Chapter 1

Cylindrical Reflectors

A cylindrical reflector was the first reflector antenna, invented by Heinrich Hertz in 1888 (Stutzman and Thiele 1998). From an engineering viewpoint, the cylindrical reflector construction complexity and cost is less when compared to many other antenna geometries because its reflector requires curvature in only one dimension. Cylindrical reflectors have been used in diverse applications including radio astronomy (Mills 1981), radar (Kildal 1984b), automotive sensing (Park et al. 2002) and compact antenna test ranges (Sanad et al. 1987). Radio astronomy requires antennas with large reflectors to detect very weak cosmic signals and the parabolic reflector antenna is most commonly used. However, cylindrical reflectors offer flexibility and a cost effective means to achieve the desired sensitivity when imaging the sky.

Section 1.1 describes the use of cylindrical reflectors in current radar and astronomical applications. Because the development of a line feed for a radio telescope is the principal goal of this thesis, an analysis of cylindrical reflectors used in astronomy is presented. Radar applications are also presented, to show the state-of-the-art in cylindrical reflector antenna systems. Specifications of the proposed upgrade to the Molonglo Observatory Synthesis Telescope (MOST) are compared with current antenna specifications. An overview of this thesis is presented in Section 1.3.

1.1 Cylindrical Reflector Applications

Cylindrical reflectors have a one dimensional curved reflector geometry which creates a focal line rather than a focal point as for parabolic reflectors. A diagram of a cylindrical reflector, with a line feed placed along the focal line, and the coordinate system used throughout this thesis is shown in Figure 1.1. Two principal planes are used for the analysis:

- Longitudinal plane: The radiation pattern plane in the line feed direction (yz-plane).
- Transverse plane: The radiation pattern plane transverse to the line feed direction (xy-plane).

A description of how the radiation patterns are produced in the principal planes is presented next. For a more detailed discussion of the focusing properties of a cylindrical reflector see Stutzman and Thiele (1998).

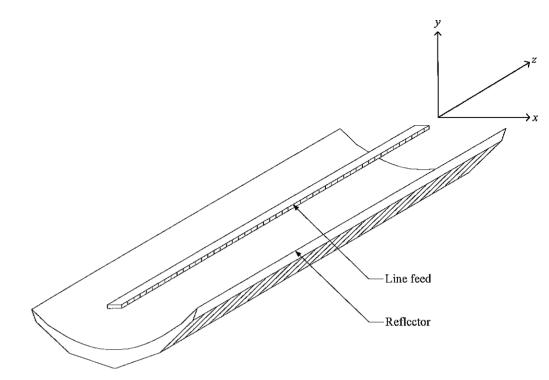


Figure 1.1 Cylindrical reflector geometry and coordinate system

The radiation pattern produced by the cylindrical reflector will be described for the transmit case, with equivalence assumed for the receive case due to reciprocity as expressed by Kirchhoffs' laws. Line feed radiation incident on the reflector is concentrated, resulting in a narrow beam in both radiation planes. In the longitudinal plane, shown in Figure 1.2(a), the radiation pattern is determined by the line feed length and amplitude weighting in the longitudinal dimension, L, which is usually large, resulting in a narrow pencil beam reflector pattern. In the transverse plane, shown in Figure 1.2(b), where D is the cross-sectional aperture diameter of the cylinder, the radiation pattern is determined by the reflector curvature and the line feed radiation pattern. Because the curved reflector dimension is usually small in comparison to its longitudinal dimension, this results in a broader beam. To enable full sky coverage, the beam is steered in both planes: The beam is steered in the longitudinal plane by electronically controlling the phase gradient on the line feed elements, whereas the beam is steered in the transverse plane by mechanically tilting the reflector about its longitudinal axis. Beam steering allows the telescope to track sources across the sky.

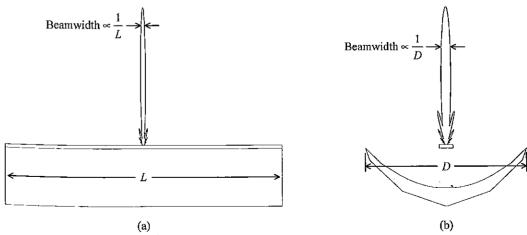


Figure 1.2 Cylindrical reflector pattern. (a) Longitudinal plane. (b) Transverse plane

1.1.1 Radar

Radar applications for monitoring atmospheric and environmental effects require an antenna that can survey a large field-of-view. Two cylindrical reflectors used for radar are the European Incoherent Scattering Radar (EISCAT; Kildal 1984b) and the Second Generation Precipitation Radar (PR-2; Rahmat-Samii et al. 2005).

EISCAT characterises Earth's auroral ionosphere and magnetosphere using an incoherent scattering technique. The antenna beam is mechanically scanned in the transverse plane and electronically scanned in the longitudinal plane. The mechanical scanning range in the transverse plane is 60° North and 30° South of zenith. The electronic scanning range in the longitudinal plane is $\pm 21.3^{\circ}$ from zenith. An offset feed configuration is used to illuminate the reflector, which operates at a frequency of 224 MHz with a 22.5 MHz operational bandwidth. The aperture is 120 m long, with a 40 m diameter and 18 m focal length. The focal length to diameter (f/D) ratio is 0.45. The line feed comprises of 128 dipole elements, spaced 0.7λ apart at the centre frequency. The dipole has two orthogonal polarisations, longitudinal and transverse, which are fed using the appropriate phases to produce circular polarisation. Patterns for both polarisations in the transverse plane were matched to improve the circular polarisation efficiency (Kildal 1980).

Since 1997, NASA has researched the measurement of tropical rainfall. A new lightweight, dual frequency, dual polarised, wide scanning cylindrical reflector radar with Doppler capabilities was prototyped to measure rainfall rate and latent heating. This new radar is the space-based PR-2. An offset-fed cylindrical reflector geometry is used, with aperture dimensions of 5.3×5.3 m. Because the radar will be deployed in space, the reflector is made from lightweight polymer with a thin metallized surface. The two frequencies used for transmit and receive are 14 GHz (Ku band) and 35 GHz (Ka band). An electronic scanning range of ±37° was chosen to provide the necessary horizontal resolution. The spacing between the elements was 0.65λ at the centre frequency for both transmit and receive bands. A half-scale PR-2 model was prototyped to demonstrate its electrical performance. Microstrip elements were used for the line feed. In the feed design, the row number in the transverse direction was selected to provide the required transverse reflector illumination. The Ka-band feed consists of 166 × 4 elements and the Ku-band feed consists of 166 × 2 elements. The Ku-band feed length in the longitudinal direction was 5.3 m and Ka-band feed length was scaled to obtain the same beamwidth in the longitudinal plane. When the line feed was scanned to 30°, in the longitudinal plane. patterns for both polarisations in the Ka-band differ along the principal radiation planes. However, this difference in beam patterns for large scan angles is corrected by appropriate calibration.

Table 1.1 presents a comparison between the cylindrical reflector specifications and electrical performance used in the described radar applications and the planned Molonglo telescope upgrade called the Square Kilometre Array Molonglo Prototype (SKAMP). The physical aperture describes the rectangular aperture dimensions of the cylindrical reflector along length and diameter, the f/D is the focal length over diameter ratio of the reflector cross section in the transverse plane, θ_{ha} is the half-angle subtended by the reflector edges to the focal point and is given by Equation 2.1.

1.1.2 Radio Astronomy

Resolution limitations of single dish radio telescopes in the 1950s required a new type of measurement technique. Ryle (1952) developed a technique based on the voltage multiplication principle, involving the use of separate antennas in an interferometric configuration to obtain high resolution. In this technique, voltage outputs from two antennas separated by a distance of several wavelengths, called the baseline, were correlated to obtain an interference pattern. This interference pattern corresponds to one measure of the radio source brightness distribution at one baseline or spatial frequency. The resolution or aperture of a large array can be constructed by varying the interferometric baselines, using a moveable antenna, and correlating the outputs from the corresponding pairs of antennas. This process is called aperture synthesis and a commonly used antenna arrangement is depicted in Figure 1.3. Aperture synthesis provides high angular resolution, inversely related to the longest baseline measured, and produces an image equivalent to a filled aperture of the largest dimension.

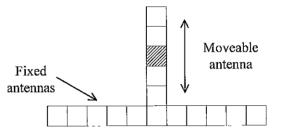


Figure 1.3 Aperture synthesis telescope configuration.

