

THE PARKES-TIDBINBILLA INTERFEROMETER

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ABSTRACT

The Parkes-Tidbinbilla Interferometer is a radio-linked interferometer using the 64 m telescope at Parkes together with one of the NASA antennas (34 m or 64 m) at Tidbinbilla. With a baseline of 275 km, it is currently the world's longest real-time interferometer, and is usable at frequencies of 1.7, 2.3, and 8.4 GHz to give angular resolutions of $0''.13$, $0''.09$, and $0''.03$, respectively, with a sensitivity of 1–3 mJy rms in 3–15 minutes at a bandwidth of up to 10 MHz. Here we describe its design and construction and give some examples of astronomy programs currently being pursued using it.

Subject headings: instruments — interferometry

I. INTRODUCTION

The Australia Telescope (AT), which is due to be commissioned in 1988, consists of a 6 km compact array at Culgoora, in northern New South Wales, and a long baseline array (LBA). The latter includes the tied compact array, a new 22 m antenna at Siding Spring, and the 64 m antenna at Parkes. The LBA will also, on a collaborative basis, make use of the NASA antennas at Tidbinbilla and the University of Tasmania's 26 m antenna near Hobart, giving baselines up to 1400 km. Data from all of these antennas will be recorded using VLBI systems similar to those to be used for the Very Long Baseline Array in the USA, and the data will be correlated at the compact array site at Culgoora. A recent review of the AT LBA is given by Norris (1987).

The Parkes-Tidbinbilla Interferometer (PTI), to be described here, uses two of these antennas (Parkes and Tidbinbilla), together with a microwave link between them, to form a real-time single-baseline interferometer with a length of 275 km.

The PTI was conceived as part of the development of the AT, and has proved its value both as a test bed on which to tackle some of the problems that we will encounter on the AT and as a first step toward the construction of a frame of reference of calibration sources for the AT. It has also proved its worth as a powerful astronomical instrument, offering a combination of high resolution, high sensitivity, and the practical advantage of real-time operation.

First fringes were obtained on the PTI in a limited mode in 1985 June (Norris *et al.* 1985). Since then the system has been upgraded so that it uses two channels, each of which can be used at a number of bandwidths ranging in binary steps from 0.5 to 5 MHz. In § II of this paper we describe the instrument, and in § III we describe some astronomy applications.

II. THE INSTRUMENT

a) Design Features

A novel feature of the PTI is that many of the interferometer functions traditionally implemented in hardware are here

software-based. As a result, the PTI has been built at very low cost and with very little specially constructed hardware. For example, the phase rotator uses a standard programmable synthesizer, and the signals are correlated in the existing Parkes correlator, which was originally designed as an autocorrelation spectrometer (Ables *et al.* 1975). By measuring a full cross-correlation function over many delay channels, most of the fine delay and phase corrections may be performed by software after correlation rather than by hardware before correlation. Only coarse phase and delay corrections (needed to prevent decorrelation in the integration time) need be applied before correlation.

Figure 1 shows the interferometer in its standard two-band configuration (i.e., using two bands each of 5 MHz bandwidth). Other configurations are also possible, including a single-band mode used primarily for spectral-line work. Table 1 shows the principal observational parameters.

b) Antennas and Receivers

At Tidbinbilla there are three antennas available for use with the PTI. Two of these (DSS42 and DSS45) are 34 m antennas equipped with maser amplifiers for 2.3 and 8.4 GHz. The remaining antenna (DSS43) has recently been upgraded from 64 m to 70 m, and is equipped with low-noise receivers for 1.7, 2.3, 8.4, and 22 GHz. In each case, system temperatures are typically 30 K, and either sense of circular polarization may be received. All local oscillators at Tidbinbilla are locked to a hydrogen maser frequency standard.

The Parkes 64 m antenna is equipped with a variety of receivers and feeds, and for PTI use it is typically configured with cooled FET amplifiers at 1.7, 2.3, and 8.4 GHz, giving system temperatures of about 50 K. All local oscillators at Parkes are locked to a rubidium frequency standard, giving a coherence time of typically 10 minutes at 2.3 GHz. Operation at 22 GHz has also been tried briefly, and fringes successfully detected, but the stability of the present local oscillator system prevents effective use being made of this frequency.

