Publ. Astron. Soc. Aust., 1997, 14, 265–73

Response of the Molonglo Observatory Synthesis Telescope to Terrestrial Interference

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Received 1997 July 13, accepted 1997 August 20

Abstract: In conjunction with the Australian Government's Spectrum Management Agency, experimental tests have been carried out to determine the susceptibility of the Molonglo Observatory Synthesis Telescope (MOST) to interference from terrestrial transmitters. The motivation for the tests was to reconcile the conflicting requirements of the MOST, which is committed to an extensive survey of the southern sky at 843 MHz, with the commercial use of the 825–845 MHz band, which is being prepared for sale. The tests show that the far sidelobe gain of the MOST, relative to an isotropic antenna is generally less than 1, and that an appropriate interference criterion would be that in-band interference irradiance should not exceed -173 dBWm^{-2}. This value is similar to that considered by the International Telecommunications Union to be detrimental to radio astronomy continuum observations at nearby frequencies.

Keywords: instrumentation: interferometers—site testing

1 Introduction

The Molonglo Radio Observatory is situated in a flat valley, ~700 m above sea level in the Great Dividing Range near Bungendore, about 30 km east of Canberra. The site was one of several considered in the mid-1950s for the 64 m radio telescope eventually built by the CSIRO at Parkes. In 1961 Bernard Mills chose the site as the most suitable for his new (408 MHz) Cross-type radio telescope (Mills et al. 1963). The land was acquired by the University of Sydney and the telescope, which became known as the One Mile Cross was opened by Prime Minister Sir Robert Menzies in November 1965. During the next 12 years the instrument was used for a number of major astronomical investigations (Mills 1991), including: production of the Molonglo Reference Catalogue of over 12 000 radio sources; discovery of supernova remnants in the Galactic Plane and the Large Magellanic Cloud; determination of accurate positions and flux densities of galaxies and quasars; discovery of a large number of pulsars including the pulsar associated with the Vela supernova remnant.

In the late 1970s it became apparent that the Cross would soon complete its planned programme of surveying the radio sky south of +18° and a decision was made to convert the east and west arms of the Molonglo telescope to an aperture synthesis instrument capable of higher sensitivity and angular resolution. This was achieved by increasing the frequency of operation by approximately a factor of two. Some constraint was imposed by the resonances of the existing line feed structure, but the choice of 843 MHz was made in consultation with Telecom to avoid likely sources of interference from radio telephony services (Mills 1981). While 843 MHz is not in an internationally protected band for radio astronomy, the use of this frequency by the Molonglo Observatory was entered as a footnote in the Spectrum Band Plan.

The Molonglo telescope in its new incarnation started observations in 1980 and has been in continuous operation, with several technical improvements, since then. It is now known as the Molonglo Observatory Synthesis Telescope (MOST). Until the early 1990s, the site proved to be free of interference in the 843 MHz band, and the MOST enjoyed quiet observing conditions. With the introduction of analogue mobile telephone services, the telescope began to experience occasional bursts of interference. At the present time (1997) such interference bursts have become much more frequent, inevitably degrading the quality of radio images and necessitating additional time consuming image processing to minimise the loss of information.

In 1995 we were dismayed to learn that the Australian Government was planning to sell the 825–845 MHz band of the electromagnetic spectrum. The use of part of this band by the MOST has been acknowledged for over 17 years, during which time the telescope has made many internationally recognised contributions to astronomy. Observations would be seriously threatened by radio frequency interference if the band were to be released for unrestricted

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use. The University entered into discussions with the Spectrum Management Agency (SMA) and it was agreed that a series of tests should be carried out to determine the sensitivity of the MOST to interfering signals from local low power transmitters. The results, together with theoretical predictions, are intended to provide the technical basis for protection of MOST observations when the 825–845 MHz band is sold for commercial use.

2 The Telescope

The MOST is a multi-element interferometer operating at 843 MHz with a 3 MHz bandwidth (FWHM). The reflectors of the MOST are two co-linear cylindrical paraboloids aligned east–west, each 11·6 m wide and 778 m long. These two *arms* are separated by a 15 m gap and have a total aperture area of more than 18 000 m^2 (Robertson 1991). The MOST incorporates 352 low noise preamplifiers, one for each 12·5 λ (4·4 m) *section*. The line feed of each section is a resonant waveguide excited by a linear array of circularly polarised ring antennas (spaced at 0·540 λ). The amplified signals from the sections are combined in groups of four, via computer controlled phase-shifters, to form the 88 basic interferometer elements (*bays*) of the MOST. The intermediate frequency signals from each bay are processed to form a set of real-time fan beams, which are sampled every 24 s. The natural coordinate system for the MOST is analogous to an alt–alt mounting: *tilt* is the angle of rotation of the entire structure about its east–west axis, measured from the zenith with north being positive; *meridian distance* (MD) is the angle between a beam and the plane of the meridian, positive to the west (Robertson 1991). In its usual mode of operation the MOST observes for 12 hours to form a high resolution image by the process of back projection (Perley 1979; Crawford 1984). During an observation, the bays track the chosen field centre. A mechanical drive system tilts the entire structure to the appropriate elevation. At the same time linear phase and delay gradients are applied to the line feed, thus guiding the beams in MD. The RF phase shifters are used to make small rapid offsets in the MD pointing of the bays. This facility, installed in 1995, enables the field of MOST to be widened by time sharing (Large et al. 1994). The MOST forms radio continuum images with a maximum field size of $2{\cdot}7^\circ \times 2{\cdot}7^\circ\mathrm{cosec}(\delta)$, a resolution of $43''\times43''$ cosec(δ) and an rms noise level of ∼1 mJy per beam.

