Instruments and Basic Astronomy

A Technique for Reducing the Grating Lobes of the Molonglo Observatory Synthesis Telescope

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Abstract: The grating ring response of the Molonglo Observatory Synthesis Telescope can be reduced by the installation of 60° phase switches into each of 176 signal paths of the antenna. A suitable voltage-controlled UHF phase switch has been designed and tested at 843 MHz. It consists of two varactor diodes in series with a microstrip. Although designed to provide only two phase states, the device works well as a continuous phase shifter with a coefficient of ~3° per volt. Details of the design, performance and application to the radio telescope are given.

1. Introduction

The Molonglo Observatory Synthesis Telescope (MOST) consists of two collinear tiltable antennas set on an east-west baseline with a small central gap. The line feed system has a periodic structure: radio frequency signals from 17.7 metre (50X) 'bays' are combined before being converted to intermediate frequency and returned to the central beam-forming circuits. The telescope uses the principle of earth-rotation fan-beam synthesis to map the 843 MHz continuum emission from the sky with a resolution of < 1 arcmin. A field of area > 1 square degree is mapped with high sensitivity in one 12-hour observation (Mills 1981).

One consequence of the periodic structure of the line-feed is that grating sidelobes are produced. At meridian distance $\psi$ the grating lobe of order $m$ is displaced $1915 \times \sec \psi$ from the main fan beam. In synthesized images the grating lobes appear as south x north cosec $\psi$ rings about all sources. Higher order rings are weak and may usually be ignored but the first order rings can detract from the appearance of images and obscure faint features. Figure 1 is a grey scale image of a field from the MOST galactic survey (Whiteoak et al. 1989; Whiteoak 1990). Prominent first order grating rings can be seen about sources which are located outside the field.

There is some scope for reducing the grating rings by image processing and judicious choice of field centres (Roger et al. 1984). However, these remedies are of little use in complex regions of sky, and we have recently looked at the possibility of modifying the telescope to reduce the grating lobe response. Fortunately there are two radio frequency pre-amplifiers on each 50X bay of MOST. By suitably switching the phase of these 176 pre-amplifiers before their outputs are combined in pairs, it is possible in principle to bring about worthwhile reductions in the amplitude of the first order grating rings in synthesis maps. To achieve this it was necessary to develop an inexpensive UHF phase switch.

Figure 1 — A back-projected synthesis image from the MOST Galactic Survey, in which grating rings appear as circular arcs. The field is centred on $\alpha(1950.0) = 13^h 58^m 57.1^s$, $\delta(1950.0) = -61^\circ 28' 38"$ and has dimensions of 70' (EW) and 80' (NS).

Figure 2 — (a) The horizontal line represents the actual phase distribution across an individual 50X bay. The two sloping lines represent the ideal phase distribution for the outer beams (32 < $n$ < 96). Note that the discrepancy between the mean phase of the east and west halves of the bay is about 60°. (b) By introducing a phase step of 60° into the line-feed when the outer beams are formed, the phase discrepancies (and the consequent grating rings) are reduced. See text.
voltage-controlled UHF phase switch compatible with the existing electronics and small enough to fit into the existing weatherproof distributed amplifier boxes.

2. The formation of MOST beams and grating responses
The MOST forms fan beams at angular displacements from the field centre of

\[ \theta_n = \pm \left( n - \frac{1}{2} \right) \times 22'' \sec \psi \]  

(1)

where \( n \) is a positive integer (\( \leq 96 \)). The phases required to form these beams are applied to the signals from the 50A bays. Consequently there is a linear departure of phase from the ideal across each bay and thus a saw-tooth pattern of phase discrepancy along the entire antenna. The size of the periodic phase discrepancy (and of the resulting grating rings) increases with \( n \). Inner beams (\( 1 < n < 32 \)) are formed in real time by hard-wired phasing circuits. When these (inner) beams are used simply to synthesize \( 23' \times 23' \) cosec \( \delta \) fields the phase discrepancies are relatively small and all the grating rings, including the first order rings, are correspondingly weak. The outer beams (\( 32 < n \leq 96 \)) are formed by offsetting the set of hard-wired beams in a 24 second switching cycle. Thus time multiplexing is used in the synthesis of the \( 70' \times 70' \) cosec \( \delta \) survey fields. There is then a large phase discrepancy for all the offset beams, and correspondingly large grating responses. The situation is summarized in Figure 2(a) which shows the phase discrepancy across a bay for \( n = 32 \) and \( n = 96 \).

The basis of our proposed method for reducing the grating rings is to introduce a phase step of 60° between halves of the bays when the set of beams is offset. Figure 2(b) shows how this can markedly reduce the amplitude of the phase discrepancies. The phase step across the bay is a first approximation to the phase gradient appropriate to the outer beams (\( 32 < n \leq 96 \)). Computer simulations carried out by Dr J. G. Robertson (Figure 3) shows the predicted reduction in the first order grating lobes of the outer beams.

3. Series tuned phase switch
The UHF phase switch that we have designed and tested consists of a length of microstrip and two varactor diodes connected in series (see Figure 4).

We have shown that there are in general two values of varactor capacitance for which the device is matched to its source and load impedances, and these two states have different insertion phases. The existence of the two solutions for \( C \) is illustrated in Figure 5, in which the operating points of our prototype model are plotted on an impedance-coordinate Smith Chart.