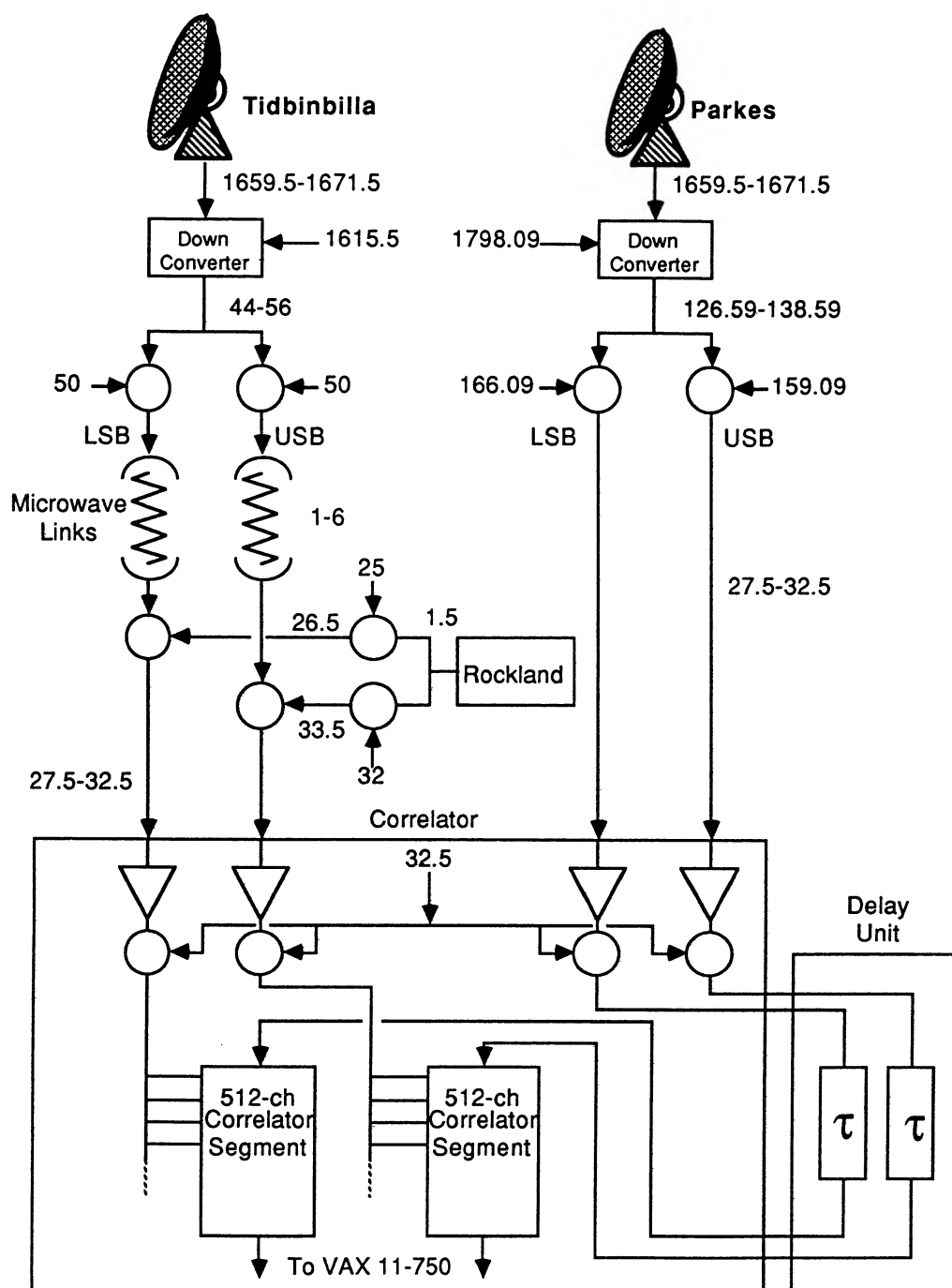


FIG. 1.—Block diagram of the PTI in a standard configuration using two bands, each of 5 MHz bandwidth, at a central frequency of 1665.5 MHz. Numbers on the diagram are frequencies in megahertz.