3 Beams and Sidelobes

A fan beam formed by the MOST at meridian distance θ is an arc of a small circle making an angle $(\pi/2-\theta)$ to due west. The beam has a width in MD of $\sim 30''$ sec(θ) and a width in the tilt coordinate of $\sim 2^\circ$ (FWHM). The principal sidelobes of the MOST are grating lobes arising from the periodic bay structure. They are also arcs of small circles spaced at equal intervals of sin(θ), i.e. $\sim 1{\cdot}15^\circ$ sec(θ). The grating lobes are largely suppressed as they lie near the nulls of the bay responses. The MOST is designed to receive right-hand circular (IEEE) polarisation. However, it has some sensitivity to left-hand circular polarisation, particularly for monochromatic interference for which there is no delay decorrelation. If the MOST is set to meridian distance θ, the corresponding left-hand polarisation beam is at meridian distance $-\theta$, and it too has an associated set of grating lobes.

For distant interfering terrestrial transmitters, the MOST is likely to have the greatest response at azimuths where the small circles defining the beams and gratings intersect the horizon. However, for local transmitters the MOST will be out of focus to some extent, and the gain of the beams and gratings will be correspondingly reduced. For example, for sources at a range of $\sim 1000\ \cos^2$(azimuth) km the curvature of the incoming wavefront reduces the gain of the fan beams by 10 dB. For transmitters much closer than this, recognisable fan beams are not formed. The sidelobe response is then quasi-random, relatively small, and at any given azimuth, varies rapidly with the MD setting of the telescope.

During a synthesis observation, this complicated sidelobe response structure sweeps across any fixed interfering transmitter, producing a signal in the fan beams which fluctuates at a rate dependent on the rate of change of MD. These fluctuations will be superimposed on those due to the transmitter modulation and propagation effects.

4 Theory

To provide some theoretical background for the practical tests, we consider the likely effect on the MOST of continuous narrow-band interference from a terrestrial transmitter. In practice the extent to which astronomical observations are affected will depend on a host of complex factors such as the modulation characteristics of the transmitter and the mode of operation of the MOST.

4.1 In-band Interference

If an interfering transmitter produces an irradiance I at one section of the MOST, then the interference power p in the low noise amplifier (LNA) input is

$$p = gI\lambda^2/4\pi\,, \tag{1}$$

where g is the sidelobe gain, with respect to an isotropic antenna, in the direction of the transmitter and $\lambda^2/4\pi$ is the effective collecting area of an isotropic antenna. The noise power N, also referred to the input of one section of the MOST, is

$$N = kT_{\rm sys}B\,, \qquad (2)$$

where $T_{\rm sys}$ is the system noise temperature (~100 K) and B is the bandwidth.

The voltages from the east and west arms are combined separately in the multibeaming networks. Power-linear fan beam outputs are then formed by multiplying the signals from the two arms. The ratio r of interfering signal to the rms noise fluctuations in a fan beam is

$$r = \frac{Fp}{N/\sqrt{B\tau}}\,, \qquad (3)$$

where τ is the integration time and F is a measure of the extent to which the interference signals from each section add coherently; F is 1 for a random walk addition.

If r is interpreted as the maximum tolerable interference-to-noise ratio, equations (1)–(3) can be combined to yield an expression for the maximum tolerable interference irradiance:

$$I_{\rm max} = \frac{r}{Fg\sqrt{B\tau}} I_0\,, \qquad (4)$$

where

$$I_0 = \frac{kT_{\rm sys}B}{\lambda^2/4\pi} = 4\cdot 1 \times 10^{-13}\ {\rm Wm^{-2}}\,. \qquad (5)$$

Thus the maximum tolerable interference irradiance is proportional to the input noise power divided by the collecting area of an isotropic antenna.