Complete synthesis of an image requires all spatial frequencies (u, v coordinates) in the u-v plane to be sampled. Where the u-v plane is the plane perpendicular to the sky direction in which the sky brightness distribution is measured and is defined by the projected baseline of the telescope (Burke and Graham-Smith 1997). Earth's rotation is used to increase sampling of the u-v plane, taking 12 hours for an E-W array and this technique is known as Earth rotational aperture synthesis. To obtain fine spatial image resolution, aperture synthesis telescopes require large baselines and an economical antenna design. One design that suited these requirements was the cylindrical reflector (Christiansen and Högborn 1985). A disadvantage of a cylindrical reflector compared to a parabolic reflector is that the rectangular aperture results in non-circular beam projection onto the sky. This non-circular beam can cause variable u-v sampling of the sky. Elongation of the beam can be minimised by subdividing the line feed in the longitudinal plane into sections approximately equal to the transverse dimension. Imaging with a cylindrical reflector interferometer with many independent subsections provides essentially complete u-v coverage, resulting in high image fidelity. Cylindrical reflectors are used to survey large sky areas (Bock et al. 1999) and Table 1.2 lists the specifications of several cylindrical telescopes.

Cylindrical Poflector	Physical	alf	6 _{ha} (°)	f/D θ_{ha} (°) Number of Feed	Feed	Feed	Freq	L	Polarisation Feed BW	Feed BW	Scan Range	ange
Nemector	Aperture $(L \times D)$ m			cicinents	position	ry pe	(zurur)	ьм (MHz)		•	Mech	Elec
EISCAT	$120 \times 40 0.45$	0.45	28	128	Offset	Dipole	224	22.5	Single	1.22:1	-30° to	±21.3°
									circular		÷90°	
PR-2	5.3×5.3 0.35	0.35	7.1	166×2/166×4	Offset	Patch	14000/	10	Dual linear	ı	∓60ء	±37°
							35000					
SKAMP	1556×11.6 0.26 88	0.26	88	*	Symmetric	*	850±550	100	Dual (*)	*	÷09∓	∓90ء

lange	Elec	z	±30°	.09∓	±45°	÷09∓	.09∓	
Scan Range	Mech	¥	z	Υ	¥	-09∓	-09∓	
Feed BW	(MHZ)		ı	15	16	30	*	pe.
Polarisation		Single Linear	Single Circular	Single Linear	Single Linear	Right Hand Circular	Dual (*)	a the line feed ty
Receiver BW	(MHZ)			15	16	e	100	dependent or
Freq (MHz)		178	611	327	408	843	850±550	ameters are
Feed Type		Dipole	Spiral	Dipole	Dipole	Ring	*	These para
Feed Position		Offset	Symmetric	Offset	Offset	Symmetric	Symmetric	y programs. *
Number of feed	elements		276	1056	1536 (E-W) 4096 (N-S)	7744	*	rrent astronom
Geometry		L	N-S array	N-S array	T	E-W array	E-W array	y. #Used in cu
Physical Aperture	$(L \times D)$ m	$442 \times 20 \text{ (E-W)}$ 58 × 20 (N-S)	121.9×182.9	530.0×30.0	$564 \times 35 \text{ (E-W)},$ $24 \times 7.5 \text{ (N-S)}$	1556×11.6	1556×11.6	Table 1.2 Cylindrical reflectors used in radio astronomy. #Used in current astronomy programs. *These parameters are dependent on the line feed type.
Completion date		1958	1960s	1970	1967	1982	2010	d reflectors use
Location		Cambridge, England	Illinois, USA	Ootacamund, India	Bologna, Italy	Bungendore, Australia	Bungendore, Australia	le 1.2 Cylindrica
Cylindrical Reflector		Radio Star Interferometer	Illinois Radio Telescope	#Ooty	#Northern Cross	#MOST	SKAMP	Tab
ξ								

Table 1.2 shows no new cylindrical reflectors used for radio astronomy have been built since 1982. The reasons why they were commonly used at those earlier times include: lower implementation costs for the reflector and simpler mechanical steering about a single axis. In comparison, parabolic reflector interferometers have been the main radio telescope of choice in recent years, for high resolution imaging, for telescopes such as the VI.A. ATCA, and ATA. Parabolic reflectors for radio astronomy represent a familiar engineering approach and many technological developments in this area have occurred simultaneously with radar and satellite communications. New technologies for parabolic reflector antennas have resulted in feed systems with polarisation capability, cryogenic cooling, integrated wideband electronics and accurate reflector panel manufacturing techniques. Improvements for cylindrical reflector radio telescopes have largely been attained through upgrades to the existing electronics. A limiting factor in cylindrical reflector radio telescope development has been the radio frequency (RF) front-end architecture selected, which used room temperature electronics for the first-stage low noise amplifier (LNA) and beamformer.

Existing cylindrical reflector radio telescopes were limited by the feed elements available at the time. An economical, easy to manufacture element with good electrical performance characteristics was required because large numbers of feeds are needed. Dipole feeds suited these requirements and were used for three of the cylindrical reflectors listed in Table 1.2. The performance of these feeds was restricted as they operated with a single polarisation and over a narrow bandwidth because of their resonant design. In contrast, developments for parabolic reflector interferometers have resulted in dual polarised, wideband feeds (James 1992b). Implementation of a dual polarised line feed design for a cylindrical reflector is more complex than for a parabolic reflector because of mutual coupling between elements, which is explained in Section 6.1. As a result, radio polarimetry has not yet been attempted using a cylindrical reflector radio telescope and the reflector pattern polarisation performance for varying scan angle is still to be tested. A dual polarised line feed has been designed for the PR-2 radar described in Section 1.1.1, but it only required to operate over a narrow bandwidth. Christiansen and Högbom (1985) state the challenges faced in cylindrical line feed design: 'the feed for a cylindrical reflector is more complicated, has higher ohmic losses and less flexible for frequency and polarisation changes than the parabolic dish'.

1.2 Summary

From a review of cylindrical reflectors used in radio astronomy, the two key developments required in overcoming previous line feed limitations of poor noise performance, narrow band and single polarisation operation are:

- Cost reduction of electronic components to enable a low noise RF front-end architecture.
- Line feed development of an economical, wideband, scannable and dual polarised

A program to demonstrate these new developments for cylindrical reflectors is called the Square Kilometre Array Molonglo Prototype (SKAMP). SKAMP will provide a new signal pathway for the Molonglo Observatory Synthesis Telescope (MOST), an existing cylindrical reflector radio telescope described in Chapter 2.

1.3 Thesis Overview

This thesis is focused on the line feed design for the Molonglo Observatory Synthesis Telescope (MOST), to extend its current scientific capability. Main requirements for the new feed to achieve the planned science goals are dual polarisation, frequency operation from 300-1400 MHz and scanning capability within a ±60° range. The relationship between the line feed performance parameters and how they affect the telescope imaging was investigated to establish a set of feed design criteria. Using these criteria, a wideband dipole element for the line feed design was selected based on a review of current state-ofthe-art phased array antenna technology. The selection of this element necessitated the use of a three-band solution, with each band covering a 1.7:1 bandwidth. A feed model and reflector simulations were used to determine the transverse line feed beamwidth range that provides optimum system sensitivity for the MOST. This beamwidth range was then used for the feed design. With a dual linear polarisation design, unequal transverse co-polar patterns result and therefore a method of compensation was investigated. Simulations of the scan element patterns showed the new line feed had acceptable performance in the frequency range from 700-1100 MHz, within a ±45° scan angle range. A novel feed excitation method was developed to produce dual linear polarisation. An 8-element line feed was constructed and element patterns were measured. These measured patterns were then used to estimate the aperture efficiencies, spillover temperatures and reflector pattern parameters for both polarisations across the acceptable performance range. Implications for future line feed developments are inferred and future research possibilities are presented in the concluding chapter, as well as the significant contributions from the thesis.

Chapter 2

Molonglo Observatory Synthesis Telescope (MOST)

Understanding the operation of a radio telescope is important in determining the influence of its feed antenna. In this chapter, the operation of the Molonglo Observatory Synthesis Telescope (MOST) is described, emphasising the influence of its line feed parameters, such as the radiation pattern, on the imaging performance.