c) Signal Transmission

The intermediate frequency (IF) signal from the Tidbinbilla antenna is converted to video frequencies by a conventional down-converter system which is locked to the Tidbinbilla hydrogen maser, and limited to two bands, each extending from 1 to 6 MHz. Each band is then frequency-modulated onto a microwave link for transmission to Parkes. Two separate bidirectional microwave links originally installed by NASA for the *Voyager-Uranus* encounter are available, and

each of these carries a 1–6 MHz IF signal to Parkes. In addition, the bottom 5 kHz of one of them is equipped with two conventional 1200/75 baud modems to provide computer communications between Parkes and Tidbinbilla.

d) Phase Tracking

During each integration period (typically 2 s) the on-line software calculates the path difference between the signals traveling through the two arms of the interferometer and from

TABLE 1
PRINCIPAL OPERATIONAL PARAMETERS OF THE PTI

Parameter	Values
Baseline (km)	275
Available bandwidths (MHz)	0.5, 1.0, 2.0, 5.0, 10.0
Maximum spectral resolution	256 complex spectral channels
Frequency (GHz)	1.7, 2.3, 8.4
Resolution (fringe spacing) (arcsec)	0.13, 0.09, 0.03
Typical coherence time (minutes) ^a	15, 10, 3
Root mean square sensitivity (mJy) ^b ...	1, 1.5, 3

^aCoherence time is the estimated time taken for the phase to drift unpredictably by 1 radian.

^bSensitivity refers to the estimated rms noise in one coherence time using 10 MHz bandwidth and the 64 m DSS43 antenna at Tidbinbilla. Greater sensitivity for detection purposes may be achieved by averaging data taken over a longer period. The sensitivity using the 34 m DSS42 or DSS45 antennas is worsened by a factor of approximately 2.

this calculates the phase difference between the two signals. Because this phase difference is changing at a typical rate of tens of hertz, it is necessary to rotate the phase of one of the input signals before correlation.

This is achieved by mixing the Tidbinbilla signal with a local oscillator whose frequency can be accurately controlled by the on-line Parkes VAX 11-750 computer. This local oscillator is a programmable Rockland Model 5100 synthesizer operating at about 1.5 MHz, and it is incorporated in the conversion chain at Parkes, which converts the two base-band signals from Tidbinbilla to 30 MHz IF (see Fig. 1). The frequency of this synthesizer is adjusted every second in a phase-continuous mode by the on-line software, which addresses it using an IEEE-488 interface. To maintain a constant interval between updates of this synthesizer, it is addressed by a separate high-priority process, which is spawned by the main PTI observing program and which receives the required frequencies, and their derivatives, through a shared common area in the VAX memory.

Despite the separation of the synthesizer addressing from the main program, the times at which the frequency is changed will still be subject to small fluctuations. To prevent these small fluctuations causing random long-term phase drifts, the absolute phase of the synthesizer must be set to a known value at a known time. This is achieved by setting the phase of the synthesizer to zero at the start of each "scan," or period of observation. This is accomplished to a precision of a few nanoseconds by using a hardware event generator linked to the rubidium clock. The resulting phase steps, together with some second-order fine phase variations, are subsequently removed by the on-line software. The residual phase error is less than a few degrees.

e) Delay Tracking and Correlation

The microwave link from Tidbinbilla to Parkes inserts a delay of about 1.3 ms into the Tidbinbilla arm of the interferometer. A matching delay to compensate both for this and for the varying difference between the signal paths from the radio source to each of the antennas must be inserted into the Parkes arm of the interferometer in order that the "white-

light" fringe may be observed. This delay tracking is performed in three stages, as follows.

The signal from the Parkes antenna is converted to two base bands by a standard down-conversion scheme and the correlator frequency-conversion chain, all of which are locked to the rubidium standard. It is then one-bit-sampled and a coarse tracking delay is applied by a circulating-RAM delay unit with a resolution of a few microseconds. This unit is controlled by the on-line software to maintain the cross-correlation function (XCF) near the center of the delay range of the correlator, so that this first stage tracks the delay to a resolution of a few delay channels.

