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LO Phase Stability, Absolute Position Measurements and Linear Polarization - Constraints Imposed by The Atmosphere and Ionosphere

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The phase error for a single interferometer is the sum of the phase errors due to the atmosphere (including ionospheric effects), the local oscillator distribution system, and the IF path to the correlator. In order to specify a tolerance for the LO and IF systems and to determine its effect on astrophysical measurements, the effect of the atmosphere on phase measurements should be assessed. A rough estimate of these errors is the subject of this document. The accuracy of point source position measurements with the 6 km array and the 115 km Culgoora-Siding Spring baseline is investigated.

At high frequencies (> 5 GHz) atmospheric effects usually dominate the error in phase measurements with an interferometer. The main cause of atmospheric phase errors is density variations in the water vapor above the site. Atmospheric phase errors are proportional to f, the observing frequency, and the difference in H2O column density above the two telescopes making up the interferometer. The size of the difference in column density depends on the distance between telescopes, or the baseline, D. A rough estimate of the magnitude of the phase error based on measurements at the VLA out to baselines of 30 km is

$$p = 360 * (f / 75\ \text{GHz}) (D / 10\text{km})^{0.7} \quad \text{degrees}$$

where f is the observing frequency in GHz. This estimate assumes that Culgoora is about as bad as the VLA on moderately unstable days.

The timescale for variations of this magnitude is between a few minutes and a few hours, depending on atmospheric turbulence. Cold winter nights are much better than hot summer days. The largest variations appear to occur on timescales greater than about 1/2 hour on the average. On this timescale the instrumental phase stability need only be somewhat better than the atmospheric stability in order to not make matters worse. Without continuous measurement of the H2O column density above each telescope (e.g. with an H2O radiometer) the atmospheric phase error is not correctable except by self-calibration. It must be remembered that the atmosphere only relaxes the LO and IF phase stability requirements for timescales much greater than an integration period. Since the short term stability of the atmosphere is assumed to be perfect, the short term stability of the LO and IF systems should be as near perfect as possible in order to avoid decorrelation. A 2% decorrelation results for an rms phase error of 10 degrees. The presently planned correlator has a maximum integration time of 100 seconds, so stability much better than 10 degrees in 100 seconds is required for the LO/IF system.

The VLA experience is that out to 30 km the atmospheric phase error continues to increase. This increase can continue only as long as the atmospheres above the two antennas remain correlated, and then it must level off. The distance at which this happens depends on the size of the largest turbulence cells above the site. This scale size is probably of the order of 100 km, but little information exists on this subject. For baselines greater than this correlation length, the only advantage of a distributed LO system over independent clocks at the two telescopes (i.e. VLBI) is the ability to use longer integration times. As long as phase reference measurements are made frequently enough to track out large atmospheric drifts, integration over the full observing period can be done without severe loss of correlation, whereas VLBI integration times are limited by clock drifts independent of the atmosphere. This feature of distributed LO systems can be important for the detection of weak sources, and similarly in using self-calibration on weak sources.

The ionosphere dominates at low frequencies and is proportional to f^-2. Its effects can probably be ignored at frequencies above 1 GHz, although 1.4 and 1.6 GHz observations could be affected.

It is difficult to give a rule of thumb estimate for the magnitude of ionospheric effects. During increased solar activity phase errors may increase by an order of magnitude. There are three main ionospheric effects: 1) phase delays, 2) refraction, and 3) Faraday rotation. It is impossible to correct for these effects without continuous information on the state of the ionosphere (cf. NFRA ITR #162, 1981 'The influence of the ionosphere on WSRT observations' T.A.Th.Spoelstra).

The ionospheric phase delay is proportional to n*l/f^2, where n is the free electron density, l is the path length through the ionosphere and f is the observing frequency. A uniform ionosphere produces no phase difference between telescopes and therefore no error. However, traveling waves and instabilities due to solar activity can cause inhomogenaities whose effects are baseline dependant. At 610 MHz (49 cm) typical phase errors are of the order 10-20 degrees on timescales of 10-30 minutes. During increased solar activity errors approaching 90 degrees may occur. Phase errors due to traveling waves are reasonably easy to recognize; the phase goes through a positive and negative excursion as the wave passes the two antennas, with an amplitude proportional to the baseline length. They are not so easy to see if they occur during a phase reference observation which is shorter than the oscillation period. The effect of ionospheric traveling waves on maps made with a linear array is radial stripes.

Ionospheric refraction is well known and is proportional to D/f. The worst effect is its diurnal variation, which can only be corrected if n and its gradients are known as a function of time. With a 6 km baseline at 610 MHz a diurnal variation of 20-30 degrees is typical. This effect may be serious when attempting to measure absolute positions at low frequencies and may reduce the dynamic range attainable without self-cal. As an example of the position error problem: a 30 degree phase error (on a 6 km baseline) with a roughly sin(ha) dependence will shift the position of a 1665 MHz OH maser by about 0.3 arc seconds. The refraction effect can be mostly calibrated out by phase referencing provided the reference source is within say, 10 degrees of the source.

Faraday rotation through the ionosphere is proportional to nBl/f^2 where B is the line of sight geomagnetic field and l is the line of sight path length. It is important for linear polarization measurements at low frequencies but does not impose any constraints on phase stability. Typical values of Faraday rotation at 610 MHz are between 10 and 50 degrees with large diurnal variations. The rotation is not dependent on baseline. In order to correct for Faraday rotation both ionospheric electron density and geomagnetic field information is required. This effect may cause the largest uncertainty on linear polarization measurements at frequencies below 1 GHz. It produces an overall rotation of the intrinsic position angle and also causes depolarization when the rotation varies with time. It is not possible to correct for Faraday effects using self-calibration techniques.