To proceed we need to assign realistic values to the quantities τ, r, g and F. The appropriate value for τ is the time for which the radio telescope integrates signals coherently. For filled aperture instruments this is generally equal to the observing time, which may be many hours. For interferometers the appropriate time is the *lobe sweep time*, typically measured in seconds (International Telecommunication Union *Handbook on Radio Astronomy*—subsequently referred to as ITU 1995). During a normal 12 hour MOST synthesis observation celestial signals add coherently, but an interfering signal lasting for much longer than one 24 s sampling time would tend to add incoherently into the synthesised image. A suitable value for τ in equation (3) would appear to be $\tau = 24$ s. In this 24 s sample time an 'acceptable' interference level would be 10% of the rms noise. While this factor is to some extent arbitrary, it conforms with the guidelines specified by the International Telecommunication Union (ITU 1995). Thus in equation (3) we set $r = 0\cdot 10$. The factor g is the sidelobe gain of a section of the MOST far from the main beam. It varies considerably with telescope pointing and the azimuth of the interfering transmitter. Provisionally we adopt the value $g = 1$, which is equivalent to saying that the gain of one section of the MOST in the direction of the transmitter is equal to that of an isotropic antenna. Interfering transmitters will generally be in the near-field of the MOST (i.e. out of focus) and at a large angular distance from the MOST fan beams. Consequently interfering signals from each section of the MOST will add essentially incoherently and the appropriate value of F in equation (3) is $F = 1$. The product Fg is the sidelobe gain, relative to isotropic, of the whole telescope. Substituting the above values of τ, r, g and F into equation (4) yields

$$I_{\rm max} = 4\cdot 9 \times 10^{-18}\ {\rm Wm^{-2}}$$
$$= -173\ {\rm dBWm^{-2}}\,. \qquad (6)$$

This expression for the tolerable interfering irradiance is subject to the uncertainties indicated in the above discussion. In particular we have taken the sidelobe gain of the MOST to be unity. Experimental values of the sidelobe gain based on the current series of tests are presented in Section 5.

4.2 Out-of-band Interference

Signals strong enough to overload the MOST receiver system can produce interference by intermodulation. By this mechanism, transmitters well outside the MOST passband can generate interference in the output. The effect is dominated by the third-order term in the receiver response. Intermodulation interference occurs when two sufficiently strong signals have frequencies such that $(2f_1 - f_2)$ lie within the MOST passband. The magnitude of the interference, expressed as an equivalent in-band power $p_{\rm e}$ at the receiver input, is given by

$$p_{\rm e} = \frac{p_1^2 p_2}{\gamma^2}\,, \qquad (7)$$

where p_1 and p_2 are the powers generated in the receiver input and γ is the third-order input intercept for the receiver. The third-order input intercept is a theoretical point on the RF input versus IF output curve where the desired input signal and third-order products become equal in amplitude as the RF input is raised (Mini-Circuits *RF/IF Designer's Handbook* 1992). Combinations of signals from three transmitters, or from one transmitter, and the input noise can also produce intermodulation interference.

To see how these effects arise in the MOST consider Figure 1 which shows a simplified block diagram of the receiver system and sketches of the frequency response at each stage. Transmitters with frequencies lying within the passband of the feed system can generate intermodulation interference in the LNAs, for which the measured third-order input intercept is $\gamma_{\rm LNA} = -65 \pm 3$ dBW. The MOST is more sensitive to intermodulation interference from transmitters with frequencies lying within the band of the interdigital filter. The non-linearity then occurs in the first stage of the IF amplifier, the third-order input intercept, having a measured value $\gamma_{\rm IF} = -78 \pm 5$ dBW. The sensitivity of the MOST to (two) out-of-band transmitters can be calculated by using these data and equation (7) in place of equation (1) to express the interference power developed at the input to one section of the telescope.

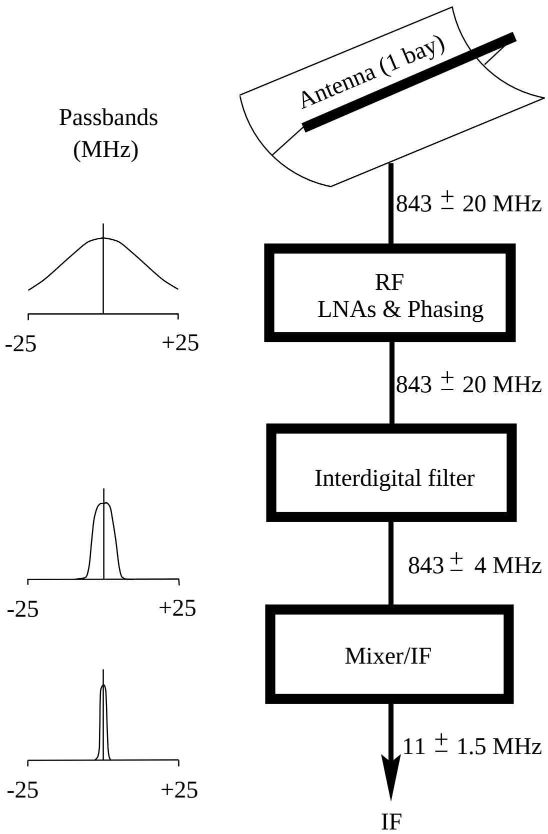

Figure 1—Block diagram showing passbands at critical stages in the signal path for one *bay* of the MOST. Sufficiently strong signals within the passband of the feed can generate interference by intermodulation in the LNAs. Similarly, signals within the narrower band of the interdigital filter can generate interference by the same mechanism in an IF amplifier.

