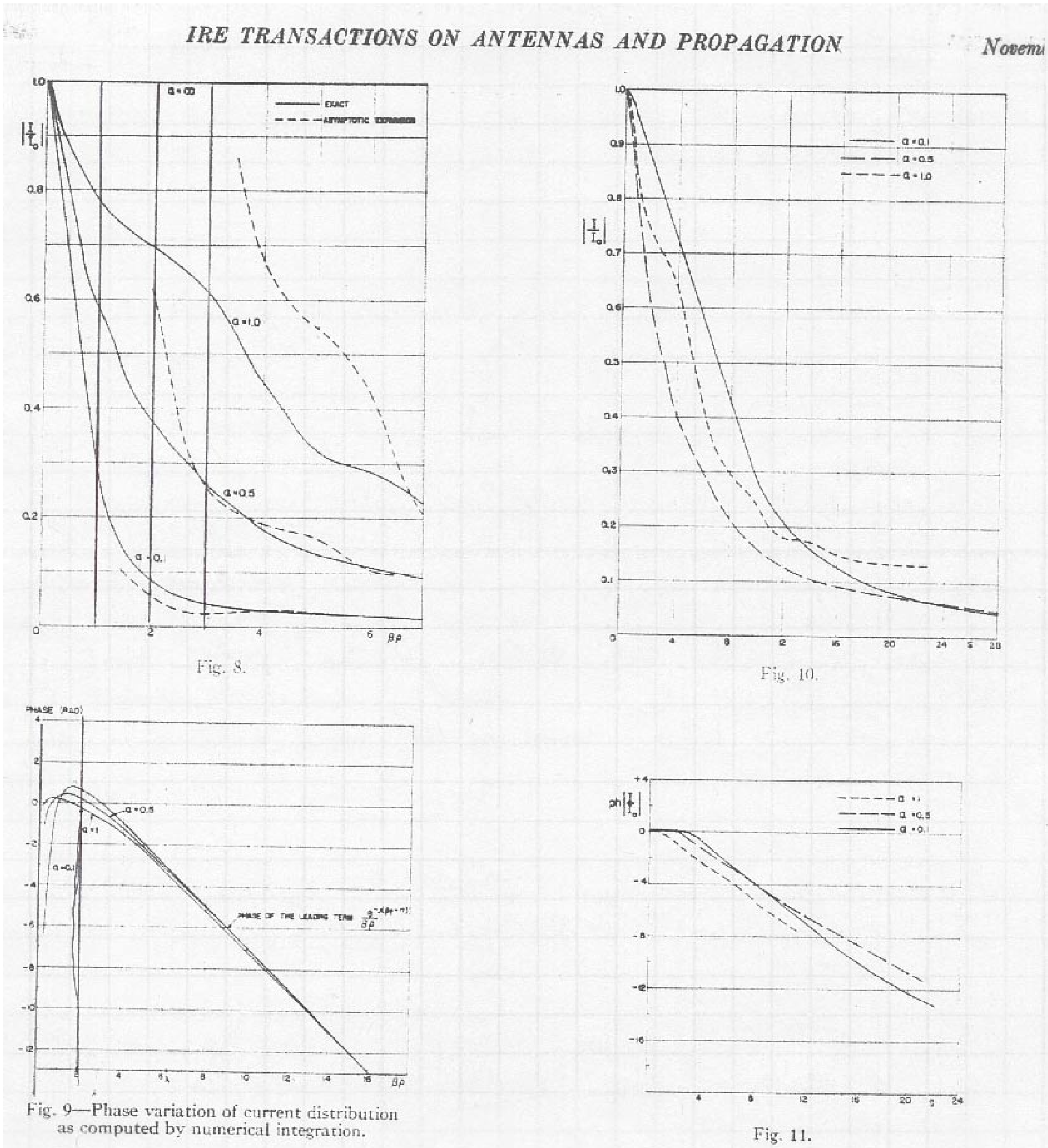

Fig. 2.— A selection of four figures from Cheo et al, 1961. They show the amplitude and phases of the current along the arms. The absicca is $2\pi r/\lambda$, where r is the radial variable.