Summary and conclusions

The fault, dear **Brutus,** is not in our stars
But in ourselves.

Cassius in *Julius Caesar*
by William Shakespeare

Then nowise worship dusty deeds
Nor seek, for this is also sooth,
To hunger fiercely after truth,
Lest all thy toiling only breeds
New dreams, new dreams; there is no truth
Save in thine own heart. Seek, then,
No learning from the starry men,
Who follow with the optic glass
The whirling ways of stars that pass --
Seek, then, for this is also sooth
No word of theirs -- the cold star-bane
has cloven and rent their hearts in twain,
And dead is all their human truth.
Go gather by the humming sea
Some twisted echo-harbouring shell,
And to its lips thy story tell,
And they thy comforters will be,
Rewording in melodious guile
Thy fretful words a little while,
Till they shall singing fade in ruth
and die a pearly brotherhood;
For words alone are certain good:
Sing, then for this is also sooth.

- From " The song of the happy shepherd"
Crossways
William Butler Yeats
1889

Chapter 6

SUMMARY AND CONCLUSIONS

In this thesis we have presented various aspects of wide field imaging with the Mauritius Radio Telescope. The hardware systems, the observations, the techniques and tools developed for wide field imaging with the MRT and some preliminary analysis of the images have been described. In this final chapter we summarize the work described in this thesis and the conclusions arrived at there from.

General background

In Chapter 1 we discussed some elements of surveying the sky at radio frequencies. Basics of aperture synthesis techniques and a few aspects of protection of radio frequencies for astronomy were also described.

The Mauritius Radio Telescope

Very few surveys of the southern sky exist at frequencies below **1** GHz, and none which are as deep as the 6C survey of the northern sky. The Mauritius Radio Telescope (MRT) was built to fill the gap in the availability of deep sky surveys at low frequencies. It is is a Fourier synthesis instrument operating at **151.5** MHz and is situated in the north-east of Mauritius at a southern latitude of 20°.14 and an eastern longitude of 57°.73. The aim of this survey using the

MRT is to contribute to the database of southern sky sources in the declination range $-70^\circ \leq 6 \leq -10^\circ$ covering the entire 24 hours of right ascension, with a resolution of $4' \times 4'.6\sec(\delta+20^\circ.14)$ and a point source sensitivity of $\sim$200 mJy. With a near-complete coverage of short baselines down to zero-spacing, this telescope is also expected to image the large scale structures and low-surface brightness features in the southern sky.

The MRT is a T-shaped non-coplanar array consisting of a 2048 m long east-west arm and a 880 m long south arm. In the east-west arm 1024 fixed helices are arranged in 32 groups and in the south arm 15 trolleys, with four helices on each, which move on a rail, are used. The primary beam of the helices has a full width at half maximum of 60°, and they are mounted with a tilt of 20" towards the south, i.e., the peak of the primary beam is at $6 = -40^\circ$. This allows a better coverage of the southern sky including the southern-most part of the Galactic plane. The outputs of the east-west and the north-south groups are heterodyned to an intermediate frequency (IF) of 30 MHz, using a local oscillator (LO) at 121.6 MHz. These group outputs are then amplified and brought separately to the observatory building via coaxial cables. In the observatory, these outputs are further amplified and down-converted to a second IF of 10.1 MHz. The filtered outputs go through an *automatic gain control* (AGC) unit, which keeps the output level constant. These are then quantized to 2-bit 3-levels and sampled at 12 MHz. These are further processed in a 512-channel digital complex correlation receiver to measure the visibility function. The variation in the background radiation as seen by the east-west and the north-south groups are measured separately by switching off the AGC, one in each of the east-west and the north-south arms and using the self-correlators to measure the total power output of these groups. A large part of the back-end including the correlator system was acquired from the Clark Lake Radio Observatory (CLRO) [31]. We adapted and modified the CLRO system for use at the MRT. The modified system was then installed and tested with the rest of the system in Mauritius. The front-end and the receiver system are discussed in chapter 2.

A recirculator system for the MRT

During the installation stage of the Mauritius Radio Telescope we identified the need for wide field imaging with this telescope to make it an efficient surveying instrument. Although the use of larger bandwidths results in better sensitivity of a telescope, it restricts the angular range over which an image can be made (i.e., if the relative delays between the signals being correlated are not compensated). When the uncompensated delay between the signals becomes comparable to the inverse of the bandwidth used, the signals will be decorrelated. At the MRT we normally use a bandwidth of 1 MHz. Since the east-west group has a narrow primary beam of two degrees in RA, a 1 MHz bandwidth does not pose a problem for synthesizing the primary beam in this direction. However both the east-west and the north-south groups have wide primary beams in declination extending from -70° to -10°. For signals arriving from zenith angles greater than 10" on north-south baselines longer than about 175 m, the uncompensated delay results in a bandwidth decorrelation greater than 20%.