4.3 Overall Sensitivity of the MOST

Figure 2 shows the expected sensitivity of the MOST to interference as a function of frequency. It is based on the preceding discussion and knowledge of the band shapes of the feed system, interdigital filters and IF amplifiers. The sensitivity to intermodulation arising between two transmitters generating equal power in the LNA inputs is typically 80–100 dB below the sensitivity to in-band interference. Two other typical power levels are marked on the graph for reference. These are the level of interference recognised by the ITU (1995) as detrimental to continuum radio astronomy (threshold of $\sim$$-183$ dBWm^{-2} interpolated from nearby frequencies), and the MOST rms noise level of $\sim$1 mJy, seen in a 12 hour synthesis image.

5 Test Transmissions

A series of tests were carried out in conjunction with the SMA and the Department of Communication and the Arts (DCA). The DCA mobile test transmitting equipment was set up, over 8 days in 1996 between July 22 and August 28, at four different elevated sites. The test sites, chosen to be representative of the future locations of transmitters, were situated to the west and north of the MOST at distances $\sim$30 km. The details are given in Table 1.

Table 1. Transmission site details

Site	Mt Taylor	Red Hill Lookout	Mt Ainslie	St Georges Hill
Bearing from MOST (°)	271	281	296	354
Distance (km)	31·7	28·4	26·6	36·6
Measured path loss (dB)	142	140	153	142

After preliminary tests the transmitter frequency was set within the MOST's bandpass at 844 MHz (vertically polarised carrier, 20% AM modulated with a 1 kHz tone). The effective isotropic radiated power (EIRP) was adjusted to avoid saturation of the MOST receiver and was switched on/off at 2 (or 5) minute intervals. The SMA/DCA team set up a standard antenna and calibrated receiver to measure the irradiance at the MOST. Both the receiver and transmitter antenna heights were set at 5 m.

5.1 Measurements of the Remote Sidelobes of the MOST

The purpose of these tests was to determine the typical sensitivity of the MOST to interference from the selected sites. For each transmitter location the MOST was steered to 5 tilts (±54°, ±30° & 0°) and 5 meridian distances (±60°, ±30° & 0°) making up a grid of 25 pointings.

The signals received by MOST during these tests were recorded in two ways:

(1) The signal from one fan beam was recorded on a chart recorder with a 0·5 s time constant.
(2) The usual MOST data acquisition system was used to calculate the rms signal across all 64 fan beams using a 24 s integration time.

On each day of testing a strong unresolved celestial radio source was observed in order to calibrate both the analogue chart records and the digital data acquisition system.