The Tidbinbilla signals are also converted to base band and sampled within the correlator, and then each of the Parkes signals is correlated with the corresponding Tidbinbilla signal in a 512 channel segment of the correlator. Because only a coarse delay correction has been applied, each of the two XCFs is allowed to drift through its 512 channel segment. However, every 2 s the on-line software calculates the position of the zero-delay fringe within the segment, and selects two 256 channel XCFs centered on this calculated delay, thereby tracking the delay in this second stage to a resolution of one delay channel. These two XCFs are then transferred to the VAX for subsequent processing.

Each of the resulting XCFs still contains a delay error of a fraction of a delay channel, which appears in the frequency domain as a phase gradient across the band. Each XCF is therefore Fourier-transformed into the frequency domain, where the third stage of delay tracking is performed in software by applying a phase gradient to the complex spectrum. The resulting complex spectra are then corrected for second-order instrumental effects, such as oscillator and clock offsets, and finally recorded on magnetic disks. The data are in the RPFITS format, which is a variant of the FITS format (Greisen and Harten 1981), adapted to make it suitable for on-line recording, and which will be used for data from the AT.

f) On-Line Software

All the observing processes described above are controlled by the PTI observing program which runs on the Parkes VAX 11-750 computer. The observing program (like all the other software described below) is driven from a multipage menu, so that all observing parameters are easily entered and checked. Once parameters have been entered into the menu, observing is started by entering one of a number of commands. Special attention has been paid to making the operation of the PTI user-friendly, so that in addition to the menus and a user's guide, on-line help is available in all the software.

The PTI can observe in a number of modes. In each of these the user may either specify the source position or else use a catalog command, in which case the observing program is able to obtain the source coordinates from the Parkes catalog or from a separate PTI catalog of calibrators. In the simplest mode the user then specifies the duration of the observation and gives a command to start. A second mode, source switching, allows the PTI to cycle automatically through a few sources. A third mode allows the PTI to read a schedule

from a file on the VAX, so that an extended set of observations may, once initiated, be left to continue automatically.

The observing program also has a number of shared common areas, which enables it to communicate with other programs running on the VAX. In addition to the phase rotator process described above, these include a MONITOR program, which provides real-time graphics displays of the data in several formats, and a COMMS program, which provides communications with Tidbinbilla via the modems described above. Through COMMS the observing program is able to send new source coordinates to Tidbinbilla and suspend observations until the Tidbinbilla antenna is on source, as well as performing other communications functions.

g) Off-Line Software

A suite of programs (LOOK) has been written for processing, analyzing, and displaying the data from the PTI. It is planned eventually to implement these functions in the AIPS package (developed by the National Radio Astronomy Observatory) for handling data from the AT; at present AIPS offers few facilities for handling single-baseline data.

LOOK offers facilities for correcting the data for atmospheric and ionospheric effects, as well as for changes to any of the source, baseline, or instrumental parameters used during the observations. It can also display the data in a variety of formats; can perform a number of operations, such as phase referencing upon the data; and can fit models or source and baseline parameters to the data. These capabilities will be illustrated below in the sections in which we discuss the achievements of the PTI in the area of astronomy.

III. THE SCIENCE

A number of projects are in progress on the PTI. Here we discuss the state of a few of them in order to illustrate the capabilities of the PTI.

a) Supernova SN 1987A

Because of its high sensitivity and high resolution, the PTI has proved invaluable for observing SN 1987A, which is located in a heavily confused region of the Large Magellanic Cloud. The PTI resolves out most Galactic emission sources and clearly distinguishes any remaining sources separated by more than a few arcseconds. The PTI observed SN 1987A within a few days of its appearance (Shelton 1987), and, in common with other Australian radio observatories, successfully detected it for several days after that date (Turtle *et al.* 1987). Since then the PTI has been monitoring the supernova at weekly intervals in order to provide early warning of any radio flareup, as predicted by some models. These observations have recently included (Norris *et al.* 1987) a configuration in which the signals from two of the Tidbinbilla antennas were sent separately up the microwave links to Parkes, and there correlated with each other using the PTI software and hardware, with minimum modification. This configuration produces a 416 m baseline interferometer, and this will hereafter be required to preclude the possibility that the supernova remnant might be resolved by the PTI.

b) Astrometric Measurements of Calibrator Sources

In contrast to the northern hemisphere, the southern hemisphere contains only a handful of sources known to be suitable for the calibration of synthesis arrays. The identification and astrometry of such calibrators constitute a major hurdle for the AT, and it was largely to surmount this hurdle that the PTI project was first initiated.