To overcome this loss of correlation one has to measure visibilities with appropriate delay settings, while imaging different declinations. To restrict the loss of coherence to less than 20% in the entire declination range of -70° to -10°, for a bandwidth of 1 MHz the longer baselines have to be measured with four delay settings. For a given delay compensation we are able to image a part of the sky, referred to as a delay zone, around the point at which the geometrical delay has been compensated. With the existing correlator system we need to observe for four days at the long north-south baselines, each day with a different delay setting. Furthermore, to be able to make interference-free maps, observations have to be repeated approximately **3** times at each location. This would make the time required to complete the survey very large – of the order of 4 years of observing! Also, because of the paucity of suitable calibrators in the field of view of the MRT, calibrating the visibilities measured in a different zone on a different day would be a problem. We could overcome this by observing different zones in a time-multiplexed way so that we would get data from all the observable declinations on the same day. This would result in a loss of sensitivity by a factor of **2.** To overcome these problems we needed a system which will allow data to be collected for each zone without degradation in sensitivity and which will also allow the visibilities with different delays to be measured on the same day. The system would store the samples for T seconds followed by a correlator system that would measure visibilities with each delay setting in $\frac{T}{N}$ seconds. Such a system is called a recirculator.

We designed and built a recirculator system which allows us to observe with different delay settings in one observation schedule. This system measures visibilities with different delay settings using the available correlators. To implement this, a dual-buffer memory system is employed between the sampler and the correlator. The data is sampled at a slower rate and stored in one bank while the data from the other bank is fed to the correlators at a rate which is 4 times faster than the input rate. In this system, the data is sampled at a rate of *2.65625* MHz, stored in a buffer memory and the correlations are measured at four times this rate (10.625 MHz). Such a processing by the correlator at a higher speed than the input rate allows the correlations to be measured with four delay settings. This ensures that the observations at each trolley location, even on longer baselines, can be carried out in one day. Thus does a recirculator improve the surveying sensitivity. The loss of sensitivity due to the reduction in the sampling rate, for a 1 MHz bandwidth, from 12 MHz to 2.65625 MHz for the 2-bit 3-level correlators is only about 10%.

The sampling frequency of 2.65625 MHz is near the optimal permissible sampling frequency, considering the bandpass sampling criterion for a 1 MHz band centered at $\sim$10 MHz with the additional requirement that the sampling clock does not have harmonics in the 1 MHz bands centered at 30 MHz (first IF) and at 151.5 MHz (RF).

To program the correlator system and the recirculator boards, and also to acquire data from the correlators, we designed and built a new data acquisition and control system (DAS). This data acquisition system comprises of a double bank of memories shared by two 80386 PCs running on DOS. The PCs are referred to as PC1 and PC2. PC1 communicates with the correlator system. It sends the control signals to configure the correlator system and the recirculator boards for different modes of operation and programs the delays in the correlator system. It also collects the data from the correlator system and integrates them onto the double bank memory. The data for different zones are acquired onto different sections in the memory bank. PC1 also reads the sidereal time from an astronomical clock and time-stamps the acquired data. At the end of one second of integration, PC1 swaps the banks and sends an interrupt to PC2. While PC1 continues acquiring data and integrating onto the second memory bank, PC2 picks up data from the first memory bank and transfers them over a point-to-point Ethernet link onto the hard-disk of a linux-based PC, which is part of a Local Area Network (LAN) connecting it to other machines through a gateway. Having a separate network for the acquisition system ensures a reliable transfer of data and any fault or breakdown in the LAN connecting other machines does not affect the acquisition of data. Using the DAS, the process of acquiring 1088 words of data from the correlator takes 11.62 ms.