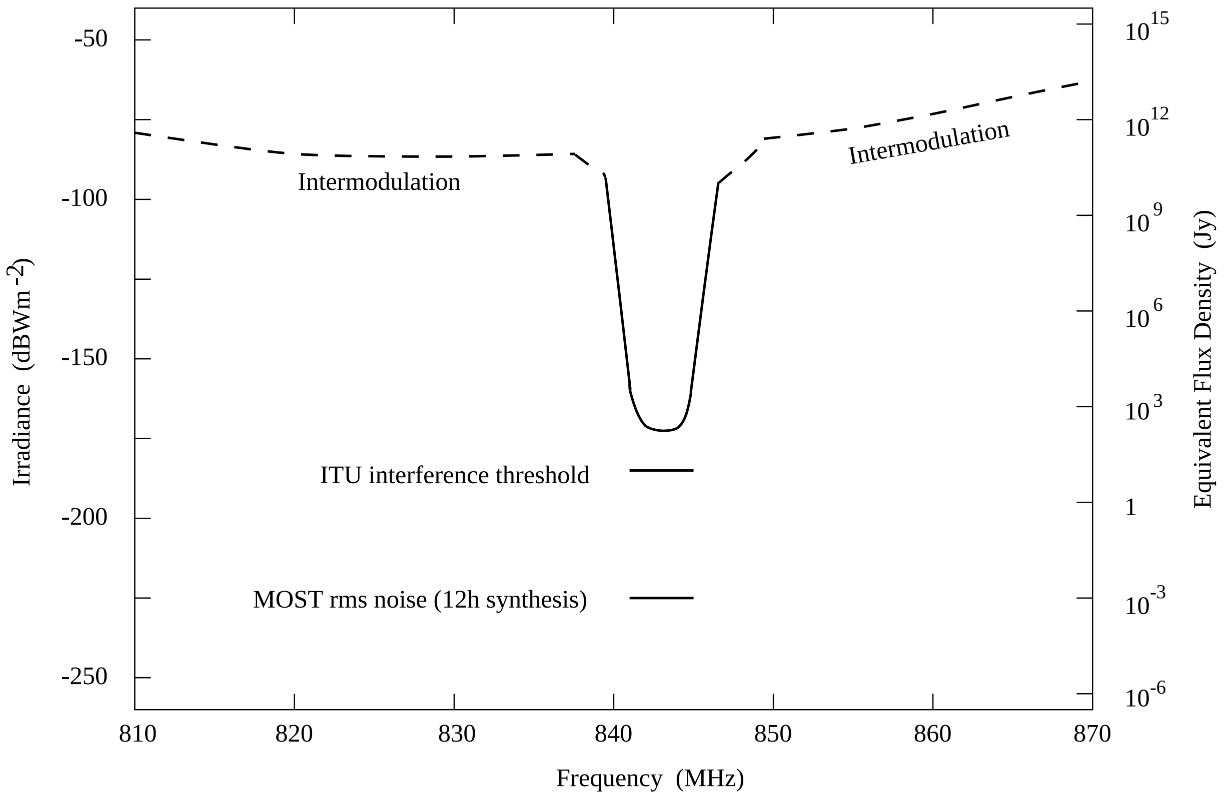

Figure 2—Expected sensitivity of the MOST to interference. The solid curve represents the response to in-band interference. Intermodulation caused by two out-of-band interference transmitters is represented by the dotted curves. The equivalent flux density is the irradiance/bandwidth expressed in Janskys.

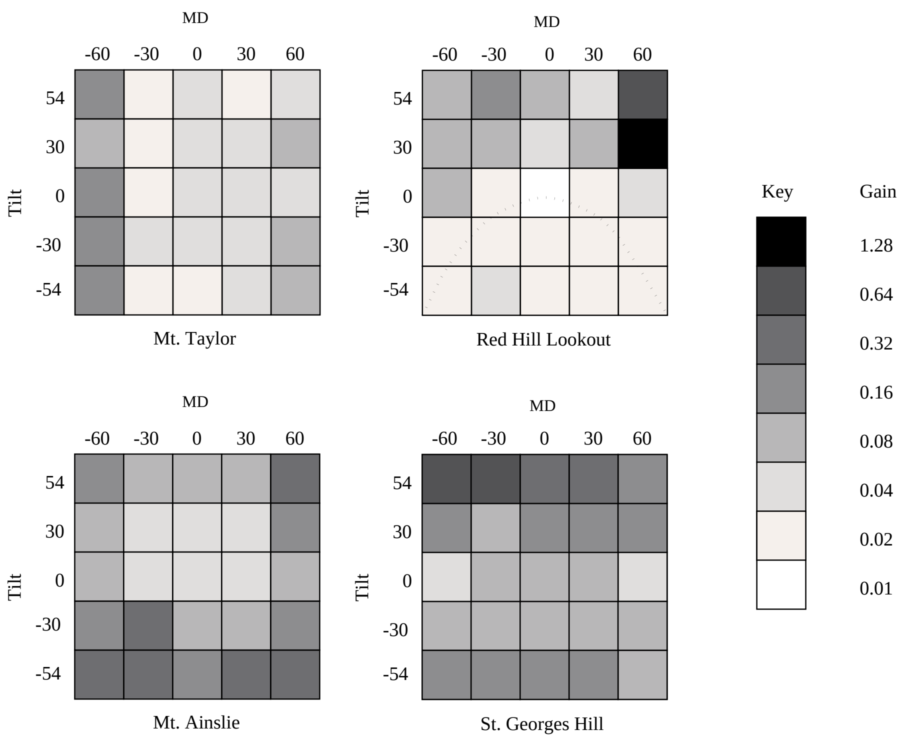

Figure 3—The sidelobe gain of the MOST shown as a function of tilt and meridian distance for the four test sites. The darker shadings indicate a higher gain value according to the key shown. The dotted line on the Red Hill site shows the track of the MOST in tilt and MD during the synthesis observations.

The chart recorder measurements of a single beam showed large short-term amplitude variations even though the signal from the calibrated test antenna was steady. These fluctuations are thought to be caused by time variable distortions of the incoming wave front over the 1·6 km length of the MOST.

As the digital data acquisition system integrated the signal over 24 s, we were concerned that some of the fine structure in the interference response might be smoothed out. A detailed comparison of the chart records and the digital results showed that the interference peaks were rarely more than 2 or 3 times the rms signal measured digitally. Accordingly we have used the digital data for subsequent analysis.

The data for all sites and telescope positions are presented not as the observed signal strength but as corresponding sidelobe gains of the MOST. These gains are calculated using the known equivalent flux density of the transmitter and the gain ($1 \cdot 0 \times 10^6$) of the MOST main beam. Figure 3 illustrates the different gain levels observed for the four interference sites. The mean gains for the sites are given in Table 2.