The two solutions correspond to the points in which the radius intersects a circle of constant resistive component. By examination of the expression for the scattering parameter \( S_{12} \) we have derived the following expressions which were used to design the phase switch

\[ \cos \frac{\Delta \phi}{2} = \frac{Z_L}{Z_0} \sin \beta \ell \]  

(2)

and

\[ C = C_0 \frac{\cos(\Delta \phi/2)}{-\cos \beta \ell \pm \sin(\Delta \phi/2)} \]  

(3)

Here \( \Delta \phi \) is the phase difference between the two states and \( C_0 = 1/\omega Z_L \). The + alternatives in Equation 3 yield the two values of \( C \), both of which are positive provided \( Z_L > Z_0 \) and \( (90° + \Delta \phi/2) < \beta \ell < 180° \).

For our purpose we require \( \Delta \phi = 60° \). By trial we selected values of \( Z_L/Z_0 = 50 \Omega, Z_0 = 40 \Omega \) and \( \beta \ell = 136° \) consistent with Equation 2 which led to two values of \( C \) (3 pF and 15 pF) easily obtained with UHF varactors.

[Figure 3 — Predicted reduction in the relative amplitude of the first order grating rings. The edge of a \( 70' \times 70' \) cosec \( \delta \) field corresponds to \( n = 96 \).]

[Figure 4 — The series tuned phase switch consists of a microstrip of phase length \( \beta \ell \) and characteristic impedance \( Z_0 \) connected in series with two varactors of capacitance \( C \). The source and load impedances are \( Z_l \), where \( Z_l > Z_0 \). The numbers correspond to labelled points on the Smith Chart (Figure 5). For the MOST phase switches, the physical length of the microstrip is 76 mm.]
Figure 5—An impedance-coordinate Smith Chart illustrating the operating points of the phase switch. The numbers refer to the labelled points on Figure 4. The varactors are voltage-tuned to give capacitances of 3 pF and 15 pF. The first varactor takes the impedance to point 2 (2'). The microstrip takes the impedance to point 3 (3') and the second varactor returns the impedance to $Z_L$ (point 1). The phases inserted by the device in the two states differ by 60°.

4. Performance
To measure the performance of the phase switch we have built several prototypes using double sided fibreglass printed circuit board. The board thickness is 1.60 mm and the relative permittivity is 3.84 at 843 MHz. The physical length of the 136° microstrip is 76 mm. The varactors, Philips type BB215, were surface mounted, as were the T-attenuators which established the input and output impedances. Bias for the varactors was applied to the microstrip through an RF choke.

The measured characteristics of the first prototype phase switch are shown in Figure 6, in which the amplitude and phase of the transmitted signal is plotted against varactor bias. A pleasing and unanticipated feature is the smooth and almost linear dependence of phase on varactor bias. The slope is about 3 degrees of phase per volt and there is comparatively little variation in amplitude over a phase range of ~90°. At the design points the amplitudes are almost equal and the insertion phase is ~60°, in agreement with the theory. The phase can be trimmed to exactly 60° by adjusting the varactor bias. Subsequent prototypes, built to the same design as the first, have very similar characteristics, auguring well for consistency in production.

To determine the sensitivity of the phase switch to mismatches at the input and output we have investigated the phase shifter with the microwave analysis computer program Puff (Compton and Rutledge 1987). Broadly speaking, our finding is that to maintain an accuracy of ±1° in phase and ±0.2 dB in insertion loss the VSWR at both ends of the phase shifter needs to be no larger than 1.2 : 1. Our bench tests confirm that conclusion. We have also shown experimentally that the same accuracy (±1°, ±0.2 dB) is maintained over a 20 MHz bandwidth, more than adequate for the 3 MHz bandwidth of the MOST.

As we are concerned with developing the phase switch for a specific purpose, we have not yet fully explored the range of its capabilities. The dual of this series circuit, in which the varactors are connected in parallel with the line and $Z_0 > Z_L$, performs the same function, but for our purpose the required varactor capacitances are less convenient.

5. Application to the MOST
Our intention is to place the phase switches into the so-called 'long boxes' on the MOST. These are the 88 distributed units which contain the final stages of 843 MHz amplification, the mixer and intermediate frequency amplifier. To maintain the required VSWR at the varactors, 8 dB input and output attenuators will be included, the loss being compensated by a single UHF amplifier chip. Control of the phase switches will (initially) be achieved by a single control line common to all bays. An analog coding is proposed in which voltages of $+V$, 0 and $-V$ correspond to phase steps of +60°, 0 and −60°. The switching, in step with the beam switching, will be controlled by the Telescope Control Computer.

6. Conclusion
The possibility of reducing the grating rings of the MOST by the installation of 176 phase switches has been confirmed by computer modelling. Bench tests have established that the microstrip phase switches described here are electrically and physically compatible with the existing MOST electronics. We believe that the work and cost involved in manufacturing and installing the phase switches will be amply repaid by the improved quality of MOST large-field images.
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Note added in proof: The 88 phase switches were installed on MOST in December 1989 and the first image obtained on 1989 December 14. This observation confirmed the predicted reduction in grating lobe amplitude.