In the recirculator mode, which uses a sampling frequency of 2.65625 MHz, the maximum/minimum correlation count for one second integration is ±179256 requiring 19 bits. Data is pre-integrated for 2^{17} clock cycles on the correlator boards and then further integrated 22 times in the DAS to get about 1 s packets. However no celestial source in our beam (not even the Sun) is expected to produce a correlation count to fill even a 16 bit counter i.e ±32768 for an integration of about 1 s . This value corresponds to a normalized correlation coefficient of about 0.2 (i.e., $\rho \approx 0.2$). Therefore, it suffices to record only two bytes of data for each correlation with a 1 s integration. Generally, only interference is expected to cause an overflow of this two byte data. In the DAS, if the addition of a pre-integration value causes an overflow, then this data is not added. This basically results in some interference clipping within the 1 s data.

We have 64 self correlators in the system. A self correlator counts the number of samples which have values between the threshold levels. For Gaussian signals with a $\frac{V_{th}}{\sigma} \approx 0.7$, this is about 54% of the maximum correlation counts, i.e., ~100,000 counts and therefore requires 17 bits for storage. We divide each pre-integrated value of self correlation by 4 before post-integrating on the DAS, thereby making an error of about 66 counts which is of the order of 1a. Although self correlation values are plagued by local pickup, the two non-AGC channels used for estimating total power are each stored separately as 4 bytes of data to avoid any deterioration in the estimation of total power due to clipping.

Every 49.34 ms, data for the 4 delay zones are integrated on the DAS to build up 1 s data packets before transferring them to a hard-disk over the Ethernet. Thus every second we store 9216 bytes of data resulting in about 800 MB of data for a 24 hour observation. To facilitate data handling and automation of data processing, the data is organized in hourly (LST) files. The allocation, the LST hour and the Julian Day information of the observation are directly obtainable from the name of the observation file.

The recirculator system was integrated into the receiver system at the MRT and tested with carrier wave and noise inputs in the laboratory. After satisfactory performance it was further tested by comparing the data on a calibrator with and without the recirculator. The design aspects and the details of the recirculator system have been discussed in chapter 3.

After testing the complete system, we carried out observations for the survey using the recirculator system up to the longest north-south baseline, i.e., up to 880 m during the period September 1995 to October 1996. More than 100 Giga bytes of data were acquired during this period. Because of the presence of the Sun and day time interference, the data set is not complete for the full 24 hours. A second set of data is being taken to cover the complete accessible sky.

Interference : detection and analysis

As a part of the data analysis, we have developed a technique to detect interference in the visibility data. Interference in the data gives rise to spurious features in the image. In addition, interference in the calibrator data causes errors in the estimation of the complex gain. These errors then propagate into the images even when there is no interference. Therefore, these interference points have to be detected and removed while making the image and while calibrating. Interference which is 'spiky' in nature has Fourier components beyond the maximum frequency which can arise from the sky and therefore can be identified. The interference detection technique employed at the MRT makes use of the fact that the visibility is sampled at rates much faster than the rate of change of visibility due to the diurnal rotation of the earth. At the MRT, the baselines with the longest east-west component $(\sim 512\lambda)$ have a maximum fringe rate of about 0.04 Hz. We would therefore need to sample this data at 0.08 Hz to satisfy the Nyquist sampling criterion. We have sampled the data at about 1 Hz, enabling us to identify frequencies up to 0.5 Hz. To further improve detectability we detect interference in the magnitude domain which has a rate of change corresponding to the primary beam of the interferometer (product of the voltage patterns of each group of antennas forming the interferometer) and is independent of the baseline used. At the MRT, the maximum fringe frequency in the magnitude domain for a celestial source is —0.003 Hz. If we have no a ***priori*** information about how the interference affects different baselines, we would need to detect interference on all possible combinations of baselines for best detection. We find however, interference generally affects all baselines simultaneously. Therefore we add the magnitudes of visibilities of all the baselines used for imaging thereby improving the detectability of interference.

In the method adopted for the MRT we take the sum of magnitudes of all the baselines. This is then high-pass filtered to get a time series from which the contribution of the sky has been removed. Interference is detected on the high-pass data in an iterative manner. In each iteration, interference points beyond a certain level are detected. These points are then removed from the original time series and the resulting data is high-pass filtered and the process repeated. The details of algorithm used are given in Chapter **4.**

Since interference generally affects all baselines simultaneously, by adding the magnitudes of all the **480** baselines we are able to detect interference to a level[1] of $\sim \frac{\sigma_m}{5}$ (σ_m is the noise per baseline) with a 4σ detection. Assuming interference is not correlated on different days, interference which is left undetected will have a contribution of about **70** mJy. This of the order of the noise in an image made using **60** days of data, i.e., all the baselines up to **880** m in the north-south.