Table 2. Mean gains of the MOST

Site	Mt Taylor	Red Hill Lookout	Mt Ainslie	St Georges Hill
Mean gain	0·06	0·12	0·13	0·16

The average gain over all sites and telescope positions is $\sim 0 \cdot 1$. Examination of the detailed results shows that the gain varies from $\lesssim 0 \cdot 01$ to $\gtrsim 1$. The scatter among the individual pointings may arise because we have grossly undersampled the complex sidelobe structure of the telescope, as discussed in Section 3. For the three westerly transmitters there is a slight tendency for the gain to increase with MD. This is not surprising as at high MD the main beam (or the left-hand polarised beam) is directed towards the west. The average gain for the Mt Taylor transmitter, situated almost due west, appears to be lower than the other three sites, but this is barely significant in view of the scatter. Overall the gain for St Georges Hill (north) is slightly higher than for the other sites and shows little variation with MD. It is perhaps surprising that the gain remains relatively high even when the MOST is tilted to the south where one would expect the reflector to screen the line feed from interference. In the next section we describe the results of interference measurements made continuously during a 12 hour synthesis observation.

5.2 Synthesis Observations

Two tests were made to determine the susceptibility of the MOST to interference during a normal synthesis observation. The first was a reference observation taken on 1996 August 4 with no interference transmissions. The other taken on August 28 had the test transmitter located at Red Hill Lookout. Both observations were made in the 70 arcminute mode with the field centred on R.A. 10 26 25·0, Dec. −30 46 56 (B1950). The transmitter had a 5 minute on, 5 minute off cycle with an irradiance at the MOST of $5 \cdot 6 \times 10^{-14}$ Wm^{-2}, equivalent to a flux density of $1 \cdot 9 \times 10^6$ Jy in the MOST bandwidth.

Figure 4 shows the rms signal across the 64 fan beams during the 12 hour synthesis observation taken on August 28. The transmitter shows strongly in the first and last 30 minutes of the observation. The strong broad feature in the middle of the observation is due to the Sun being recorded in a sidelobe. Short duration spikes are due to nearby out-of-band mobile phone interference. The interference seen strongly at the beginning and the end of the observation corresponds to a telescope gain g, which appears inconsistent with the measurements of the gain at fixed pointings (see Figure 3). The track of the MOST, shown as a dotted line in Figure 3, has a corresponding gain of the order 0·02 for most of the fixed pointings. In fact the strong response in the synthesis observation is the result of a known (near end-fire) grating lobe scanning through azimuth 281°, the bearing of the transmitter located at Red Hill Lookout. Figures 5a and 5b show the effect of interference on an image. These have been prepared from the two observations using standard MOST reduction software.

The image constructed from data taken on August 28 shows the effects of interference from the test transmitter as well as interference from the Sun, the strongest radio source in the sky. The horizontal structure is caused by the transmitter and the vertical structure by solar interference. It can be seen in Figures 4 and 5b that the transmitter and the Sun are contributing about equally to the degradation of the image. Observations with the MOST are usually made at night and, when daytime observations are required, the usual practice is to schedule them to avoid the Sun in known sidelobes as much as possible. Scheduling of the August 28 observation was determined by the availability of the transmitter and hence we could not avoid the Sun showing in a sidelobe.

6 Discussion

In Section 4 we analysed the expected sensitivity of the telescope to interference as a function of frequency by assigning a nominal value of 1 to the remote sidelobe telescope gain. The experimental tests have shown that this gain ranges typically from 0·01 to 1 and may be higher in directions where grating beams are formed. Thus Figure 2 may be used to define the interference tolerance of the MOST.