A number of techniques are currently being investigated, but one which appears particularly interesting is the use of relative positions between nearby calibrator sources. The 10 minute coherence time of the PTI at 2.3 GHz allows phase to be maintained while switching back and forth between two sources a few degrees apart. By subsequently interpolating the phase, and then subtracting the phase of one source from that of the other, a measurement of relative phase may be made, from which the relative displacement of one source from the other may be calculated (in principle) to a few milli-arcseconds.

By starting from a calibrator source with a known position, and then sequentially measuring relative positions between adjacent members of a network of calibrators, we hope eventually to establish a complete framework of calibrators. By incorporating several sources with known positions into the network, we will also obtain an estimate of systematic errors.

This technique is still being investigated, and in particular we are measuring the maximum separation of two sources between which phase may be maintained. This distance is related to the scale size of atmospheric and ionospheric perturbations. Our preliminary tests, an example of which is shown in Figure 2, indicate that it is at least 5° in extent.

c) Determination of Pulsar Proper Motions

A project led by R. N. Manchester and M. Bailes has already made first epoch measurements of the distances between pulsars and nearby compact extragalactic sources. This technique, first pioneered in the northern hemisphere by Lyne, Anderson, and Salter (1982), measures the difference in interferometer phase between the pulsar and a calibrator source (selected as the result of a search by the PTI) close enough to the pulsar for both to be within the primary beams of the Parkes and Tidbinbilla antennas at 1.7 GHz. It is planned to repeat these measurements at intervals of about 6 months and so measure the proper motion of the pulsars. An extension of this technique, in which the antennas are rapidly switched between a pulsar and a continuum source separated by over a beamwidth while the interferometer phase center is kept constant, has also been exploited for the Vela pulsar.

d) Studies of OH Maser Sources

A number of interstellar OH maser sources have been observed in a spectral-line mode with the PTI. The aim of these observations is to produce a map of the OH maser sources by assuming that each maser component is pointlike, so that its phase relative to a reference component, as measured by a single-baseline interferometer, is sufficient to determine its position relative to the other maser components in a cluster. This technique has been shown elsewhere to produce maps which are confirmed by full synthesis observations