Section 2.1 presents a description of the MOST reflector geometry and use of beam steering to track objects over a 12 hour synthesis observation. A description of the beam formed by a cylindrical reflector is presented in Section 2.2, to establish the terminology used to describe radiation patterns. Section 2.4 examines how the beams are formed at the MOST and presents parameters used to characterise the telescope performance from an astronomy viewpoint, being its field-of-view, resolution and sensitivity. Current modelling approaches for the MOST radiation patterns are presented in Section 2.5. Inaccuracy in the current beam model at large scan angles led to a new modelling approach proposed in Section 2.5.1. Existing calibration strategies for line feed parameters are evaluated in Section 2.6. A sensitivity analysis is presented in Section 2.7 to determine how limitations in the existing sensitivity can be overcome by extending the feed performance. Section 2.8 describes the dynamic range limitations at the MOST and the implementation of self-calibration to improve its performance.

2.1 Description of MOST

MOST consists of two co-linear cylindrical parabolas (arms) separated by a 15 m gap, with their horizontal axes aligned East-West. Each cylinder has an aperture length of 778 m, diameter, D, of 11.6 m and focal length, f, of 3 m. The reflector focal length on diameter ratio (f/D) is 0.26 which corresponds to a subtended half-angle (θ_{ha}) of 88° calculated from Equation 2.1 (Stutzman and Thiele 1998). The subtended half-angle refers to an angle subtended by the reflector edges at the focal point and is illustrated in Figure 2.1.

$$\theta_{ha} = 2 \tan^{-1} \left(\frac{1}{4(f/D)} \right) \tag{2.1}$$

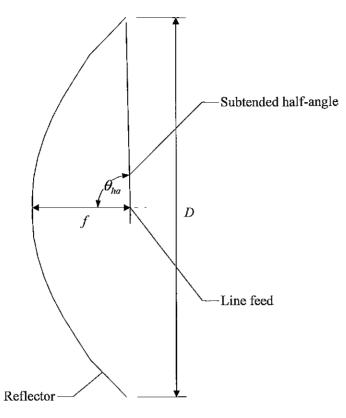


Figure 2.1 Cross-sectional view of the MOST reflector in the transverse plane, depicting the subtended half-angle.

Earth rotational aperture synthesis is used to fully sample a field-of-view larger than the single beam synthesised by the telescope in the u-v plane over a 12 hour period. MOST detects continuum radiation at 843 MHz, using right-hand circularly polarised resonant ring elements (Mills and Little 1972), with a 3 MHz instantaneous bandwidth. During the 12 hour synthesis, the MOST imaging beam tracks a single position in the sky, by mechanically rotating the reflector about its horizontal axis and electronically scanning the beam, along the reflector length. The coordinate system used for steering the MOST beam are tilt and meridian distance (MD) as depicted in Figure 2.2. The tilt angle, θ_{tilt} , describes the angle between zenith and the reflector tilt in the North-South plane. Meridian distance describes the angle, θ_{scan} , between the MOST scanned beam and zenith in the East-West (meridian) plane. As a point at declination (dec) moves across the sky, its meridian distance is related to its instantaneous hour angle (HA) by (Bock 1997):

$$\sin MD = \sin HA \csc |dec| \tag{2.2}$$

Each telescope arm is divided into 44 bays, with each bay consisting of a 17.8 m reflector length and a line feed containing 88 ring elements. During an observation, all bays are steered to the same meridian distance by mechanically rotating the ring elements, to create a uniform phase gradient along the bay. The elements are spaced 0.54λ apart at the operating frequency. Similarly, all the bays point in the same tilt direction by mechanically rotating the two reflector arms about their horizontal axis. This combination of mechanical and electronic steering of the beam, together with real-time beam-forming and time-multiplexing (Perley 1979; Crawford 1984), enables the MOST to image large areas of the sky. A description of the beam created by a cylindrical

reflector is presented in Section 2.2 to establish the terminology used in this thesis and investigate how it can be modelled.

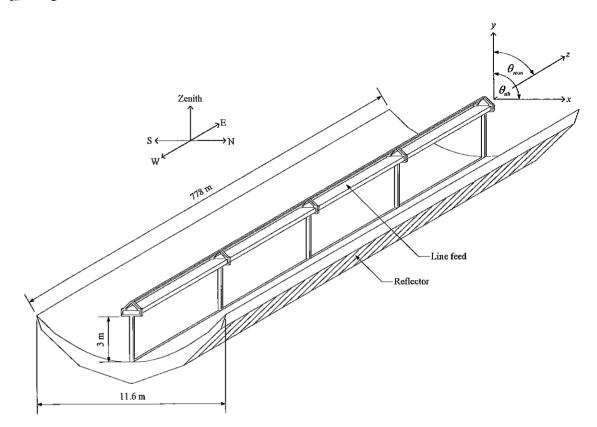


Figure 2.2 The MOST reflector geometry, showing the coordinate system and angles used to define the beam scanning.

2.2 Cylindrical Reflector Beam Definition

A cylindrical reflector consists of a one-dimensional curved reflector and a line feed placed at its focus. It has a rectangular aperture and its radiation pattern may be analysed in two orthogonal planes. These planes are defined as longitudinal and transverse with respect to the horizontal axis of the cylinder and are shown in Figure 2.3. The radiation pattern generated by the cylindrical reflector is produced by the radiating line feed illuminating the reflector, which is then collimated to form a narrow beam. This beam is described in this thesis as the reflector pattern in the transverse and longitudinal planes. Similarly, radiation from the line feed in both planes is described in this thesis as the transverse and longitudinal feed patterns.

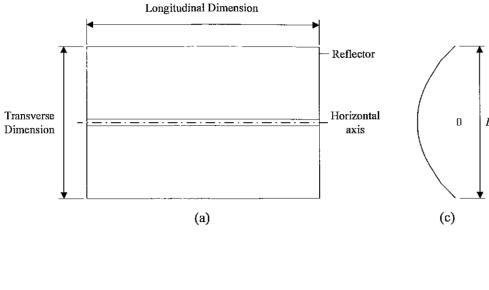




Figure 2.3 (a) Top view of a symmetric-fed cylindrical reflector. (b) Longitudinal plane, showing a side view of the line feed and reflector. (c) Transverse plane, showing the cross-sectional view of the reflector and line feed.

In the transverse plane shown in Figure 2.3(c), the reflector pattern is determined by the transverse line feed pattern which illuminates a curved parabolic reflector cross-section. Therefore, the transverse feed pattern is also referred to as the line feed illumination pattern. Accurate modelling of the pattern in this plane requires an electromagnetic simulation of the interaction between the feed and reflector. The modelling approach that is currently used for the MOST is described in Section 2.5. In the longitudinal plane, the feed elements are arranged as a linear array as shown in Figure 2.3(b). Radiation from the line feed will illuminate the reflector in the longitudinal plane. If the longitudinal reflector dimension is large compared to its transverse dimension, the pattern can be assumed as the radiation pattern due to a uniform line feed. The derivation of the radiation pattern and half-power beamwidth (HPBW) for a uniform line feed follows from Stutzman and Thiele (1998):

The electric field intensity, **E**, for a z-directed line source I(z') of length L, centred symmetrically about the origin, at an observation angle θ in the longitudinal plane, can be represented by Equation 2.3.

$$\mathbf{E} = \hat{\mathbf{\theta}} j \omega \mu \frac{e^{-j\beta r}}{4\pi r} \sin \theta \int_{L/2}^{L/2} I(z') e^{j\beta z' \cos \theta} dz'$$
 (2.3)

Where ω = angular frequency

 μ = permeability

 $\beta = 2\pi/\lambda$ (wavenumber)

 λ = wavelength

r = radial distance

I = line current

 $\hat{\theta}$ = unit vector in the direction of the observation angle, θ

The pattern factor is obtained by normalising the integral in Equation 2.3, which enables the pattern to be determined by the current distribution I(z'). The current distribution of a line source, with a uniform amplitude distribution and linear phase can be represented by:

$$I(z') = \begin{cases} I_0 e^{j\beta_0 z'} & -\frac{L}{2} < z' < \frac{L}{2} \\ 0 & \text{elsewhere} \end{cases}$$
 (2.4)

Where β_0 is the phase shift per unit length along the line source given by Equation 2.7. By integrating the current distribution along its length, L, the un-normalised pattern factor for a uniform line source becomes:

$$\zeta_{un}(u) = \int_{-L/2}^{L/2} I(z') e^{j\beta z' \cos \theta} dz' = I_0 L \frac{\sin u}{u}$$
(2.5)

Where

$$u = (\beta \cos \theta + \beta_0) \frac{L}{2} \tag{2.6}$$

An angle θ_0 can be introduced to represent the phase shift or pointing direction of the line source, such that:

$$\beta_0 = -\beta \cos \theta_0 \tag{2.7}$$

Thus, *u* becomes:

$$u = \frac{\beta L}{2} (\cos \theta - \cos \theta_0) \tag{2.8}$$

The electric field far-field pattern can be obtained from substituting Equation 2.5 into 2.3:

$$E_{\theta} = \frac{j\omega\mu e^{-j\beta r}}{4\pi r} I_0 L \sin\theta \frac{\sin u}{u}$$
 (2.9)

Therefore, the pattern of the uniform line source can be represented by Equation 2.10 and is depicted in Figure 2.4.

$$\zeta(u) = \frac{\sin u}{u} = \operatorname{sinc}(u) \tag{2.10}$$

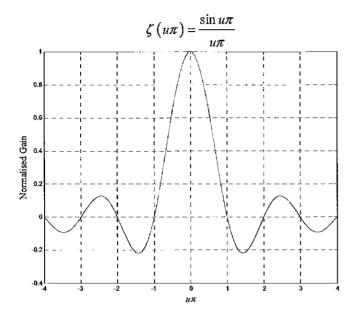


Figure 2.4 Pattern factor for a uniform line source having a length L and $u = (\beta L/2) \cos \theta$.

