AT OPERATION AT MILLIMETRE WAVES

PROGRESS REPORT FOR USERS

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1. Introduction

In an earlier document (Hall, P. J.: *Millimetre Wave Capability for the Australia Telescope: A Discussion Document for Users*, April 1991) some of the scientific, technological and educational benefits of a millimetre wave program for the AT were outlined. The commitment to such a program has now been made and it is timely to report early progress to the user community. Furthermore, the next part of the program requires some CA and Mopra time allocation, so it is proper that users receive advance notice of the proposals.

At the outset we recognise that the low-altitude Narrabri site is far from optimum for mm-wave interferometry. In addition, our antennas, Telescope systems and operations strategy will all need attention if we are to make the CA a workable millimetre instrument. Considerable effort will therefore be required to make the upgrade successful but the potential gains are enormous. The CA 15-m antennas with their unique southern sky outlook give us a telescope which is likely to equal or exceed the scientific utility of any operating instrument. Since it will be some years before plans for other southern mm-wave interferometers are finalised and even longer before the instruments are operational, the AT "window of opportunity" is real. Appendix 1 is a summary of important CA mm-wave specifications.

The Mopra Observatory also has an important role to play in the AT millimetre program. In the short term it has the potential to accomodate much of the over-subscription on the ESO SEST instrument in Chile. This, combined with its role in cm-wave and future mm-wave VLBI, its role in the SETI program, and its stand-alone capability for specialised cm-wave programs, should ensure a healthy future.

2. The Story So Far

The ATNF millimetre efforts are presently centred on two observatories: Narrabri and Mopra. At Narrabri a team is undertaking site surveys and antenna tests to determine the feasibility of using the Compact Array as a 3-mm band interferometer. Peter Hall and David Abbott have been conducting atmospheric measurements, while Michael Kesteven, Mark Wieringa, David McConnell, Du Hong and Ron Beresford have been involved with the antenna tests. Turning to Mopra, a team led by Graham Moorey is developing a 3-mm band spectral line receiver scheduled for installation and testing in the second half of 1993. This receiver will also be the prototype for any future CA receivers. A secondary project for Mopra involves the possible installation of the VLBA spare 7-mm band receiver in late-1993. This receiver would be used in conjunction with part of the VLBA to observe the galactic centre with micro-arcsecond resolution.

3. Narrabri Testing To Date

In mid-1991 the ATNF began a collaborative atmospheric opacity monitoring project with Telecom Research Laboratories (TRL). TRL has supplied a 30-GHz water vapour radiometer which will remain at the Observatory until mid-1993. Although the particular radiometer in use is not ideal for measuring the low opacities of interest to astronomers, valuable preliminary data have been obtained. The results are summarised in Appendix 2. In essence the opacity measurements indicate a stable and relatively transparent atmosphere during winter nights. In the past year July and August were the best months. We estimate that on about 12 nights spread over these two months, "straightforward" 3-mm band synthesis would have been possible. In other words, 12-hour sessions requiring no special phase calibration techniques could have been conducted. With more sophisticated observing methods (e.g. phase correction using line-of-sight water vapour measurements or calibration based on simultaneous 3-cm and 3-mm observations) a much higher proportion of the time would have been usable.

Early results from interferometer tests indicate that, in spite of the low altitude of the Narrabri site, the atmosphere displays no un-anticipated turbulence characteristics: the phase versus baseline behaviour is quite similar to that noted at, for example, the VLA site. More extensive atmospheric monitoring and modelling is necessary to arrive at firmer conclusions, and to plan optimum calibration and phase correction strategies; proposals are discussed in the next section.

As well as site tests, an antenna metrology program has centred around producing rapid Fourier ("holographic") measurement methods with a spatial resolution sufficient to allow identification of at least individual reflector panel setting errors. The new antenna control computers have proved essential in tackling programs of this nature and will be increasingly valuable as the metrology becomes more ambitious. Most measurements to date have been done using strong cosmic sources although some use has been made of out-of-band 4-GHz satellite signals. Measurements have been signal-to-noise limited but results indicate that although panel setting errors of up to 1 mm are present, the rms surface deviations are of the order of 200-300 micron, making the antennas usable in the 3-mm band. With more precise panel adjustment, considerably better results should be achievable. Significantly, indications are that the antennas deform only slightly under varying gravitational loads. Appendix 3 discusses some early results.

Attempts to produce more accurate antenna pointing models are also being made and inclinometers have been installed on CA02 and CA05. While there is scope for much more work, early indications are that absolute pointing errors of < 10 arcsec. rms should be attainable.

It is also worth noting that with the commissioning of CASNAP, the on-line processing, reduction and display program, our capacity to share data conveniently between telescope applications will increase considerably. For example, we envisage calibrator visibility data being shared between astronomy, engineering or system test tasks. Our capability for on-line "tweaking" should also improve. It may be possible, for example, to assess quickly whether the phase corrections made on the basis of columnar water vapour measurements have improved (or worsened!) the situation.

Appendix 4 gives a brief description of CASNAP as it currently exists, the likely development paths, and some possible uses for the program.

4. The Mopra 3mm Spectral Line Receiver (details courtesy of G. Moorey)

This receiver is a dual channel, beam-switching, type, remotely tunable across the range 80-115 GHz. The front end stages will employ SIS mixers manufactured by NRAO and it is anticipated that system temperatures of <180 K for each polarization (combined $T_{sys} \sim 130$ K) will be obtained at Mopra. The instantaneous bandwidth is 600 MHz, corresponding to a velocity coverage of 1800 kms^{-1} at 100 GHz. Spectral data will be acquired via a standard AT single-dish digital correlator having a maximum bandwidth of 250 MHz. Longer term plans include the provision of extra correlator bandwidth and the installation of an acousto-optical spectrometer.