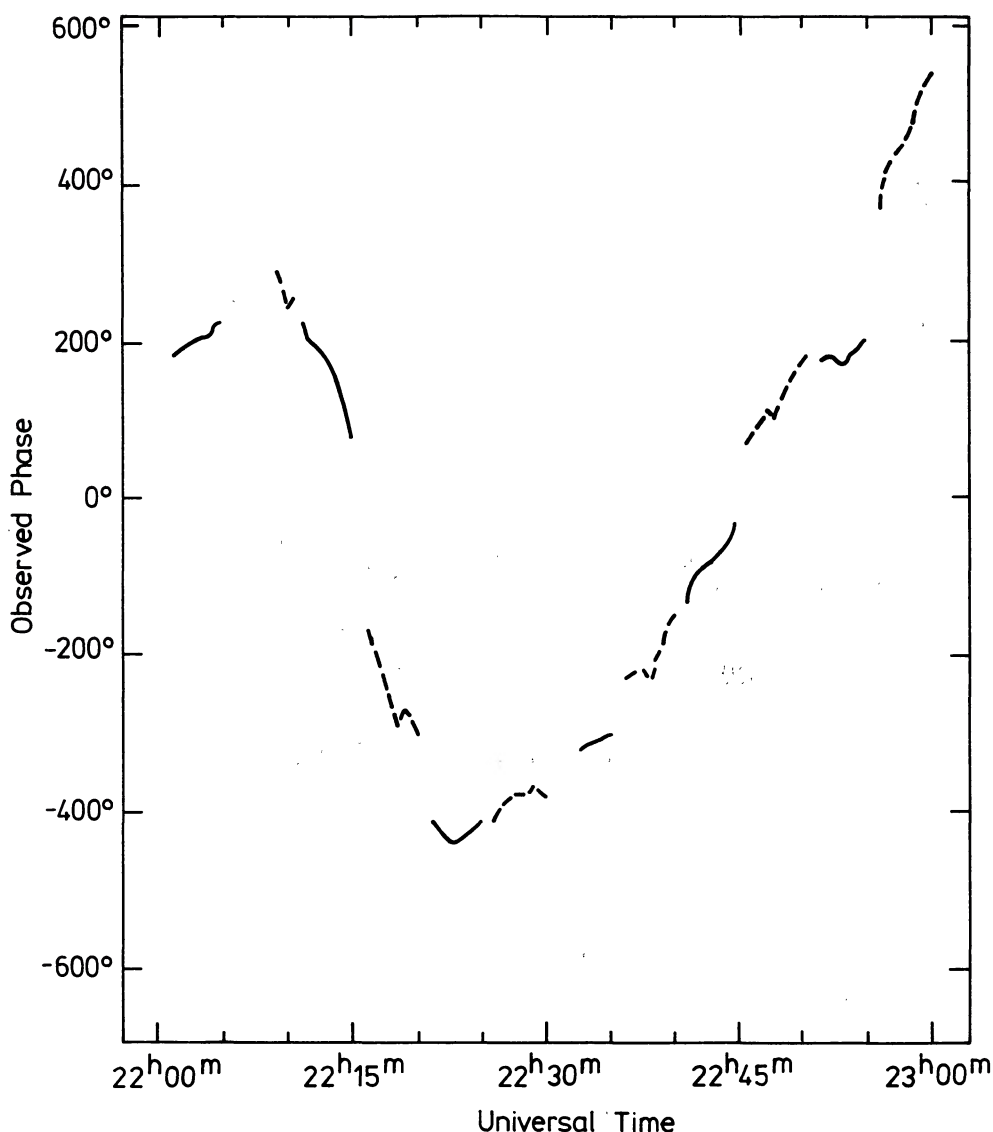


FIG. 2.—Observed phase from the two calibrator sources 0414–189 (*solid line*) and 0434–188 (*dashed line*), which are separated in the sky by about 5° . They were observed by switching the antennas between them at 5 minute intervals. The large fluctuations occurring on a time scale of tens of minutes are dominated by the atmosphere and the stability of the rubidium clock at Parkes, and are largely common to the two sources.

(e.g., Norris and Booth 1981). An example of the preliminary results is given in Figure 3.

e) Compact Nuclei in Active Galaxies and Quasars

The combination of high sensitivity and high resolution of the PTI renders it invaluable for searching for compact structure. A number of projects have started using the PTI for this purpose. Typically, the PTI is used in the source-scheduling mode to examine a large number of candidates at three hour angles (rising, transit, and setting), each for a few minutes so that linear structure may be distinguished from true pointlike structure. One of these projects (led by G. L. White and R. A. Duncan) aims to investigate the occurrence of compact nuclei in flat-spectrum quasars and, in addition to its astrophysical interest is expected to provide candidate calibrators for the

astrometry project. Another (led by R. P. Norris) will search for the occurrence of active nuclei in faint *IRAS* galaxies.

IV. CONCLUSION

The Parkes-Tidbinbilla Interferometer is now fully operational, giving millijansky sensitivity with tens of milli-arcseconds resolution at 1.7, 2.3, and 8.4 GHz in both continuum and spectral-line modes. Plans in the immediate future include the extension of its capability to cover the 12.2 GHz methanol masers (Batra *et al.* 1987) and the 22.2 GHz water masers. Looking further ahead, the PTI will become an integral part of the long baseline array of the Australia Telescope. Because of its relatively low demand on telescope time, and because real-time operation offers substantial operational advantages over the normal tape-recording mode (for