The process of interference detection was automated and is carried out at the end of each sidereal hour during the observations. This data also helps us in determining the hours to be re-observed for a given trolley location.

We have studied the statistics of the strength, numbers, time of occurrence and duration of the interference at the MRT. The statistics indicate that most often the interference excision can be carried out while post integrating by giving zero weighting to the interference points. There are generally less than **20** instances in the full **24** hours when the interference lasts more than **6** consecutive seconds. Most of the interference appears to be local because it is seen to occur during the working hours of the local industries.

Wide field imaging with the recirculator

The observed data is calibrated to remove instrumental effects. Because of the broad primary beam, the calibration is affected by other sources present

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[1] $\frac{4\sigma_m}{\sqrt{480}}$

in the primary beam at the same time as the calibrator. The effect of other sources is minimized by doing a least square fit of the expected visibilities to the measured visibility. We describe this method along with its limitations in chapter 4. Because of the lack of suitable calibrators over the wide field of view of the MRT, we could not calibrate the different delay zones independently. It was therefore necessary to apply the calibration obtained from the zone in which we have the calibrator, to other zones. This forced us to look into various system parameters, particularly at the differences in the effective bandshapes of the different baselines. We established the various bandshapes by cross-correlation measurements. The band-centers for different baselines were not identical. Most of them were centered at 10.1 MHz while some ranged from 10 MHz to 10.2 MHz. For small delays, the variation in the center frequencies does not affect the calibration. However, at larger delays this effect cannot be ignored and has to be taken into account while calibrating. In an array, small variations in the center frequencies of different baselines can be dealt with by looking at them as having different spatial frequencies. We have incorporated the variations in the band-centers in the calibration and in the imaging programs.

Apart from the variations in bandshapes, system stability and errors in time stamping and in the positions of the antennas also affect the calibration. Timing errors are detected by comparing the phase difference of the east-west groups for sources at two different declinations. The positions of the antennas are calibrated using 3 sources at different zenith angles. Some groups were found to lie outside the east-west line with a maximum displacement of 55 cm towards the south. The initial markings on the north-south rail track were also found to be in error. The marked positions have now been measured to about

1 cm accuracy using a tension tape. These measurements agree with those estimated using the sources for baselines up to about 200 m. The position measurements beyond 200 m have not been confirmed using the sources and will be undertaken in the future. Because of lack of calibrators at different RAs the calibration of the array at RAs away from the calibrator depends on our system stability. The array calibrated on two successive days using the same source shows a difference typically having an RMS ~ 10° in phase. The RMS of gain ratios in 24 hours is typically —0.1 dB. Amplitude and phase variations from one calibrator to another are also of this magnitude. To improve the calibration process in the future, we have also acquired data in the NS × NS mode and in the EW x EW mode. This will allow us to carry out redundant baseline calibration (RBC). This method has not been used to calibrate the images presented in this thesis.

The FWHM of the primary beam response of an east-west group is 2° (HA= ±1°). This limits us to imaging only this region of the sky at any given time. The sampling of the visibilities in the east-west direction is at intervals of 64 m. This is also the size of an east-west group. Therefore when the beam is synthesized along the meridian, the grating responses fall at the null points of the primary beam response of the east-west group. However, when the beam is synthesized away from the meridian, the grating responses fall within the primary beam of the east-west group. The synthesized beam (including the aliasing) varies with' the hour-angle at which it is synthesized. This makes the deconvolution process rather complex. Therefore, at this stage we chose to image on the meridian only. The scanning in right ascension is provided by the motion of the earth.

At the MRT, we are imaging a very large field of view, ~ 60°, with a non-coplanar 'array. For such an array, the brightness distribution is not a three-dimensional Fourier transform of the visibilities. We use two different methods of transforming the visibilities to brightness at the MRT. The first one uses a combination of the FFT along the north-south track (y axis) and direct phasing along the z axis. In this method, the parts of the north-south track with different slopes are treated separately (we assume that the y axis is uniformly sampled). The second one uses only direct phasing - a brute-force approach. There are no assumptions made about uniform sampling here but this method is somewhat expensive in terms of computer time. The images presented in this thesis were transformed by using the second method. The measured heights and distances along the track were used without assuming any particular value for the slope of the track and without assuming a uniform sampling of the visibilities in any direction. Therefore the different parts of the track with different slopes are not treated separately.