At present the design of the receiver optics and the dewar internal arrangement is being finalised. A large part of the 4 K cryogenic system is complete and work is continuing on adapting a new type of compressor to the AT installation. It is hoped that much of the hardware developed for use in the lower frequency AT receivers can be incorporated into the new package, resulting in considerable savings in development and manufacturing time. At this stage the the target for initial tests is around August 1993.

5. Further CA Tests

The next year or so can be used very profitably to continue the site and system evaluation tests at Narrabri and to begin the formulation of plans for atmospheric phase correction (or calibration) and flexible scheduling. In the list below we have attempted to identify the main issues, to propose strategies and where possible, to estimate the time required or the impact on Telescope users. Note the reliance on scheduled system test (ST) time for many studies.

• *Site Testing*

We plan to continue the atmospheric opacity measurements, probably using a new radiometer of our own design. As well, some systematic evaluation of the phase perturbing properties of the atmosphere above the Observatory is required. While it is possible to extrapolate single radiometer water vapour measurements to interferometer phase perturbations (as the MMA site survey has done), it is necessary to first acquire much more array data as a reference. Accordingly, we will be seeking allocated time on the CA to perform phase stability measurements and measurements relating to the phase variability with baseline length and time.

The time required will be of the order of 8 nights per month spread over 3-4 months starting in April 1993. During dry winter weather we will also be asking that 6 and 3-cm observers observe calibrators for up to 30 minutes at intervals of a few hours so that even more phase stability data can be extracted.

In the longer term (1994) time will be sought to assess the effectiveness of water vapour radiometry as a means of real-time path length correction. The idea is to eventually have radiometers on each telescope, allowing the differential atmospheric path length seen by the array elements to be estimated rapidly. As well as this study, we hope to assess the feasibility of performing simultaneous or near-simultaneous 3-mm and (for example) 3-cm observations of the same field, an observing strategy which should often permit more precise phase corrections to be made during processing.

• *Antennas*

The antenna metrology program will be expanded and we hope to have two 12-GHz Optus (formerly Aussat) receivers available for our tests in the new year. Development of the software is proceeding and a complete package should be available in early 1993. ST time will be used to perform initial measurements but we will seek additional time on at least two antennas for trial panel adjustments. In the longer term it may be possible to use 30-GHz Optus receivers, allowing more accurate antenna assessments.

As well as the metrology, a systematic study of antenna pointing will be undertaken. This will involve using astronomical data and data from sensors (e.g. inclinometers) in an attempt to model more precisely the antenna pointing characteristics. Studies of antenna pointing as a function of, for example, temperature will also be done. It is likely that time allocated for other purposes can be used for many pointing studies.

• *System and Scheduling*

ST time will be used to perform evaluations of the electronic and mechanical sub-systems critical in mm-wave work. For example, the suitability of the LO reference, distribution and antenna-based generation system will be examined. These measurements are difficult to make and are likely to be disruptive, so are best undertaken during test periods.

Use of the CA at high frequencies will require a much more flexible observing schedule than the type now used. It will be necessary, for example, to interchange mm-wave and cm-wave programs at short notice (most usually on the basis of prevailing or predicted weather). Fortunately the engineering of the AT makes this fairly easy; the logistical problems associated with scheduling are more difficult. In fact, it may be the scheduling requirement that finally forces us to employ operators or develop a remote observing capability. It is likely that experience with the flexible scheduling required for the 1993 tests will be valuable in determining our long-term strategy.

6. Conclusion

The next few years will see considerable effort in site characterization, development of mm-wave hardware, and the formulation of observing and scheduling strategies. System test time allocations will become increasingly valuable and requests for allocated observing time (amounting to perhaps 32 winter nights in 1993) will be also submitted to the Time Assignment Committee. In addition, the co-operation of 3 and 6-cm band observers will be sought in observing phase calibration sources for slightly extended periods during the winter season.

PJH, 11/92

APPENDIX 1

BRIEF CA SPECIFICATIONS AT 3 mm

• Individual telescope diameter	15 m
• Primary beam ("field of view")	43 arcsec.
• Synthesized beam (3 km baseline)	0.2 arcsec.
• rms sensitivity (mJy, 5 dishes)	~ $(68/\sqrt{BT})$ (B in MHz; T in min.)

(assumes Tsys ~ 150K, 2 bit correlation, 2 IFs, 60% aperture efficiency, point source)

For B = 128 MHz, T = 10 s,	rms = 15 mJy
T = 1 min.,	rms = 6 mJy
T = 10 min.,	rms = 2 mJy
T = 12 hr.,	rms = 0.2 mJy

(c.f. MMA specification of ~ 1 mJy for 1 min. at 115 GHz)

PJH, 11/92

APPENDIX 2

FIRST RESULTS OF NARRABRI SITE TESTS

Contributed by P. J. Hall and D. A. Abbott

1. Introduction

The opacity of the atmosphere above the Paul Wild Observatory has been monitored using a 30 GHz water vapour radiometer on loan from Telecom Australia. The radiometer has been in use since September 1991 and, except for about 4 weeks down-time due to technical problems, data have been recorded continuously. In this first report we do not attempt to summarise all data but rather to distill the component most relevant to AT users. In particular, the results presented are for night-time hours of the coldest months. While our overall results show that other times may be usable for 3 mm observations, this block of time is the most favourable. As well as the water vapour data, a limited amount of Compact Array data relating to atmospheric phase stability tests has been analysed; early indications are that the power-law phase versus baseline relationships established at other observatories apply to the relatively low-altitude (205 m above mean sea level) Narrabri site.