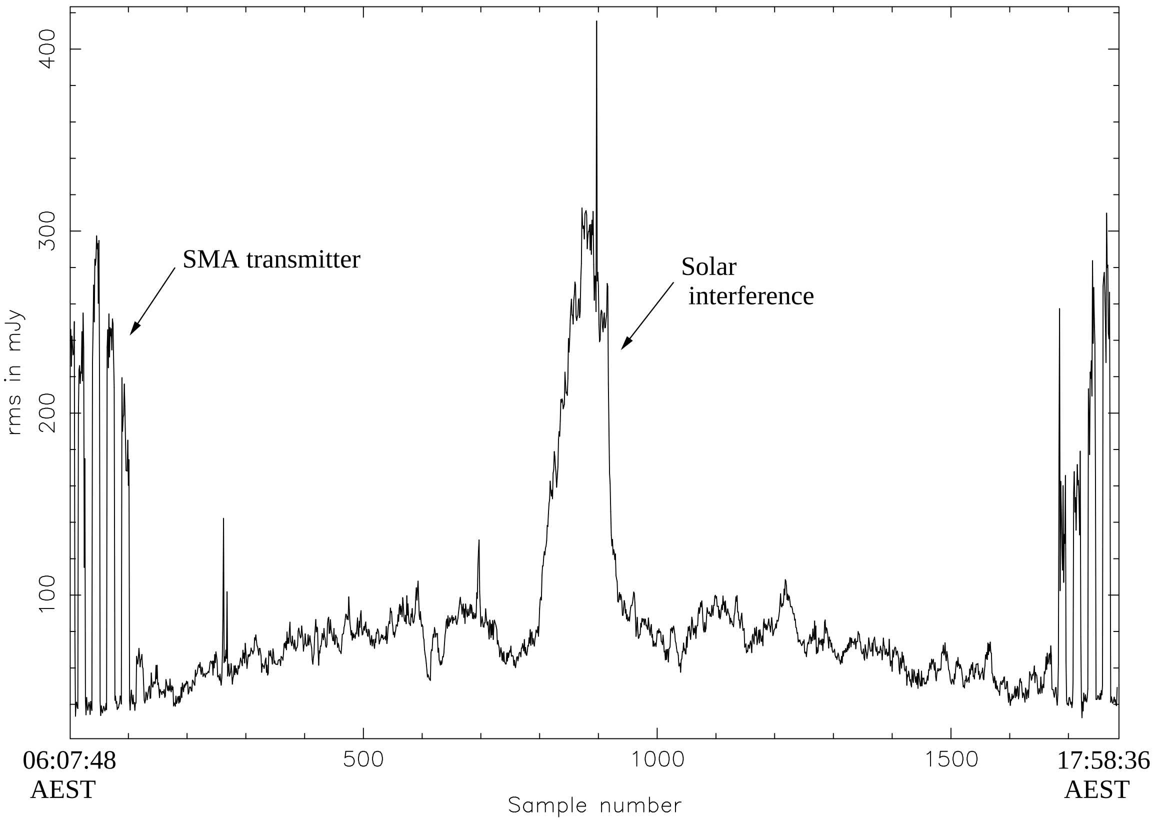

Figure 4—Data from the 1996 August 28 synthesis observation plotted as flux density (rms mJy) versus sample number. The response to the test transmitter's on/off cycle is obvious at the start of the observation (MD near −60°) and the end of the observation (MD near +60°). Solar and mobile phone interference are also visible.

The site for the telescope was originally chosen hoping that the surrounding hills would provide a measure of protection from radio interference. The interference tests with the SMA have incidentally provided an opportunity to check the level of protection afforded. By comparing the measured path losses for the four test sites with those calculated for the same distance over a smooth Earth, we find that the hills provide about 20 dB of additional protection.

The SMA has independently analysed the data from the tests and come to similar conclusions about the sensitivity of the MOST to local in-band transmitters: for the worst case the maximum tolerable irradiance is −184 dBWm^{-2} (−174 dBm in an isotropic antenna). The SMA have used the data from the collaborative tests and path loss calculations to establish criteria for restricting the future use of the 825–845 MHz band. Their report (SMA 1997) includes a table of permitted radiated powers, which would not cause detectable interference, as a function of distance and azimuth from the MOST, antenna height and frequency. As an indication of the power limits implied by the table we quote three examples. For a transmitter located 38 km north of the telescope (antenna height of 10 m) the maximum radiated power (EIRP) is 5 μW. The corresponding maximum allowable power at 66 km is 50 μW and at 99 km is 1 mW. The SMA recommendations, if adopted, would therefore rule out the use of mobile phone transmitters in the MOST passband throughout the Canberra and Queanbeyan regions.

The Australian Communications Authority (ACA), which has subsumed the Spectrum Management Agency, has used the SMA report as the technical basis for Attachment 9 of the Draft Marketing Plan for the PCS Spectrum Auction (www.aca.gov.au/spectrum/auction/pcs). Attachment 9, entitled *Radiocommunications Advisory Guidelines (Protection of Molonglo Observatory Synthesis Telescope) 1997*, sets out the compatibility requirement that would provide the MOST with a reasonable level of interference protection from transmitters. A suggested approach to assessing the compatibility is also provided. Spectrum licences in the relevant bands will require that operation of transmitters under the licence must not interfere with the MOST. This requirement to protect the MOST will cease at the end of 2008.

We believe that the ACA guidelines would adequately protect the MOST provided they are strictly followed. After the sale of the spectrum it will be the responsibility of the University to monitor interference at the observatory site and, in the event of any problems, to negotiate directly with