Equation 2.8 shows that the selection of the uniform line feed length, L, influences the radiation pattern shape, $\zeta(u)$. The HPBW in the longitudinal plane is determined by solving for $u_{\rm HP}$ in the following equation:

$$\frac{1}{\sqrt{2}} = \frac{\sin u_{HP}}{u_{HP}} \tag{2.11}$$

Alternatively, u_{HP} can be determined graphically from the sinc(u) function, in Figure 2.4, giving $u_{HP} = \pm 1.39$. By substituting u_{HP} into Equation 2.8, θ_{HP} , can be found:

$$\theta_{HP} = \cos^{-1}\left(\frac{2}{\beta L}u_{HP} + \cos\theta_0\right) = \cos^{-1}\left(\pm 0.43\frac{\lambda}{L} + \cos\theta_0\right) \tag{2.12}$$

Where the \pm refers to half-power points either side of the main beam (0°), so the HPBW an be calculated by combining the two half-power points:

$$HPBW = \left| \theta_{HP \text{ left}} - \theta_{HP \text{ right}} \right|$$

$$= \left| \cos^{-1} \left(-0.43 \frac{\lambda}{L} + \cos \theta_0 \right) - \cos^{-1} \left(0.43 \frac{\lambda}{L} + \cos \theta_0 \right) \right|$$
(2.13)

For a uniform line source pointing at zenith, $\theta_0 = 90^{\circ}$, Equation 2.13 becomes:

$$HPBW = 2\sin^{-1}\left(0.43\frac{\lambda}{L}\right) \tag{2.14}$$

For long line sources this can be approximated using:

$$HPBW \approx 0.87 \frac{\lambda}{L} \text{rad} \approx 51 \frac{\lambda}{L} \text{degrees}$$
 (2.15)

Therefore, at a particular frequency, the line feed length can be selected to determine the HPBW of the pattern or vice versa. The first sidelobe level maximum, for a uniform line source, is obtained by differentiating Equation 2.10 or graphically from Figure 2.4. This level corresponds to a value of approximately 0.2 or -13 dB from the main beam (0 dB). For many astronomy observations, a telescope beam with sidelobe levels around 0.01 or -20 dB is required to minimise noise in the image. Sidelobe levels for a line feed can be reduced by using a tapered amplitude distribution along the feed instead of a uniform distribution. However, the trade-off is a reduction in gain or aperture efficiency, as described in Section 2.7.1. Equations for various line source amplitude tapers and their corresponding pattern factors and sidelobe levels can be found in Stutzman and Thiele (1998) and Kraus (1966).

2.3 Half-Bay Beam

For many astronomy projects, it is desirable to have a circular beam. However, the use of a cylindrical reflector produces an elliptical beam from its rectangular aperture. The true sky distribution can be recovered by deconvolution, although not perfectly. The beam ellipticity is determined by the difference in aperture dimensions between longitudinal and transverse planes.

It was shown in Section 2.2 that the transverse reflector pattern is determined by the curved reflector profile, whereas the longitudinal reflector pattern is determined by a uniform line source. Equation 2.14 shows that for a fixed frequency (wavelength), the length of the line source can be adjusted to produce a radiation pattern with a desired HPBW. Therefore, a roughly circular beam can be achieved by selecting the line feed length for a longitudinal reflector, which produces a HPBW equal to the transverse reflector pattern HPBW.

The measured transverse reflector pattern at the MOST is approximately 2° at 843 MHz, pointing at zenith (Bock et al. 1999). The length of line feed required to produce an equivalent HPBW in the longitudinal reflector pattern is approximately 9 m. Line feed elements are electrically combined in contiguous 9 m sections known as 'half-bays', in the longitudinal (East-West) direction along the length of each cylinder arm, to achieve the desired aspect ratio. For MOST observations, two half-bays are combined to form a 17.8 m bay.

2.4 Imaging Beam

The MOST operates as an interferometer comprising 88 independent antennas (bays), with 44 antennas on each arm. Received signals are produced by correlating a phased array beam from the East-arm with a phased array beam from the West-arm. They are fed as inputs to an analogue beamformer to create a set of 64 real-time fan beams. A procedure known as fan beam synthesis is used for imaging (Perley 1979; Crawford 1984), employing a different data acquisition system from other astronomical interferometers. Real-time fan beams are produced and recorded, rather than visibilities in the *u-v* plane. A radial profile of the theoretical MOST visibility function in the *u-v* plane is shown in Figure 2.5. In the East-West or longitudinal plane, each fan beam has a half-power beamwidth of 22" (Bock et al. 1999). The beamwidth in this direction is determined by the combining and weighting used in the analogue beamformer. In the North-South or transverse plane, the fan beam has a half-power beamwidth of approximately 2°. The beamwidth in this plane is defined by the transverse reflector HPBW.

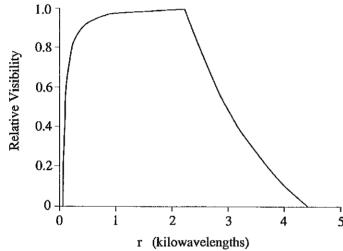


Figure 2.5 Radial profile of the u- ν plane antenna visibility function (Bock et al. 1999).

Beamforming with the MOST produces 64 individual fan beams. The performance of the telescope can be defined by its imaging field-of-view, resolution and sensitivity over a 12 hour synthesis interval. The field-of-view for the imaging beam is approximately $2^{\circ} \times 2^{\circ}$ cosec|dec| and is determined by the transverse reflector HPBW. The angular resolution is determined by the interferometric pattern formed by the pair of independent antennas separated by the largest baseline, 1556 m and is $43'' \times 43''$ cosec|dec| at the half-power point. Since the MOST uses a linear aperture in an East-West alignment, many parameters vary with the scanning angle. The sensitivity or rms noise in MOST images is due to a quadrature combination of system sensitivity and confusion. System sensitivity includes thermal noise, artefacts from the telescope's electronics and systematic errors and fluctuations in various subsystems. The continuum confusion limit set by the surface density of source is much less, at 0.1 mJy/beam for a 43'' resolution. A single fan beam has a sensitivity of approximately 1 mJy at a declination of -70° near the centre of the image (Bock et al. 1999). The effect of the MOST beam and line feed on the sensitivity are described in Section 2.7.

2.5 Beam Modelling

The MOST reflector pattern in the longitudinal and transverse planes will vary across the 12 hour synthesis period. These include variations in HPBW, maximum sidelobe levels and back radiation. Modelling of the reflector pattern and how these variations affect the imaging performance will enable corrections to improve imaging accuracy. For the MOST, there are two separate models used to represent the radiation pattern in the longitudinal and transverse planes.

In the longitudinal (East-West) plane, high sidelobes result if the radiation is due to a uniform line source, as described in Section 2.2. To reduce these sidelobes, a triangular taper can be applied to the 88 independent antennas. The triangular amplitude taper, I_t , for a z-directed line source of length L can be represented by:

$$I_{t}(z) = 1 - \frac{2}{L}|z| \qquad |z| \le \frac{L}{2}$$
 (2.16)

With a corresponding pattern:

$$\zeta_{t}(u) = \left[\frac{\sin u/2}{u/2}\right]^{2} \tag{2.17}$$

Where u is obtained from Equation 2.6.

The sidelobe level for a line source with a triangular taper is -26 dB (Stutzman and Thiele 1998). This pattern model has been verified using measurements for a bay beam (L = 17.8 m) by allowing an unresolved source to drift through the field-of-view and is accurate to 1% within $\pm 0.6^{\circ}$ either side of the main beam (Reynolds 1986).