2. Results

Opacity data from the 30 GHz radiometer have been scaled to yield 100 GHz values according to the model proposed by Liebe (*Rad. Sci.*, **20** (5), 1985, pp. 1069-1089). At the low opacities of interest to astronomers the model is quite accurate and, if anything, slightly over-estimates the 100 GHz opacity.

Figure A2-1 shows the fraction of time that the 100 GHz night-time atmospheric opacity is less than a given value at Narrabri for the months April - October 1992. Also shown is a representative plot for the proposed NRAO Millimeter Array site of South Baldy, New Mexico (elevation 3200 m). The best months at Narrabri were clearly July and August; the advantage of the much higher South Baldy site is obvious.

Figure A2-2 is an attempt to estimate the number of nights when the atmosphere at Narrabri was stable, at approximately the ±2% 100 GHz transmission level, for a period of 12 hours or more. We have shown the data in histogram form since we suspect that nights with overall atmospheric transmissions greater than 75% form the usable times for aperture synthesis using only conventional (cm-wave style) calibration procedures. Of course, much more time is probably usable with more advanced techniques.

Figure A2-3 is a first attempt at assessing the phase structure of the atmosphere at Narrabri. The plot shows interferometer phase fluctuation as a function of baseline for a six-hour period (1500 - 2100 UT) on July 7, 1992: a night available to us for system test purposes. This night would not have been selected as a particularly good millimetre-wave observing night on the basis of water vapour radiometer data. Furthermore, the array configuration in place at the time did not yield many shorter spacings. Despite this, the plot obtained is rather similar in form to that noted at, for example, the VLA or Nobeyama. The widely-used Kolmogorov model for turbulence seems to fit quite well, with the initial power-law slope in the Narrabri data being ~0.6 and the outer scale length being ~2 km. Much more data is needed but it appears that, for the <1 km baselines dictated by source brightness considerations at 100 GHz, the turbulence behaviour is not anomalous.

3. Future Work

We propose to continue the atmospheric monitoring program for at least two years. The intention is not just to acquire statistics but to use the results to formulate phase and amplitude calibration techniques. The results of this work may have eventual implications for the CA receiver design (e.g. provision of simultaneous 3 mm and cm-wave observing). In the coming year we see a need to make much greater use of interferometer phase measurements, hence our time requests outlined in the main body of this report.

In the next few months we will begin development of a new type of precision water vapour radiometer. This instrument, based on a switched front-end and a digital back-end, will be much more suitable for ATNF site survey purposes than the existing Telecom instrument. The design will also be the prototype for radiometers which could eventually be fitted to the CA antennas, allowing at least coarse on-line phase corrections (based on columnar water vapour measurements) to be made.

Percentage Time Opacity Is Less Than Given Value (09:00-21:00 UT)