Images were made using data collected over **2** years. Separate images for each day of observation were made and these were later combined. The images were calibrated using MRC 1932-464 with an assumed flux density of 87 Jy at 151.5 MHz. Different zones were calibrated by applying the phase expected for the different band-centers obtained from the laboratory measurement. Errors in the time stamping and in antenna position were estimated by comparison of the instrumental phases obtained through calibrators at different zenith angles. Direct phasing of the visibilities was used for transforming the visibilities measured using non-coplanar baselines to brightness distribution. We applied a running .mean average (boxcar) of 4 seconds on each image. Interference excision was incorporated at this stage by giving zero weighting to the points corrupted by interference.

At the MRT, different visibilities are measured on different days which have to be combined appropriately to get the final images. The observations were divided into 10 blocks each covering 90 m of the north-south baselines. In each block six allocations of 15 trolleys spaced at 6 m are used (inter-trolley spacing of 6 m is to avoid the shadowing of one trolley by the next). After obtaining data for 24 sidereal hours in one allocation the trolleys are moved by one meter. Therefore, after 6 consecutive allocations we get visibilities measured over 90 m with 1 m spacing. Therefore, for 10 blocks we need to observe with 60 allocations.

To take into account precession of the images on different days, we make the images on different days separately[2]. The errors due to precessing dirty images cause the sidelobes to be precessed differently from the source. We cannot avoid this as our observations with different baselines are on different days. We regrid the images to a common epoch before adding them to get the final map. The common epoch is chosen to be close to the midpoint of the observations.

The other problem related to combining the data is due to different bandwidth decorrelation at different positions along the north-south direction. For block-1 and block-2, the visibilities are measured with only one delay setting. For block-3 there are 2 delay settings, for block-4 there are 3 delay settings and for block-5 onwards there are 4 delay settings. We have made four sets of images by combining block-1 and block-2 data with different delay zone data in block-3, block-4 and block-5. To keep the average bandwidth decorrelation

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[2] Combining the data for a block of data would not cause any serious errors due to precession and bandwidth decorrelation. However, other than saving hard-disk space there is no particular gain in doing so with the present direct phasing algorithm used for transforming the visibilities to brightness. In fact having images on different days separately provides an additional check-point in the processing stage.

to less than 5%, we made four sets of images by combining images of block-1 and block-2 with images from appropriate delay zones in block-3, block-4 and block-5 (Section 4.4). The different zone combinations are summarized in Table 4.3.

Images and their analysis

A one hour region around the calibrator MRC 1932-464 with the full declination range of the MRT has been imaged with a resolution of $4' \times 9'.2 \sec(\delta + 20^\circ.14)$. We particularly chose the region near the calibrator MRC 1932-464 for the first full-declination images using the recirculator data from the MRT. This helps us in the flux density calibration of the image. Comparison of the estimates of the flux density and the positions of sources from this image with the existing data helps us gain confidence in various tools developed for imaging. The different stages of processing the visibilities are summarized in chapter 5.

We have carried out some preliminary analysis of these images. The noise in our image was estimated and compared with what is expected. To estimate the noise in these images, we selected regions which appeared to be devoid of sources. The RMS measured in several such regions were then averaged to get an estimate of the noise. This is about 550 mJy. To calculate the system noise one needs to know the system temperature. An estimate of the brightness temperature at the RA imaged was obtained by convolving the 408 MHz image of Haslam *et.al.*[9] with the beams of the elements of the interferometer (east-west group and a north-south trolley). A temperature spectral index α_T ($T \propto \nu^{-\alpha_T}$) of 2.7 for regions away from the Galactic plane was assumed to get the brightness temperature at 151.5 MHz. A system temperature of 1200 K is obtained at the RA of 19hrs. This gives the expected noise in the images to be about 300 mJy. Since the images under consideration are not deconvolved there will be contributions from the sidelobes of various sources in the estimation of the RMS noise in the images. To estimate the contribution from the sidelobes of sources, we formed an image in the RA range 19h02m to 19h52m by convolving all sources listed in the MRC with the synthesized beam of the MRT. Sources in the RA range 18 hrs to 21 hrs and in the entire declination range of MRC ($-85° \leq \delta(1950) \leq -18.5°$, $|b| \geq 3''$) were used. We chose sources from a region much larger than the region of interest to minimize edge effects of convolution and to ensure inclusion of sidelobes of sources which are outside the region imaged. We find the contribution due to the sidelobes to be ~80 mJy in regions away from bright sources. The contribution to noise from undetected interference is estimated to be about 300 mJy. The total noise in the image due to contributions from receiver noise, sidelobes of sources, undetected interference and confusion is expected to be 450 mJy. We therefore have 20% more noise in the images than expected.