In the transverse (North-South) plane, the reflector pattern model assumes the radiation resembles a Gaussian beam profile, using a single parameter to represent its HPBW. The modelling of the radiation pattern in this plane is more complicated than the longitudinal plane because the pattern varies as a function of scan angle. A description of the modelling of the pattern in this plane follows from Reynolds (1986):

To determine the MOST HPBW variation with scan angle, measured HPBWs in the transverse plane are compared with the East-West gain function (EWGF), which measures the gain variation due to beam scanning in the longitudinal (East-West) plane. It is obtained from the averaged measurement of several strong radio sources across the $\pm 60^{\circ}$ scan angle range. Gain contributions from the telescope antenna elements, waveguide cavities, combining networks, LNAs, and other 'real world' effects such as strut and ground plane scattering effects are included in the measurement. The EWGF, shown in Figure 2.6, has a gain modulation with scan angle, caused by secondary scattering between the reflector and ground plane.

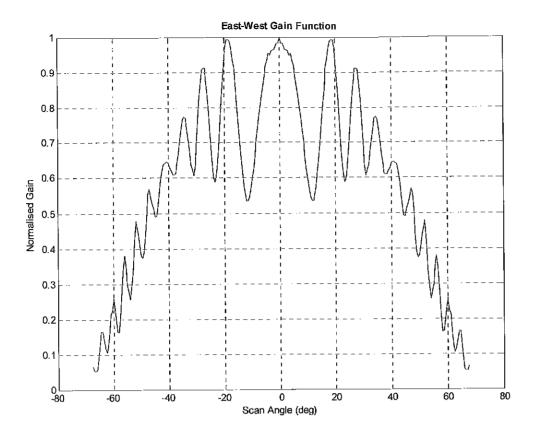


Figure 2.6 East-West gain function (EWGF), showing gain variation as a function of scan angle in the East-West (longitudinal) plane. (Gaensler and Hunstead 2000).

Although the EWGF shows gain variation as a function of scan angle, information regarding the HPBW or radiation pattern variation is embedded in the function and cannot be retrieved. From separate measurements, the HPBW was found to be proportional to the inverse square root of the EWGF for scanning angles within $\pm 20^{\circ}$ (Reynolds 1986):

Transverse Plane HPBW =
$$2.31^{\circ} \times (EWGF)^{-0.5}$$
 (2.18)

However, for scanning angles outside $\pm 20^{\circ}$ the best fit to the measured data required adding a cosine dependence due to the scan angle:

Transverse Plane HPBW×
$$(\cos \theta_{\text{scan}})^{-1.2} = 2.31^{\circ} \times (EWGF)^{-0.5}$$
 (2.19)

A Gaussian beam with a HPBW given by Equation 2.19 was used to model the pattern in the transverse plane. Figure 2.7, taken from Reynolds (1986), compares the empirical model with measured HPBW, showing good agreement up to 30° scan angle, but exhibits poorer accuracy for larger angles. Another effect occurring at large scan angles is that main beam pointing errors exist in the transverse reflector pattern, which are not represented in the Gaussian model. Furthermore, there is an additional standard error of 4% for measured fluxes of some outlying sources ≥ 35 arcmin North or South of the field centre due to uncertainties related to the transverse reflector pattern.

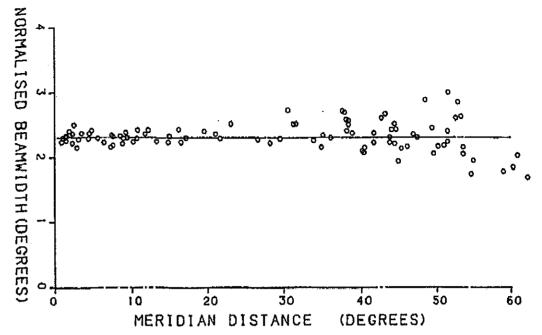


Figure 2.7 Normalised half-power beamwidth (HPBW) for varying scan (Meridian Distance) angle, comparing the empirical model represented by the horizontal line, with the measured values (open circles). (Reynolds 1986).

Although the telescope beam has been adequately modelled in the longitudinal plane, there are inadequacies in the model used for representing the radiation pattern in the transverse (N-S) plane. Currently at the MOST, the use of a single parameter, HPBW Gaussian model to represent the pattern is insufficient for wide-field imaging (Bock 1997). A better model for the transverse reflector pattern is necessary to understand the pattern variation at large scanning angles.

2.5.1 Proposed Transverse Beam Model

Inadequacies in the existing model for the transverse reflector pattern are due to a breakdown in the assumption that the pattern represents a Gaussian profile at large scanning angles, although the model is accurate for scanning angles within $\pm 20^{\circ}$. From Fourier transform theory, a Gaussian reflector pattern corresponds to a Gaussian line feed illumination pattern (Hansen 1966a). However, the reflector pattern in the transverse plane is a distorted Gaussian because of the following effects:

- Line feed ground plane blockage.
- Reflector curvature.
- Line feed illumination pattern variation with scan angle.

Ground plane blockage causes an inverse aperture distribution and increased sidelobes in the reflector pattern (Kraus 1966). In addition, blockage causes gain modulation with scan angle due to secondary scattering off the reflector, as shown in Figure 2.6. At particular scan angles, the line feed illumination pattern may become elliptical (Hansen 1966b) or skewed, causing pointing errors in the reflector pattern. The line feed illumination pattern varies with scanning angle due to increased coupling between elements. This is known as 'mutual coupling' and is described in greater detail in Chapter 6. Accurate modelling of the reflector pattern requires the inclusion of mutual coupling.

Typically, the coupling currents on the elements are stronger in the array direction and at large scan angles.

A single-parameter Gaussian beam model does not include the effects of mutual coupling due to inter-element coupling in the line feed and does not provide information about the sidelobe levels and pointing errors in the reflector beam. In the analysis developed in this thesis, the line feed and reflector patterns are modelled separately. A separate model for the line feed is desirable because information concerning the illumination pattern such as beam skewing, beam asymmetry, back radiation levels and polarisation purity can be examined individually. This enables a study of the line feed illumination pattern variation with scan angle, pointing errors and any HPBW fluctuations. Mutual coupling effects are included in the model by implementing a full-wave electromagnetic analysis of the line feed across the frequency and scanning angle range, as described in Chapter 6. Another advantage of a separate line feed model is that optimisation of the line feed design becomes more efficient.

Once the line feed illumination pattern has been modelled, the reflector pattern is analysed. The reflector model assumes the mutual coupling effects are included in the line feed illumination patterns. The reflector pattern over the 360° azimuth¹ angle range is simulated by illuminating the reflector profile with a feed illumination pattern and then calculating the currents on the reflector using an electromagnetic analysis. Reflector pattern sidelobe levels, HPBW and back radiation variation with scanning angle can be obtained. This simulation includes effects such as ground plane blockage, secondary scattering, and reflector curvature, as presented in Chapter 5.

The line feed and reflector can be modelled separately providing the relevant 'physical' coupling effects are included for each respective model. The reflector is situated at a distance, r = 3 m, from the line feed and the effects of mutual coupling between the two can be neglected providing the reflector may be considered in its far-field region when:

$$r > \frac{2L^2}{\lambda} \tag{2.20}$$

This condition is satisfied at the MOST, where $L=0.5\,\mathrm{m}$ is the transverse line feed dimension and $\lambda=0.356\,\mathrm{m}$ for 843 MHz. Therefore, the only mutual coupling is due to the interaction between the line feed elements which is included in the line feed illumination pattern model. However, the secondary scattering, ground plane blockage between the line feed and reflector must be included in the reflector model. Other gain variations, not dependent on the radiation patterns, such as the modulation of the input impedance due to secondary scattering are predicted from the EWGF measurement. These variations can be corrected by calibration procedures.

To recover accurate images of the sky, calibration procedures are needed to remove systematic instrumental effects caused by the telescope and the external environment. For the MOST, calibration involves compensation for gain and phase differences between interferometer pairs, telescope gain variation with scan angle, as shown in Figure 2.6, gain variation due to the temperature of the electronics and the reflector patterns in the transverse and longitudinal planes. The effectiveness of calibration for instrumental effects at the MOST depends on repeatability. Any random or unpredictable gain fluctuation corrupts the process.