In principle the accuracy of point source position measurements with an interferometer is a fraction of the minimum fringe size. The fraction depends on the signal-to-noise ratio plus systematic phase errors. A rough estimate of the position uncertainty is given by

$$p = F * 360 / P\ err \quad \text{degrees}$$

where F is the fringe size and P err is the phase error in degrees associated with the measurement. Usually it is systematic errors which limit the accuracy of position measurements. The minimum fringe size in arcsec for a selection of baselines and frequency bands is tabled below:

FREQUENCY (GHz)	BASELINE LENGTH (KM) 6	12	115	310
115	0.09	0.04	0.005	0.002
90	0.11	0.06	0.006	0.002
45	0.23	0.11	1.012	0.004
22	0.47	0.23	0.024	0.009
10	1.03	0.52	0.05	0.02
5	2.06	1.03	0.11	0.04
1.5	6.88	3.44	0.36	0.13
0.84	12.28	6.14	0.64	0.24
0.33	31.25	15.63	1.63	0.60

A fundamental limit to the position accuracy is the error in the positions of the calibrate sources used in the baseline solution and as phase references. This is presently about 0.1 arcsec for the optically identified sources. From the table, it should be possible to measure positions to 0.1 arcsec with the 6 km array at 5 GHz and above. At the higher frequencies atmospheric refraction may be the most serious cause of systematic phase errors, assuming the LO/IF system is stable. This can be overcome either by monitoring the atmosphere with a water vapour radiometer, or by using nearby phase calibrators. At frequencies above 10 GHz,however, it may become diffioult to find suitable calibrators.

At 1.5 GHz phase errors less than 5 degrees are required to obtain a positional accuracy of 0.1 arcsec on a 6 km baseline. Although it may be possible to reach this level of stability, longer baselines would be preferable. A 12 km baseline relaxes the stability requitement to 10 degees, while a 115 km baseline brings it to 100 degrees In view of the importance of accurate position measurements of OH masers, the 115 km baseline is highly desirable. So long as the true phase is within 100 degrees of the measured value during the interval between calibrations, a positional accuracy of 0.1 arcsec will be obtained. Measurements at 6 km will also be necessary in order to locate the source within a single (0.4 arcsec) fringe.

For frequencies below 1 GHz, baselines of 100 km or greater are necessary for accurate position measurements. Here ionospheric refraction will probably limit the accuracy. Uncorrected, refraction produces apparent position offsets of 0.5 to 1.0 arcsec at small zenith angles, and larger offsets near the horizon. Corrections based on a standard ionosphere are probably good to a few tenths of an arcsec well above the horizon, and would improve if, for example, ionosonde data were available. The most accurate means of correcting, however, is probably referencing to nearby calibrate sources. For most sources an accuracy of 0.1 arcsec could be realized on a 115 km baseline. It is doubtful that this accuracy could be achieved on baselines of 12 km or less at 327 MHz.

SUMMARY

(1) The LO/IF system should have a short term phase stability of a few degrees in 100 seconds.

(2) The long term stability at 5 GHz should be better than 10 degrees in 10 minutes for a 6 km baseline. At higher frequencies and longer baselines drifts may be allowed to increase by the factor f*D^0.7 without seriously degrading the observations. The reslting phase error will then depend on the interval between phase reference observations which is set by atmospheric stability at about 1/2 hour.

(3) Better phase stability above 1 GHz would be useful if a water vapour radiometer were available for continuous atmospheric monitoring. In this case IF/LO stability of a few degrees per hour would be desirable.

(4) At frequencies below 1 GHz the long term phase stability should be a few degrees per hour since faster phase variations are only observed during increased solar activity.

(5) Continuous monitoring of the ionosphere by bottomside ionosonde or satellite observations would be very useful. Absolute positions and linear polarization measurements at frequencies below 1 GHz will probably be limited by our knowledge of slow variations in the ionosphere.

(6) The resultant phase error at any frequency or baseline will ultimately depend on the interval between phase calibrations and the nearness of the calibrator to the source of interest, so long as the instrumenal phase stability is better than the atmosphere or ionosphere, and provided that repointing the antennas has no effect on the phase. At all frequencies a calibrator as near as possible to the source should be chosen. It may in some cases be wiser to use a weaker but closer calibrator and integrate longer. The interval between calibrations should be adjusted for current atmospheric and ionospheric conditions.

(7) The 6 km array will in principle allow measurement of absolute positions to an accuracy of 0.1 arcsec at frequencies of 5 GHz and above. The accuracy is fundamentally limited by the accuracy to which the calibrate source positions are known. This limit is likely to improve over the next decade.

(8) At 22 GHz and higher atmospheric refraction and the scarcity of good phase calibrators may reduce the positional accuracy obtainable. A water vapour radiometer for atmospheric monitoring would be of great value in obtaining, for example, accurate positions of interstellar H20 masers.

(9) In order to reach a positional accuracy of 0.1 arcsec at the OH frequency (1.6 GHz) and below, the Culgoora-Siding Spring baseline (115 km) is suitable.

Ionospheric refraction will cause the largest uncertainty, but this can probanbly be kept below 0.1 arcsec by phase referencing to nearby calibrators.

(10) Faraday effects may cause large errors in the measurement of linear polarization below 1 GHz. The best way of correcting for this is by continuous monitoring of the ionosphere. The use of satellites would be of highest value; earth based ionosonde observations could also be used, but with reduced accuracy.