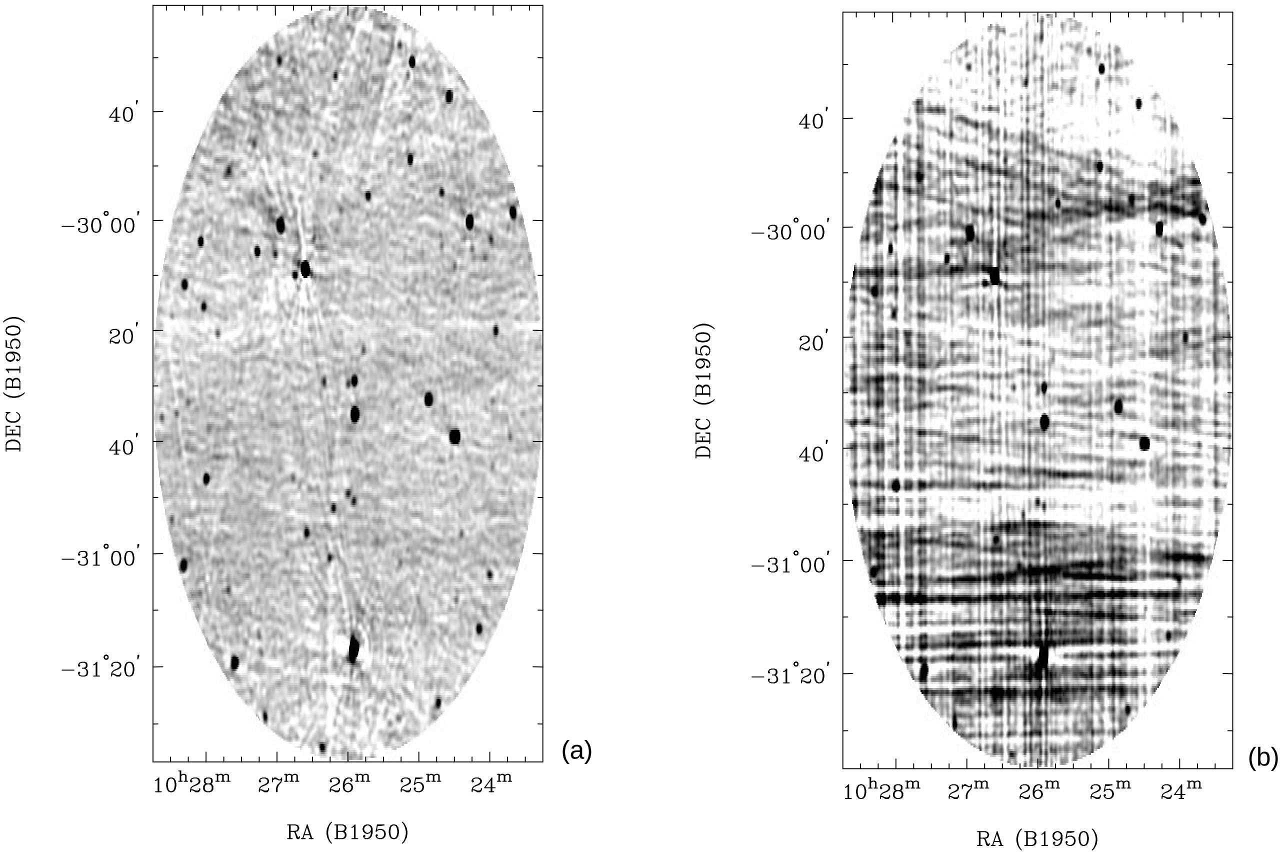

Figure 5—Images made from synthesis observations during August 1996: (a) A MOST image of the reference field from the observation on August 4. Grey-scale range is from −5 to 20 mJy per beam. (b) Image (August 28) of the same field as in Figure 5a with the transmitter on/off in a 5 minute cycle. The transmitter is responsible for the the horizontal structure. In this instance a similar degree of image degradation is cause by solar interference (vertical structure).

the users of the bands. In such negotiations the ACA would be prepared to act as a paid consultant.

At the same time the spectrum sale is proceeding, the DCA is setting up a Review of Spectrum Management Legislation to be completed by 30 June 1998 (www.dca.gov.au/whatwedo/govtrev.html). The terms of reference of this review make no mention of scientific uses of the spectrum.

7 Conclusion

The MOST forms a complex pattern of weak remote sidelobes which sweep the horizon during normal observations. The grid of 25 pointings used to measure the MOST's susceptibility to interference showed that in general the remote sidelobe gain of the telescope is $\sim 0{\cdot}1$, but these tests proved inadequate to specify the complete sidelobe pattern. In particular, they did not reveal the formation of out-of-focus grating lobes such as that found in the synthesis test. However, the collaborative test program has been broadly successful in determining the degree of protection required by the MOST to continue its high sensitivity Galactic and extragalactic radio observations.

The ITU has listed threshold levels of interference detrimental to radio astronomy continuum observations at internationally recognised frequencies for both single dish and interferometer modes of operation. Interpolating their values to 843 MHz yields a threshold of -183 dBWm^{-2}. The MOST is generally some 10 dB less sensitive to interference than the ITU threshold, except in the directions of grating lobes.

The ACA advisory guidelines, which are based on the analysis of the test data by the SMA, are adequate to protect the MOST.

Acknowledgments

The MOST is operated by the University of Sydney and supported by a grant from the Australian Research Council. We thank our colleagues in the Department of Astrophysics for their continued advice and encouragement in all aspects of this paper. In particular we thank the telescope staff, Jeff Webb, Michael White and Boyd Smithers, for their technical support and for reorganising the telescope maintenance schedule to allow us to make daytime observations.

We acknowledge the professional approach of Roger Smith, Geoff Hutchins and Jim Cleaves of the Spectrum Management Agency in addressing the difficulties arising from the proposed sale of the spectral band used by the MOST. The measurements depended on the loan of the mobile transmitter from the Department of Communication and the Arts, and we thank Alastair Gellatly (SMA), Suvath Lee (SMA) and Ian Waters (DCA) for their collaboration in planning and carrying out the field tests at Molonglo.

We thank the referee for bringing to our attention the status of the interference threshold published by the ITU.

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