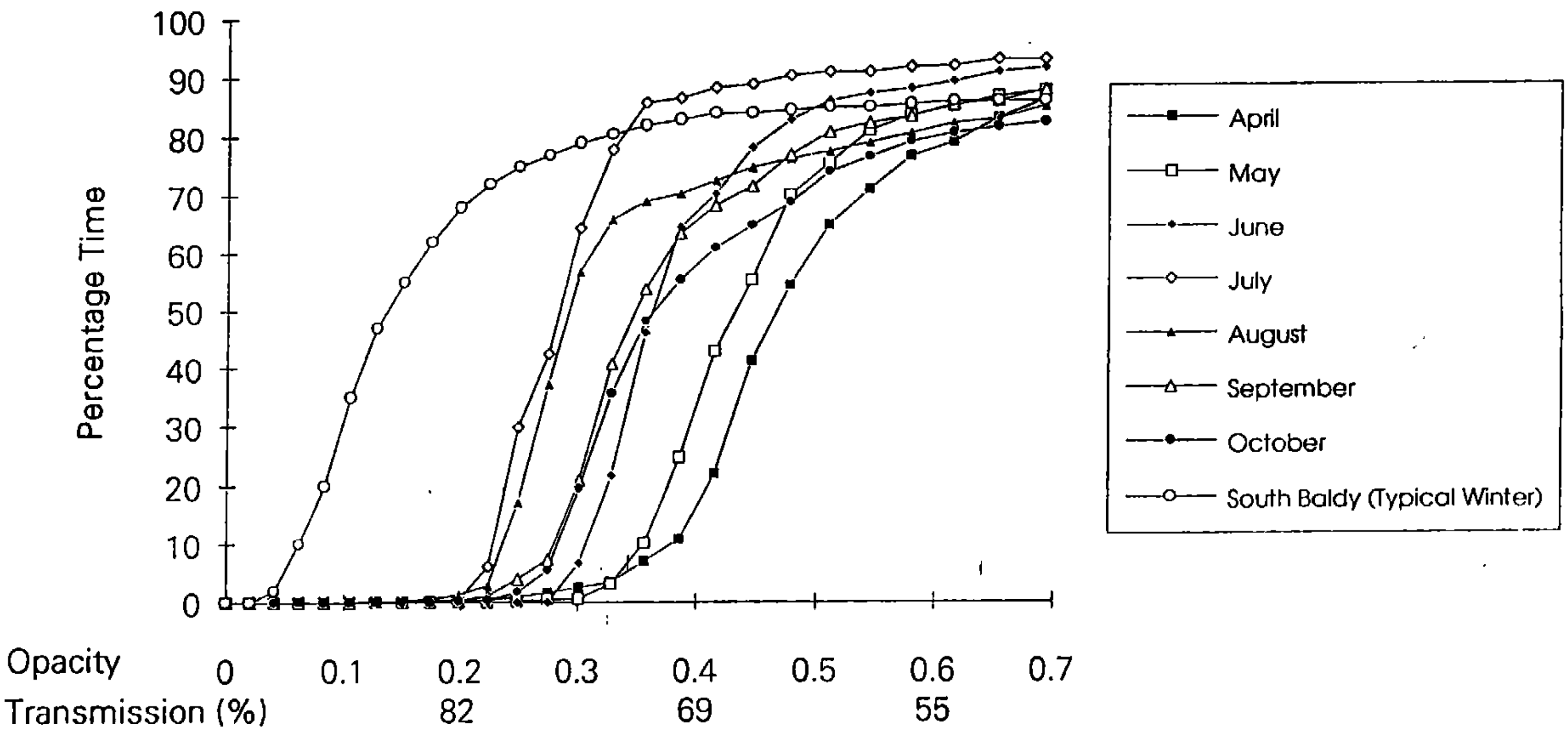

Figure A2-1. Plot showing the fraction of time for which the opacity at Narrabri is less than a given value. The data are for night-time periods from April - October 1992. Also shown is a typical winter result for the proposed MMA site at South Baldy, New Mexico.

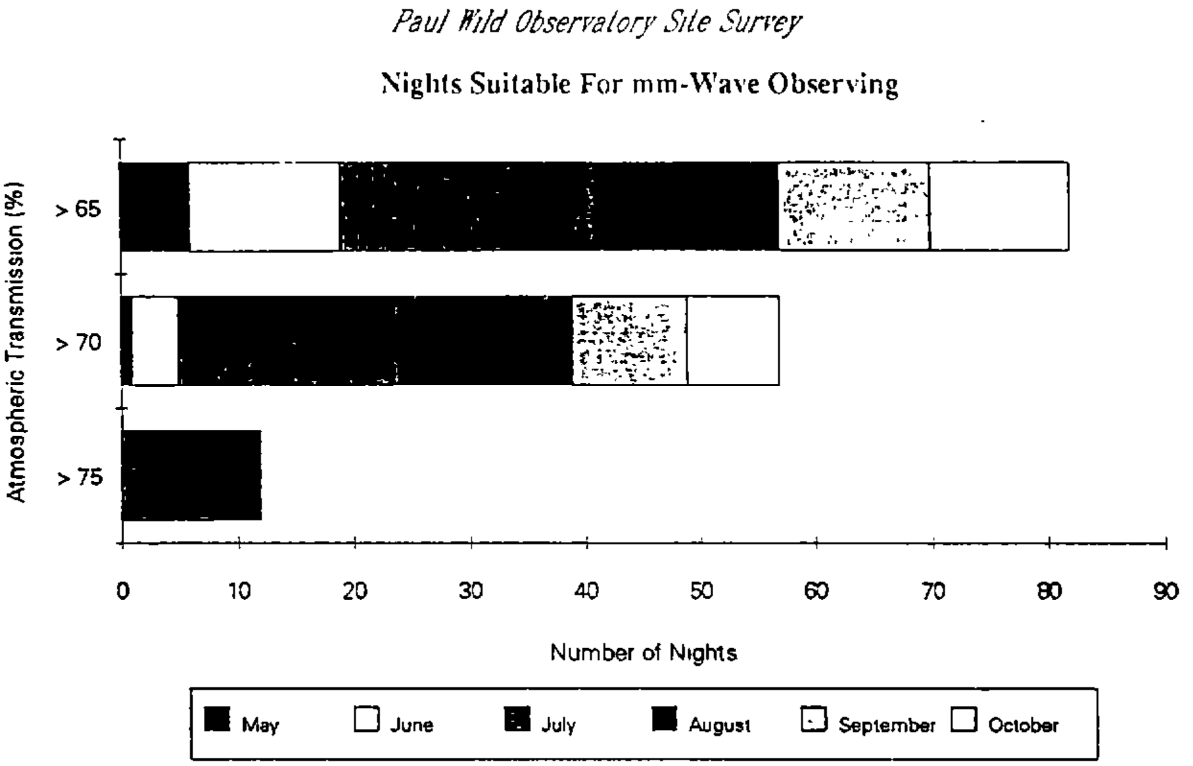

Figure A2-2. Histogram showing the number of nights for which the 100 GHz atmospheric transmission at Narrabri remained stable to within ±2%. Data are grouped according to overall transmission.