Line feed parameters are calibrated using a combination of methods such as theoretical modelling, e.g. for the reflector beam, and telescope measurements, e.g. for the EWGF. Telescope measurements come from observations of a sample of strong unresolved point sources (Campbell-Wilson and Hunstead 1994). Table 2.1 presents a list of line feed parameters and the corresponding calibration approach currently used at the MOST. The parameters are categorised as near-field (NF) or far-field (FF) with respect to their spatial relationship with the line feed. For example, mutual coupling is a near-field effect because the element spacing is less than the line feed transverse dimension at the centre frequency. Pattern parameters in the longitudinal plane shown in Table 2.1 can be adequately calibrated by using a line source model described in Section 2.2. However, in the transverse plane the Gaussian model is inadequate. The model assumes low sidelobe levels, which do not affect the dynamic range of the image. But this is only likely to be true for moderate scan angles near the field centre. Furthermore, ground plane blockage affects the transverse plane sidelobes and is not included in the current model. Sidelobe levels in the longitudinal reflector pattern can be reduced to an arbitrary level by amplitude tapering, as described in Section 2.2. In the transverse plane, the sidelobe levels for the reflector pattern can be reduced by optimising a line feed illumination pattern.

Although an accurate beam model can characterise the sidelobe variation in the transverse plane, this does not allow improvements in the antenna temperature because the sidelobe levels are determined by the line feed hardware and are not reducible by subsequent signal processing. However, the model can be used as an analysis tool to identify possible improvements in the hardware. As well as sidelobes in the transverse plane, there are others in the longitudinal plane caused by the periodic radio frequency (RF) combining of the contiguous interferometer sections, called quantisation lobes. An additional sidelobe is caused by beam scanning out to large scan angles, called grating lobes. All these sidelobes create artefacts in the image known as grating rings. Grating rings due to the quantisation lobes have been substantially reduced by installing phase switches (Amy and Large 1990). The grating lobes excited at large scanning angles for the current MOST line feed do not significantly affect the image except at the edges of the map. However, they will affect the planned wideband operation described in Chapter

¹ Azimuth is related to the cylindrical coordinate system of the line feed attached to the cylindrical reflector and is described as the angular direction referenced to the feed in the plane transverse to its length. This is different to how azimuth is used describe the angular direction of rotation for a parabolic dish.

Antenna Parameter	Modelling Approach	Calibration Accuracy	Limitation
Longitudinal Reflector Pattern [FF]	Modelled assuming radiation due to a line source with triangular amplitude taper.	Adequate	None
Transverse Reflector Pattern [FF]	Gaussian beam shape.	Inadequate	Model is poor for scanning angles: $ \theta_{scan} > 30^{\circ}$
Longitudinal Reflector Pattern First Sidelobe [FF]	Assumes radiation due to a line source with triangular amplitude taper.	Adequate	None
Transverse Reflector Pattern First Sidelobe [FF]	No sidelobes for Gaussian beam shape.	Inadequate	The sidelobe levels are not modelled and will limit the dynamic range.
Pointing Errors (Transverse Reflector Pattern) [FF]	Telescope Measurement.	Adequate	None: Provided the pointing is stable and quantifiable.
Gain Variation due to Scanning [FF+NF]	Telescope Measurement (EWGF)	Adequate	None
Antenna Temperature [FF]	Telescope Measurement.	Adequate	The antenna temperature will limit the sensitivity. Requires knowledge of the line feed pattern for spillover temperature.
Transverse Line feed Illumination Pattern [NF]	Modelled assuming Gaussian illumination.	Inadequate	Gaussian model does not contain information about beam skewing and pattern variation with scan angle; requires knowledge of the effects mutual coupling.
Input Impedance [NF]	Telescope Measurement. (EWGF)	Adequate	Information about input impedance is implied in the EWGF measurement but cannot be accessed directly.

Table 2.1 MOST antenna parameters and the current calibration methods. FF = far field, NF = near field.

The antenna temperature is determined by the RF hardware and is a fundamental property of the telescope. In addition to the intrinsic system noise of the RF signal chain, the feed receives a component from ground radiation at 300 K. The antenna temperature is a function both reflector geometry and transverse plane line feed pattern. The effects of antenna temperature due to the line feed and reflector are described in Chapter 3 and its limitation on the imaging sensitivity is described in Section 2.7. Although the input impedance is adequately calibrated using the EWGF telescope measurement, this approach is not ideal because the measurement combines all telescope gain variation effects. So individual gain variations, such as line feed input impedance variation due to mutual coupling, cannot be determined. Information about these variations is useful in the design and analysis of the line feed, and a model for the input impedance is described in Chapter 6. In addition to the antenna parameters in Table 2.1, there are random or external errors to be calibrated, which are due to operational characteristics and the environment. These errors include ionospheric effects, solar interference, extreme weather, terrestrial radio frequency interference (RFI) and electrical or mechanical subsystem failures. Ultimately, these errors may limit the final achievable performance, regardless of how accurately the parameters in Table 2.1 can be modelled. Therefore,

telescope measurements under 'real world' operating conditions are crucial to the complete calibration assessment.

2.7 Sensitivity Analysis

The sensitivity of a telescope, described by Equation 2.21, determines the minimum source flux density it can detect and is a function of resolution, system sensitivity and sky noise.

$$\sigma_{obs} = \sqrt{\sigma_{conf}^2 + \sigma_{sys}^2 + \sigma_{sky}^2}$$
 (2.21)

Where σ_{obs} = observation sensitivity

 σ_{conf} = confusion limit

 σ_{sys} = system sensitivity

 σ_{skv} = sky noise

A telescope with a particular resolution is continuum confusion limited (σ_{conf}) if the surface density of the weakest detectable sources is so high that the sources overlap. For confusion not to be a problem, there should be > 10 beam areas per weakest detectable source. Figure 2.8 shows a graph of the continuum confusion limit (10 beam areas per source) of current aperture synthesis telescopes across a 325–1420 MHz observation frequency range at a declination south of -60° . For the MOST, the synthesised beam resolution is 43" × 43" cosec|dec| at 843 MHz (Bock et al. 1999), corresponding to a 0.12 mJy continuum limit. Because the angular resolution is determined by its largest baseline, the confusion limit can only be improved by extending this baseline.

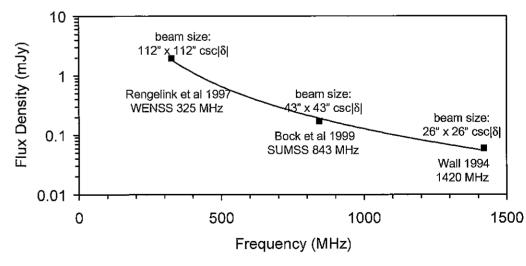


Figure 2.8 Continuum confusion limit vs. frequency for given telescope resolutions at a declination south of -60°. (Jackson 2005).

The system sensitivity describes the minimum detectable source flux density due to instrumental telescope effects. For a synthesis telescope, the system flux density sensitivity is given by (Thompson et al. 2001)²:

$$\sigma_{sys} = \frac{2kT_{sys}}{A_{eff}\eta_Q\sqrt{n_p\left[N(N-1)\right]\Delta\nu\Delta t}} \frac{w_{rms}}{w_{mean}} W/m^2/Hz$$
 (2.22)

Where

k = Boltzman's constant

 $T_{\text{sus}} = \text{System temperature}$

 $\eta_{\scriptscriptstyle O}$ = Correlator quantisation efficiency

 A_{eff} = Antenna effective area

 n_n = Number of simultaneously sampled polarisations

N = Number of antennas in array

 $\Delta v = Instantaneous bandwidth$

 Δt = Integration time

 w_{max} = mean weighting factor over all correlations used to form the image

 w_{rms} = rms weighting factor over all correlations used to form the image

The system sensitivity parameters that influence the MOST line feed performance are T_{svs} , A_{eff} , n_p , N and bandwidth (Δv) .