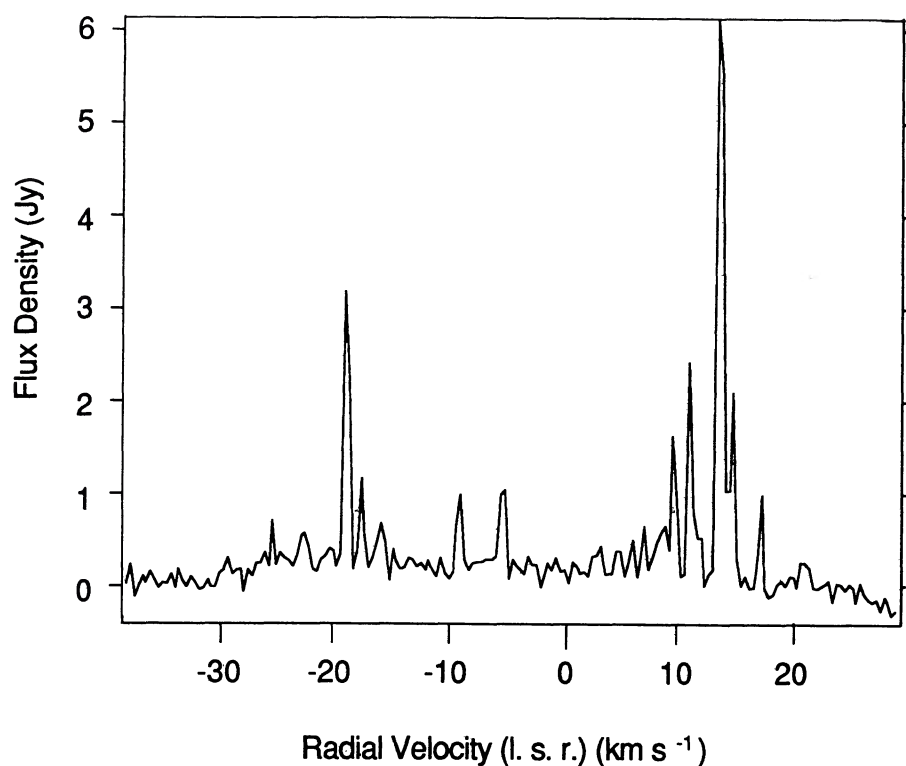


FIG. 3a

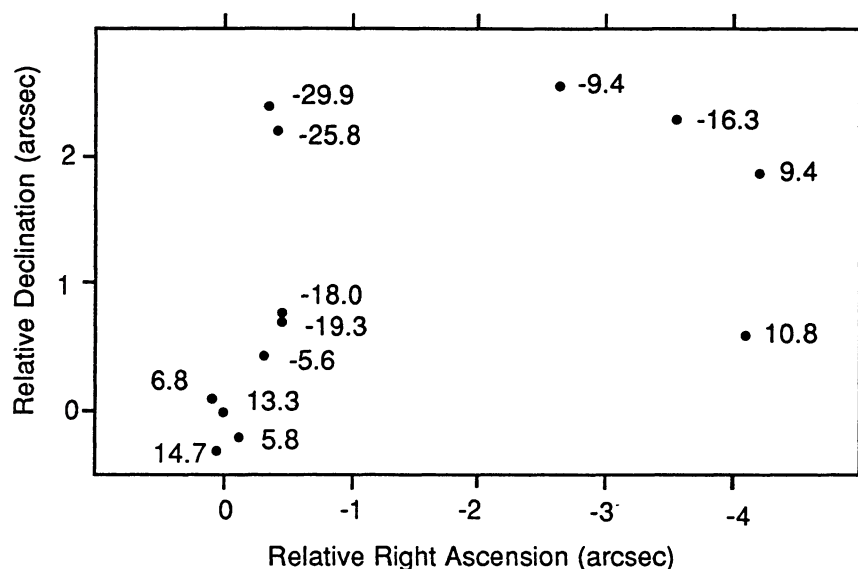


FIG. 3b

FIG. 3.—Preliminary results from PTI observations of the 1665 MHz OH emission of G5.88–0.37. (a) Cross-power spectrum. (b) Resulting map. Numbers next to the points give their velocities relative to the local standard of rest in kilometers per second. The position of each point is subject to an estimated uncertainty of $0''.05$.

those projects which do not need full synthesis observations), we expect that the PTI will function both as part of the synthesis array and as a single-baseline instrument.

We are grateful to many colleagues both at Epping and at Parkes who have contributed in many ways to this project.

We would particularly like to thank Mark Calabretta, who wrote the routines for the ephemeris and path calculations; David Loone, who built the delay unit; John Murray, who built much of the intermediate-frequency hardware; and Dave Cooke and Graham Carrad for considerable help in implementing the system at Parkes. We would also like to thank

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