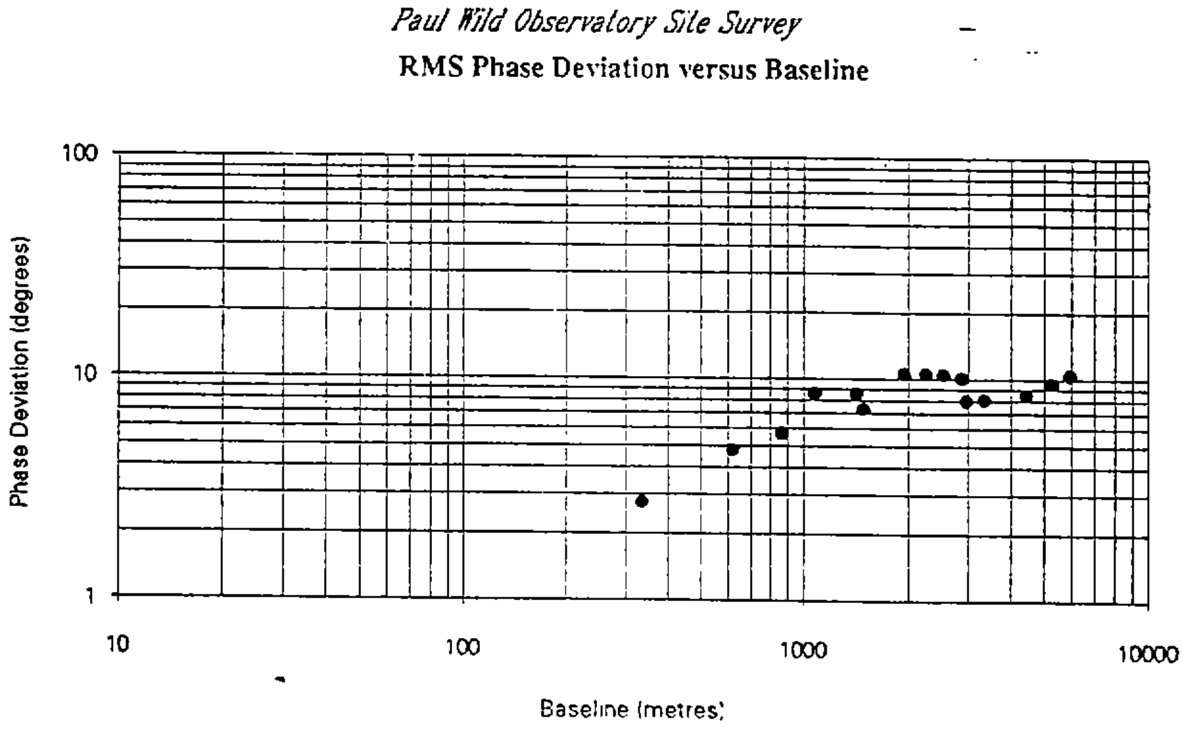

Figure A2-3. Plot of CA rms phase versus baseline for the period 1500 - 2100 UT on July 7, 1992. The initial slope is ~ 0.6 and the turnover point is ~ 2 km.

APPENDIX 3

HOLOGRAPHY OF THE AT COMPACT ARRAY ANTENNAS

Contributed by M.H. Wieringa and M.J. Kesteven

Summary

We have made measurements of the surface accuracy of the AT CA dishes using "holography" techniques on astronomical sources. First results, for CA03 and CA05, indicate panel setting errors of up to 1 mm, with most effects spanning more than one panel. The overall rms errors are presently about 300 micron; within an inner 8 m radius the errors are around 200 micron. Thus, even with no adjustment the antennas would be usable for observations in the 3 mm band. Significantly, we detect no obvious gravitational deformation at the 200 micron level.

1. Introduction

Over the past year we have made several attempts at obtaining good quality holographic measurements of the AT CA dishes. In this technique one antenna (the reference) points at the source while the other antennas point away from the source. We used a variant of the mosaicing mode of observation to measure the correlated signal between the reference antenna and an offset antenna on a rectangular grid in azimuth and elevation. Fourier inversion of this grid of measurements, after correction for phase slopes and pointing errors, gives a direct measure of the path length errors over the dish. Taking into account the curvature of the dish, these path lengths errors can be transformed into a map of the surface deviations of the dish.

2. Observations and Reduction

The first successful observations with a large grid were made on the 25 and 26th of September 1992, a night with very stable atmospheric phases (<20 degrees variation over several hours). We observed the calibrator 1934-638 twice, at elevations of around 50 degrees and 36 degrees. As well, we observed 3C84 once at 17 degrees elevation. The observations were done at 3 cm (8.6 GHz, 128 MHz bandwidth), using an 8 s integration cycle of which 3 s (during which the antennas moved to the next point) was blanked. We measured grids of 25 x 25 points with a gridstep of 5 arcminutes: one primary beam at 3 cm. CA01 and CA02 were not operational at the time of the observations; CA04 was used as the reference antenna. The results for CA06 suffer from larger atmospheric phase fluctuations due to its large distance from the reference.

The observations on 1934-638 are signal-to-noise limited (S/N ~ 400) while those on 3C84 are limited by the effect of atmospheric phase variations (2-3 degrees per point); the signal-to-noise on 3C84 was 3000. These limits translate to surface errors of ~100 micron.

We measured the grids in elevation strips of 25 points, with an "on source" integration of 4x8 s between strips. We processed the data using ATNF AIPS.

First we calibrated the amplitude and phase using the "on source" data. Subsequently we used the ATNF AIPS task HOLGR (Kesteven, Calabretta) to correct the calibrated visibilities for offsets, pointing and phase slopes and to produce the surface illumination and deviation maps. A slight gaussian taper was applied to reduce edge effects. The resulting maps have a resolution of 1.25 m; the smallest panels of the CA dishes measure about 1 x 1.5 m. A set of lower resolution maps (2 m) was also made to investigate large scale effects.

3. Results

To reduce the noise in the maps made using 1934-638 we averaged the data from the two elevations, giving slightly better maps for an average elevation of 43 degrees. Fig. A3-1 shows the illumination pattern of the CA03 dish at 17 degrees elevation. The central blockage and the effects of the support legs for the secondary are clearly visible. Note that the illumination is quite strongly tapered: the average illumination over the dish is about 60 percent of the peak. In Fig. A3-2 we show the surface deviation maps for 43 degrees elevation (using 1934-638). The maps made using 3C84 have slightly lower noise levels but are for the less typical elevation of 17 degrees; they are shown in Fig. A3-3. Results for different elevations and using different sources show quite good agreement, giving us confidence that the effects seen are real.

The maps show several areas with deviations of 0.5 to 1.0 mm. For CA03 three low panels are visible at the upper left edge of the dish, and high areas are visible about two thirds out from the centre in both vertical directions. The map for CA05 seems to indicate a whole ring of panels (4th ring from the centre) which is 300 to 500 micron higher. For both CA03 and CA05 there are also quite large effects visible in the innermost ring of panels.