The system temperature is a function of antenna temperature, feed losses, reflector mesh leakage and receiver temperature:

$$T_{sys} = T_A + T_{feed} + T_{Mesh} + T_R (2.23)$$

Where $T_{sys} =$ System temperature

 T_4 = Antenna temperature

 T_{feed} = Temperature due to feed losses

 T_{Mesh} = Mesh leakage temperature

 T_p = Receiver temperature

The line feed contributes to the system temperature in the form of antenna temperature and feed element losses. Antenna temperature is determined by the radiation pattern and was briefly described in Section 2.6. The antenna temperature can be controlled in the longitudinal plane by applying an amplitude weighting to the bay beams. However, it is fixed in the transverse plane by the reflector and line feed illumination pattern. In the current Gaussian model for the beam in the transverse plane, information regarding the antenna temperature due to the feed illumination is unknown, so back radiation and sidelobe data are not included. The current antenna temperature at the MOST can be approximated by determining the remaining temperature contributions in Equation 2.23. Feed losses relate to the impedance characteristics, physical construction and design of the line feed element and include return loss, path loss, noise coupling loss from mutual coupling, conductivity and dielectric losses. These losses can be measured in the form of an encapsulating noise measurement or analysed individually for design purposes. An analysis of the line feed losses is presented in Chapter 7. The losses are low for the element currently on the telescope because of the construction technique and choice of materials used; they are pressed out of metal, so conductor losses are minimal and contribute around 3 K. The reflector surface at the MOST uses a 25.4 × 12.5 mm mesh. which behaves as an adequate reflecting surface at 843 MHz. However, some ground radiation (300 K) 'leaks' through the mesh and is detected by the line feed, causing an increase in system temperature. An estimate for the MOST mesh leakage at 843 MHz is around 15 K (Duncan Campbell-Wilson, personal communication, 2005).

The receiver temperature is a function of contributions from various electronic components used in processing the received signal from the line feed. It is influenced by the electronics architecture and in particular the first electronic component placed after the antenna (Kraus 1966). For the MOST, this is an LNA (Low Noise Amplifier), which has a measured temperature around 20 K (Bock 1997). However, there is an additional beamforming network loss because the current MOST RF front-end architecture combines the signals from 22 elements in a quarter-bay (12.5 λ section) before connecting to the first stage LNA. Receiver components connected at various stages after the LNA, such as the down-conversion system and intermediate frequency (IF) amplifiers will also contribute some additional receiver noise. It is assumed that the major contributor to the receiver noise is the first-stage LNA and the following stages contribute around 10 K. This gives a receiver noise temperature of around 35 K, assuming 5 K from connector and path losses.

Table 2.2 shows the contributions to the system temperature for the MOST. No measured data are available for the antenna temperature and any estimate will change when the beam is scanned away from the meridian and for different mechanical pointing angles. This variation is described in Chapter 3 and a new beam model that enables the calculation of antenna temperature is described in Chapter 5. Although no estimate was available for the antenna temperature, it was estimated as 2 K in Table 2.2 by subtracting other temperature contributions from the measured system temperature.

Temperature Parameter	Temperature contribution (K)
Antenna temperature	2 K
Element loss	3 K
Mesh leakage	15 K
Receiver temperature	35 K
System temperature	55 K

Table 2.2 The noise temperature contributions to MOST.

 A_{eff} , is the effective area of the antenna aperture and represents the amount of the physical antenna aperture illuminated by the feed pattern. It is determined by the aperture efficiency, which is described in Section 3.3.1. The sensitivity has an inverse relationship with the effective area, which can be improved by optimising the line feed pattern or increasing the physical collecting area of the aperture. Feed pattern optimisation for maximum effective area involves a performance trade-off with the antenna temperature.

² Equation 2.22 assumes that each antenna is independently correlated with each one, but this does not occur at the MOST. The equation is used in this section to analyse the MOST line feed RF parameters which affect the sensitivity and this analysis is not dependent on how the antennas are correlated

For astronomical purposes, the feed pattern is designed for the best sensitivity and to maximise A_{eff}/T . This trade-off is investigated in Chapter 5.

 n_p , describes the number of polarisations that are simultaneously detected by the telescope, which is currently one for the MOST. The parameter N refers to the number of independent antennas used in the synthesis observation. For the MOST this is 88, determined by the number of line feed elements combined to form independent contiguous interferometric antennas. The instantaneous bandwidth, Δv , is determined by the sampling rate of the electronics or the feed bandwidth for the particular telescope. At the MOST, the instantaneous bandwidth is currently 3 MHz, set by the IF filters. The relationship between the feed bandwidth and instantaneous bandwidth is described as follows: the feed performance over the full synthesis interval must be acceptable across the instantaneous bandwidth. Another parameter limiting the sensitivity of a telescope is the sky noise temperature. This noise is frequency dependent $(1/\lambda^2)$ and for the MOST observation frequency of 843 MHz, contributes about 10 K.

The current sensitivity for MOST images at the field centre is typically 0.8–1 mJy per beam at declinations near –70° (Bock et al. 1999). Using Equation 2.21, with a confusion limit of 0.12 mJy and neglecting sky noise, the system sensitivity is calculated to be around 1 mJy. It is desirable that any upgrade ideally reduces the system sensitivity below the confusion limit to obtain the best possible results for the given telescope configuration.

2.7.1 System Sensitivity Improvements

Possible improvements to the system sensitivity can be evaluated using Equation 2.22. The continuum confusion limit for a resolution of 43" is 0.12 mJy and currently the overall sensitivity is 1 mJy. To achieve system sensitivity comparable to the confusion limit, increasing the effective area is impractical. A more accessible approach is to increase the bandwidth. The current line feed bandwidth is 14 MHz for a 0.1 reflection coefficient or -20 dB return loss (Mills and Little 1972). The bandwidth can be extended if a reduction in received signal is acceptable. The current feed is a resonant ring design and its bandwidth is limited to 3–5%, of the operating frequency 843 MHz, or around 30 MHz. An improvement in system sensitivity of $\sqrt{3/30}$ is achieved by increasing the instantaneous bandwidth from 3 to 30 MHz, corresponding to a system sensitivity of 0.3 mJy.

Further improvement to the system sensitivity requires a new line feed for the existing reflector. The characteristics of this new feed are dual polarisation sensing capability, wideband frequency operation, low feed loss and a transverse feed pattern that maximises the $A_{\rm eff}/T$. The feed pattern is dependent on the element type chosen for the new line feed. The system sensitivity improvement using a dual polarised line feed $(n_p=2)$ will be $\sqrt{n_p}$, which is 0.7 mJy for the MOST. Assuming the line feed is capable of wideband frequency operation, the instantaneous bandwidth, x_{BW} , required to improve the system sensitivity from 0.7 mJy to the confusion limit, 0.12 mJy, can be calculated using the ratio:

$$x_{BW} = (3) \left(\frac{0.7}{0.12}\right)^2 \sim 100 \text{ MHz}$$
 (2.24)

Assuming a line feed can be designed with dual polarisation capability and acceptable performance over an instantaneous bandwidth of 100 MHz, the resulting observation sensitivity can be calculated from Equation 2.21, for the condition where the confusion limit and system sensitivity are equal. This gives a 0.17 mJy observation sensitivity (σ_{obs}). Small modifications in resultant sensitivity can be achieved by modifying the telescope configuration to trade-off its aperture efficiency and sidelobe levels. Sidelobe levels for the reflector pattern can be adjusted in the longitudinal plane by amplitude weighting and minimised in the transverse plane by optimising the feed pattern in the design. Further improvements to the system sensitivity can be obtained by minimising the receiver noise, increasing the integration time for the measurement and implementing a new RF frontend architecture to minimise path losses.

The observation sensitivity ($\sigma_{obs} = 1$ mJy per beam) used in the analysis was measured for a declination South of -70° at the field centre. The sensitivity is degraded towards the edges of the synthesised field-of-view and for declinations toward the North. Elongation of the beam means less integration time per pixel and large scan angles cause foreshortening of the effective aperture and other gain fluctuations as shown in Figure 2.6.

2.8 Dynamic Range

Limitations to the dynamic range were described in Section 2.5 and 2.6 and result from aperture foreshortening and gain reduction at Northerly declinations, and sidelobe confusion either from the main sidelobes or quantisation lobes. These effects, along with random gain variations restrict the current dynamic range at the MOST to about 100:1 (Robertson 1991). The limitations due to sidelobe confusion can be reduced by weighting the amplitude of the line feed, described in Section 2.2 and anti-grating ring phase shifters, described in Section 2.6 have been used to reduce the grating ring amplitude. Further improvements in dynamic range will be achieved through the use of self-calibration, which requires individual antenna-based gain and phase variations to be recorded. A correlator based signal processing system currently being developed (Adams et al. 2004) will record visibilities for the first time and enable improved dynamic range.