We estimated the position and flux densities of the MRC sources in our image. For this, the expected (theoretical) two-dimensional beam was least-square fitted around the position of the point sources given in the MRC. We have been able to detect in the MRT image, all the 54 sources listed in the MRC catalog in the RA range 19h02m to 19h52m (J2000 coordinates) which are expected to have a flux density $S_{150} \geq 3$ Jy/beam (5σ) in the MRT field of view. The positional discrepancies in declination are within 2 arcmin. The positional discrepancy in RA is within 0.8 arcmin. We find no systematic errors in position of the declinations and of the right ascensions. We also carried out positional analysis on artificial point sources of various strengths which were added to the images at different places. The errors in these detection were within **1.5** arcmin in declination and **0.7** arcmin in RA. From the ratios of the measured flux to the expected flux we have estimated the primary beam of our helix. We find this to be close to the expected primary beam. The deviation is less than **10%** in the declination range of interest. From the flux density measurements, we have also estimated the bandwidth decorrelation in these images. The bandwidth decorrelations estimated are mostly within **10%** of the expected decorrelation. The images made for the different delay zones and the results of preliminary analysis carried out on these images are given in Chapter 5.

We have been able to detect a number of sources which are not listed in the MRC. A detailed study of these sources will be undertaken in the future and will hopefully produce some interesting results.

6.1 Scope for future work

The images presented here are dirty images. There are some tasks that still need to be done in the image processing to get the final images with the expected sensitivity and dynamic range.

- Improving the Calibration: The calibration process is particularly limited by the calibration scheme used so far. We need to improve on the present technique to improve the dynamic range of the images.

  Instead of using a single source calibration we need to do a 'field of view' calibration which would take into consideration contribution of several sources in the field of view. Since the flux and positions of sources are not known at this frequency, there is a need to produce an initial image with the final resolution and make estimates of the position and flux densities of the sources and use them in the calibration process. The process may require more than two iterations of calibration and imaging.

As mentioned earlier, in the second round of observations we have acquired data in the NS x NS mode and in the EW x EW mode to enable us to carry out redundant baseline calibration. Using this data could improve our calibration process and would be independent of the knowledge of source structure and position. However the limitations due to the baselines not being entirely redundant because of height variations and due to variation in bandshapes need to be considered for understanding the limitations of this technique at the MRT. Unequal bandshapes also limit the use of closure phase in calibration and in deriving antenna based gains from baseline based gains.

- Deconvolving the Images: The deconvolution process for the MRT images is complicated mainly due to three reasons discussed in chapter 4. 1) The non-coplanarity makes the beams different for different declinations. 2) The PSF also varies with declination due to different decorrelations. 3) The effect of precession on the PSF. There is another factor we need to look into, i.e., the effect of grating response due to the helices being spaced 2 m apart in the groups which affects some RAs of our image (Chapter 4). All these factors can be corrected for in principle. However, incorporating these in the deconvolution scheme is time consuming and laborious. Also, standard deconvolution tools available in softwares like AIPS cannot be used and we need to develop our own software.

- 2-D synthesis: To improve the sensitivity so that the noise in the images reach the confusion limit, we need to image the full 2° available[3] instead of imaging only at the transit. Imaging away from the transit would require the deconvolution scheme to take into account the variation of the synthesized beam with hour angle (Chapter 4).

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[3] The FWHM of the beam of an east-west group.

Journal abbreviations

The abbreviations in most cases follow that of the NASA Astrophysics Data System.

- A&A...... Astronnmy and Astrophysics
- A&AS..... Astronomy and Astrophysics Supplement Series
- AJ........ Astronomical Journal
- ApJ....... Astrophysical Journal
- ApJS...... Astrophysical Journal Supplement Series
- AuJPA..... Australian Journal of Physics Astrophysical Supplement
- AuJPh..... Australian Journal of Physics
- El........ Electronics
- ITAP...... IEEE Transactions on Antennas and Propagation
- JApA...... Journal of Astrophysics and Astronomy
- MNRAS..... Monthly Notices of the Royal Astronomical Society
- Natur..... Nature
- PIRE...... Proceedings of the Institute of Radio Engineers
- RaSc...... Radio Science
- RSLPS-A... Proceedings of the Royal Society of London, series A

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