The overall rms deviation of the CA03 and CA05 dishes is about 300 micron. An rms weighted with the measured illumination gives a similar value. The rms in the inner 15 m of the dishes (and excluding the central area and the support leg areas) is about 200 micron. With some panel adjustments a factor of two improvement seems easily achievable.

To look for possible large scale gravitational deformation effects we made difference maps between 43 and 17 degrees elevation. No obvious warping or other deformation is visible in these maps at the 200 micron level. There is some indication of deformation at the outer edge (200-400 micron), but most structure in these maps lies in the low S/N areas below the support legs.

4. Future work

To be able to start improving the surface accuracies of the AT CA antennas we will need at least one new set of observations where we displace one or two panels by a known amount. This will allow us to calibrate both the oriention of the maps and the direction and magnitude of the adjustments needed. For the final panel setting we need more accurate measurements than is possible using astronomical sources. In practice, we will use 12 or 30 GHz observations of a geo-stationary satellite beacon to improve the S/N ratio. To reduce the effects of atmospheric phase fluctuations we will observe in the most compact configuration and do the observations as quickly as possible (i.e., shortest time between calibrations). For measurements of the Mopra antenna, a small reference dish will used and special arrangements made to record the correlated signal.

5. Conclusions

We have done an initial survey of the surface accuracy of three of the AT CA dishes. Without adjustment the surfaces are good to about a tenth of a wavelength at 3 mm and even to a fifteenth in the inner 15 m section of the primary reflector. Using the results of high quality holographic measurements to guide panel adjustment should yield at least a factor of two improvement. Importantly, we have also found that there are no large gravitational deformations between 43 and 17 degrees elevation. Thus, the surface accuracy of the AT CA dishes will not seriously limit the performance of the proposed 3 mm interferometry system.

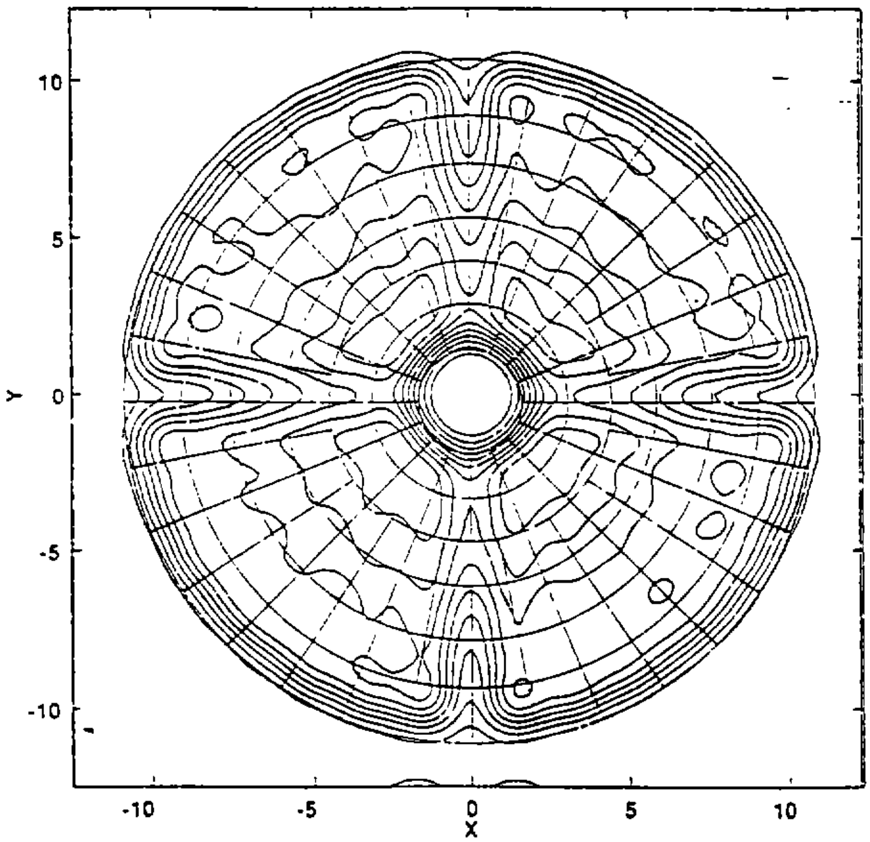

Figure A3-1. The illumination pattern for CA03 at 17° elevation (3C84 observations). The scale is in arbitrary units; contours are at 10, 20, ..., 90% of the peak illumination.