2.9 Summary

The MOST radiation characteristics and the current imaging beam modelling approach were described. Although the current approach used to model radiation in the longitudinal plane is accurate, the model used for the transverse plane is inaccurate for scan angles outside $\pm 30^{\circ}$. This inaccuracy arises because the model assumes a Gaussian beam shape and mutual coupling effects between feed elements are not included. Therefore a new transverse beam model was presented in Section 2.5.1, to model these feed effects and facilitate the line feed design. The proposed modelling approach uses two separate methods to analyse the radiation from the MOST: the reflector model,

presented in Chapter 5, and the line feed model, presented in Chapter 6. From a sensitivity analysis of the MOST described in Section 2.7, it was determined that the system sensitivity was limiting the overall sensitivity due to the performance of its existing electrical and mechanical subsystems. Improving the current sensitivity to match the continuum confusion limit was investigated by designing a feed with dual polarisation capability and extending its bandwidth to 100 MHz. These improvements along with other upgrades to extend the scientific capability of the MOST are realised in a project called the Square Kilometre Array Molonglo Prototype (SKAMP) and is presented in Chapter 3.

Chapter 3

Square Kilometre Array Molonglo Prototype (SKAMP)

The MOST survey of the southern sky, Sydney University Molonglo Sky Survey (SUMSS), is complete. The telescope has been operating in wide-field mode since 1997 and only minor changes have been made to the MOST in the period 1997–2006, to preserve uniform sensitivity for SUMSS (Bock et al. 1999). It is now timely to consider an upgrade to the MOST, to improve its imaging sensitivity, dynamic range and scientific capability to ensure it operates as a scientifically useful instrument into the next decade. There is also an opportunity to demonstrate technologies and science relevant to the international Square Kilometre Array (SKA) project.

An overview of the Square Kilometre Array Molonglo Prototype (SKAMP) upgrade to the MOST is described in Section 3.1. Section 3.2 presents key enabling technologies to overcome previous limitations in cylindrical reflector development, as discussed in Chapter 1. The relationship between the SKAMP line feed engineering requirements and the MOST performance are investigated in Section 3.3. A set of line feed design specifications are developed in Section 3.4, which will enable the selection of a feed element, as described in Chapter 4.

3.1 SKAMP Overview

SKAMP is a three-stage signal pathway replacement for the MOST. This approach enables implementation and commissioning to occur whilst minimising disruption to observing programs.

The goals of SKAMP are:

- Improve the system sensitivity, so that it is comparable to the confusion limit.
- Extend the current scientific capability, for wideband continuum imaging, low frequency spectroscopy and polarimetric imaging.
- Improve the dynamic range by implementing self-calibration.
- Demonstrate technologies relevant to the SKA.

One goal of the SKAMP upgrade is to demonstrate the possibility of incorporating cylinders as part of the SKA design. The SKA is an international project to build a powerful next generation radio telescope with a collecting area of one square kilometre at 1.4 GHz with a planned observation frequency range of 0.1–22 GHz (www.skatelescope.org). Instruments being demonstrated for the SKA include an aperture array (Schaubert et al. 2003), focal plane array feeds (multi-pixel feeds) in a

parabolic reflector (Ivashina et al. 2004) and a wideband feed (single-pixel feed) in a parabolic reflector (DeBoer and Bock 2004). Relevant technology for the SKA demonstrated in SKAMP are wide field-of-view imaging, wideband dual polarised line feeds, high-speed digital signal transport and processing. Whilst the existing MOST offers a large collecting area, it does not have optimal reflector geometry because it uses a centre-fed configuration and was constructed using materials and technologies developed in the 1960s. The use of cylindrical reflectors for the SKA offers fast survey speed with large field-of-view imaging, low reflector cost per unit area and simplified mechanical control. On the other hand, cylindrical reflectors require a large number of feed elements, and cryogenic cooling of the receivers and wideband polarisation imaging are untested for this instrument.

The MOST system sensitivity was analysed in Section 2.7. For SKAMP it will be improved by increasing the number of simultaneous sampled polarisations to two, increasing the instantaneous bandwidth and re-meshing the reflector to reduce leakage. The new spectral line capability requires a correlator and polyphase filter banks. Polarisation capability is facilitated by a new dual polarised line feed. An improvement in dynamic range can be achieved by implementing self-calibration, as described in Section 2.8. A brief description of the three stages for SKAMP follows:

SKAMP 1 is aimed at testing the FX correlator architecture in narrowband mode for continuum imaging. Existing analogue beamformers are replaced with a new programmable logic chip continuum correlator (Adams et al. 2004), which has 96 independent inputs, and an instantaneous bandwidth of 4.4 MHz. The FX architecture enables intra-arm correlations, thereby increasing the number of independent baselines to over 4,000. Eight correlator stations will be allocated to reference antennas, providing opportunities for radio frequency interference (RFI) mitigation. The existing RF frontend is maintained and hence, the operating frequency remains at 843 MHz.

SKAMP 2 will enable spectroscopy capability, by implementing a spectral line correlator with polyphase filter banks. The new correlator will have an instantaneous bandwidth of 100 MHz and a maximum spectral resolution of 5 kHz. The same FX architecture is used for the correlator and 6000 spectral channels will be produced using polyphase filterbanks (Adams et al. 2004). A new optical fibre intermediate frequency (IF) distribution network buried to a depth of at least 0.7 m is used to transfer the digital data and new tuneable local oscillators (LO) enable down-conversion of the RF signal over a wide frequency range. These new systems provide improved system sensitivity and less gain variation from temperature and humidity fluctuations. The existing RF front-end is maintained for this stage. Although the instantaneous bandwidth of the spectral line correlator is 100 MHz, the observing frequency range is limited to 830-860 MHz by the existing line feed bandwidth. The instantaneous bandwidth can be increased using the existing line feeds but this limits the sensitivity due to a higher feed reflection coefficient. The system sensitivity for this stage is expected to be around 0.2 mJy/beam and is improved on the 0.3 mJy/beam sensitivity, described in Section 2.7.1, due to the use of an intra-arm correlation scheme and new receiver architecture.

SKAMP 3 is aimed at increasing the observing frequency range to 300–1400 MHz and providing polarisation capability. This requires a new wideband RF front-end architecture and associated hardware, with a single LNA matched to each feed element (for each polarisation) placed before the first-stage RF beamformer. This architecture

reduces the antenna noise temperature by removing the path losses between the combined line feed elements, as described in Section 2.7. A LNA on each element enables gain control and improvements in dynamic range. Antenna temperature from mesh leakage, described in Section 2.7, is reduced by re-meshing the reflector surface with a finer mesh. The current mesh has a spacing of 25.4×12.5 mm and the new mesh will have a 6.0×6.0 mm spacing, which is expected to improve the system temperature by around 15 K (D. Campbell-Wilson, personal communication, 2006). For the receiver electronics, the SKAMP 2 correlator is retained and the 100 MHz bandwidth intervals are selected using the tuneable LO across 300–1400 MHz range. The instantaneous bandwidth is set by the sampling speed of the digitisers (200 M samples/sec).

Expected system sensitivity from the SKAMP 3 upgrade is around 0.1 mJy/beam which is at the confusion limit for continuum surveys. However, spectroscopy and polarimetry measurements will not be confusion limited. Table 3.1 shows a comparison of the three SKAMP stages with the existing MOST wide-field operation. The reduction in system temperature for SKAMP 3 is due to the expected improvement from re-meshing the reflector. Additional temperature contributions from the antenna temperature and feed losses are investigated in Chapter 7.

A SKAMP block diagram is shown in Figure 3.1. To reduce engineering complexity and data processing requirements, two stages of RF beamforming are planned. The first-stage RF beamformer combines 8 elements in a module, which determines the transverse plane pattern performance. The second-stage combines 6 modules, equivalent in length to a half-bay as described in Section 2.3. This provides a roughly equal HPBW of around 2° at 843 MHz. Digitising the received signal at each element in Figure 3.1 would allow the individual patterns for each element to be adjusted and weighted for optimum sensitivity, gain, polarisation or low sidelobes. However, the cost and complexity of digital electronics prohibit this option. Instead, the digitisation occurs after the second-stage of RF beamforming.

The first two stages of SKAMP use the current RF front-end and will be commissioned on the existing telescope. For SKAMP 3, the new RF front-end will be tested on a separate 17.8 m test bay, pictured in Figure 3.2, with identical mechanical specifications to the MOST. In addition, the finer mesh will be installed on the test bay to evaluate mesh leakage and mechanical attachment. When observations are conducted at frequencies outside the current protected bandwidth, they will be susceptible to terrestrial RFI. Mitigation techniques are planned, using additional antennas that can be steered towards the location of known interferers, such as mobile phone basestation sites or the Sun. RFI mitigation techniques implemented in the post-correlation stage of Figure 3.1 are described in Mitchell et al. (2005).