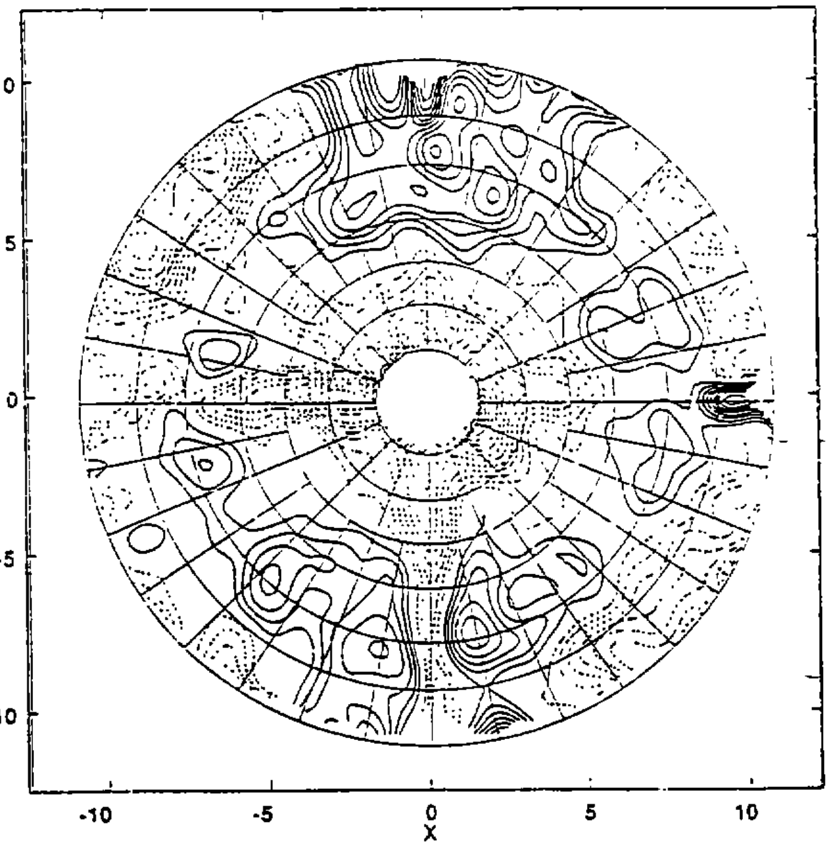

Figure A3-2. Surface deviation of CA03 at 43° elevation (two observations of 1934-638). Contours are at multiples of 100 micron; dashed and full contours indicate deviations in opposite directions.

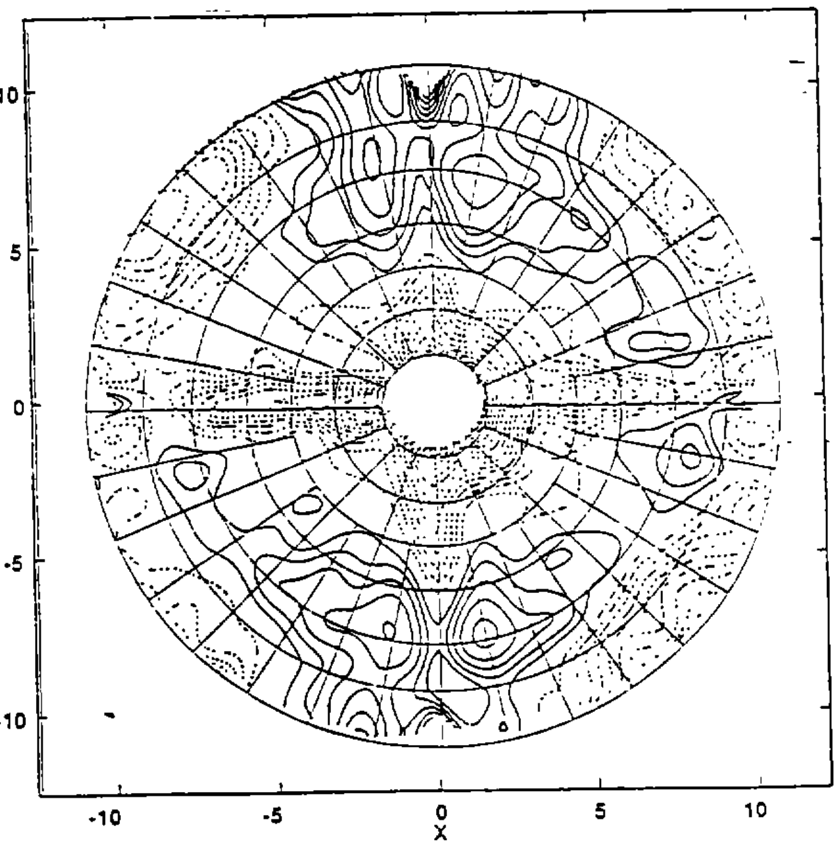

Figure A3-3. Surface deviation of CA03 at 17° elevation (3C84 observations). Plotting convention as for Fig. A3-2.

APPENDIX 4

ON-LINE DATA ANALYSIS AT THE COMPACT ARRAY

Contributed by D McConnell

Summary

The ability to analyse interferometer data is being developed as part of the on-line software at the Compact Array. Ultimately, a number of utilities will be available to telescope users, including short Array setup and calibration times, realtime characterisation of system performance (including the effects of the atmosphere), and one-dimensional imaging. The basis of this system has been established and a one-dimensional imaging program has been developed and is available for general use.

The System

There are three components forming the basis of the on-line analysis programs software.

Summaries of visibility data are computed by the Correlator Control Computer and transmitted to the Array Control Computer. These summaries are vector averages over some subset of spectral channels in each correlation product. The full correlator output is too voluminous to be transmitted on the computer network and is written directly to a FITS disk file. The summary data represents a reduction by a factor of at least 32 in the data volume and is easily handled by the network. The range of spectral channels to be averaged for summary data is selectable by the user.

Reticulation of summary data (in addition to antenna monitor data and observing status information) from the Array Control Computer to other "off-line" computers is performed by the task CADATA. This allows compute intensive tasks to analyse the data without interferring with the critical processes on the "on-line" computers.

Recording of summary data in a rolling buffer is performed by the task SNAP. The length of the buffer is sufficient to hold 12 hours of data. A new record is written to the rolling buffer each Array Synchronisation cycle (typically 10–15 seconds). The contents of each record are as follows.

Source name		
Calibration identifier		
Phase reference position		
Direction cosines of unit baseline vector	(u, v, w)	
Visibilities	$\{V_{ijk}\}$	i = 1..15 (baselines) j = 1..2 (polarisations) k = 1, 2 (frequencies)

One-dimensional Imaging

The program CASNAP (it produces snapshots) makes use of the data in the rolling buffer to estimate the one-dimensional distribution of intensity across the chosen field. The data from the two polarisations are summed before image formation. As the Fourier inversion involves only 15 complex quantities (per frequency), the gridding and FFT stages used in two-dimensional imaging are not required. A direct transform method is used. The CLEAN algorithm is used to provide an intitial estimate of the parameters of a model consisting of a number of gaussian sources. The parameters are then optimised using a function minimisation process. The object function is the summed, squared differences between model and observed visibilities.

The CASNAP program is being used to locate radio sources detected in the PMN survey of the southern sky. Those observations are being made at 6 cm with a bandwidth of 64 MHz. Experience shows that with no confusion, sources down to 15 mJy are easily detected. Amongst other outcomes, it is expected that the PMN survey study at Narrabri will greatly increase the density of known calibration sources in the southern sky. Figure A4–1 shows example output from the CASNAP program.

Applicability to mm-wave project

The on-line data analysis at the Compact Array promises a number of benefits to astronomers. For the mm-wave program, it will assist in the following areas:

site testing – access to data during normal operations will simplify the phase stability stage of site testing and assessment;

dynamic scheduling – on-line analysis of data will allow rapid assessment of mm-wave conditions and will be essential if dynamic scheduling is used to optimise Array efficiency;

calibration sources – the present PMN program will result in a greater number of potential phase calibration sources.

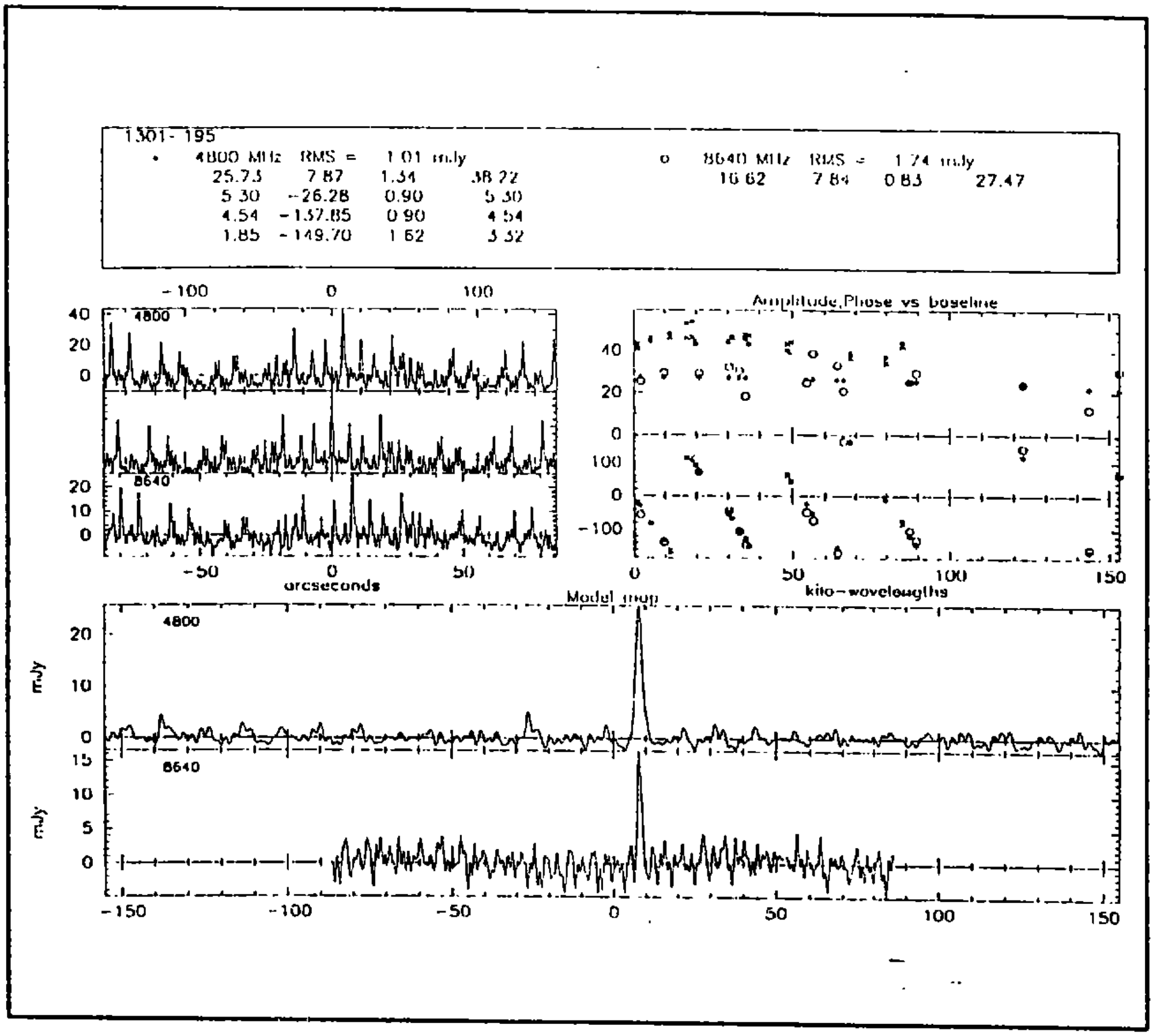

Figure A4–1 A sample output from the one-dimensional imaging program CASNAP for the field 1301-195. The observations were made in July 1992 with the '6D' Compact Array configuration as part of the PMN survey project. The centre-left panel shows the synthesised beam pattern and the 'dirty' maps at each of the two observing frequencies. At centre-right are plots of observed amplitude and phase as functions of projected baseline length. On the same plot the visibilities corresponding to the fitted model sources are shown as crosses. The bottom panels show the model source distribution. In the top panel, the fitted parameters of each gaussian model source are listed as peak brightness (mJy/beam), position relative to phase centre (seconds of arc), full width at half brightness (seconds of arc), and total flux density (mJy).