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CLOSURE ERRORS

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Closure errors are the non-factorizable gains in the calibration equation,

$$V_{ij} = G_i G_j V'_{ij} + G_{ij} V'_{ij} + \varepsilon_{ij} + \sigma_{ij}$$

where V_{ij} is the measured visibility, V'_{ij} is the true visibility, ε_{ij} is the baseline offset and σ_{ij} is the thermal noise. The factors G_k are the gains associated with the individual antennas; the factorizable gains. The gain associated with the antenna pair, G_{ij}, is not factorizable into gains associated with each antenna and is called the closure error (Perley,1985).

The closure errors are generally small and not of concern to all VLA users. However, they have become the limiting factor on the dynamic range in the scientifically important high fidelity maps, thus making an understanding of them a worthy step in image quality improvment.

METHODS OF INVESTIGATION AND CHARACTERIZATION OF ERRORS

In the first part of the project, existing data from noise runs dating from August 1984 to March 1985 were used. Files of residuals calculated in ANTSOL on the DEC-10 were analyzed to obtain the error magnitudes and to compare the errors on the AC and BD sides.

In general, the amplitude errors were on the order of one to two percent and the phase errors were less than one or two degrees. The BD sides were better than the AC sides as indicated by dispersions of the distributions (see figures 1, 2, and 3). In August and September 1984, the BD side phase dispersions were .05 degrees better than the AC side. The amplitude dispersions were also better on the BD side, but the amount varied. After January 1985, the BD and AC side dispersions were on the order of .4 and .6 degrees in phase, and .9% and 1.0% in amplitude, respectively, indicating that there may have been a change in the system between the two sampled periods that caused the difference between the AC and BD side phase error dispersions to increase from .05 to .2 degrees (see table 1).

The second part of the project was to investigate the consistency of the errors over time, between bandwidths, between bands, and between frequencies within bands. To accomplish this, observations of OJ287 were performed on six days between March 25 and April 7, 1985. In these observations, the band, frequency, and bandwidth were varied on time scales of minutes, and one hour blocks of systematic changes were repeated on timescales of hours and days. L, C, and U bands were used with bandwidths of 50, 25, and 12.5 MHz. In C band, a bandwidth of 6.25 MHz was also used. Alternate frequencies of 1385 and 1665 MHz in L band, 4735 and 4785 MHz in C band, and 15015 and 15065 MHz in U band, were used in one (one hour) block of observations. The observations are shown schematically in figure 4. Analysis of the errors was done on the AC side data only, purely for reasons of expediency. In retrospect, since the dispersions were smaller on the BD side, it might have been a better choice to use that data. The data were calibrated in ANTSOL, written to export tapes and taken to VAX3. On the VAX, a 1 Jy point source was used to calibrate the data, and the closure errors were calculated in Craig Walker's program, BCAL1, which finds the closure errors on each baseline and the RMS and mean of real and imaginary errors over all baselines. A fortran program available under the name VAX3::[AOD.FORTRAN]DIFSTAT was then written to find the differences between the errors on each baseline and to calculate the RMS of the differences over all baselines for both the real and imaginary.

The RMS of the errors as found in BCAL1 ranged from 0.5% to 2.5% for the various band/frequency/bandwidth combinations. The expected noise is less than this (≈.1% to .5%) for all bands and bandwidths (see table 2). The RMS of differences was generally around a percent in C and U bands, and around 2% in L band. The real and imaginary errors were nearly the same (RMS), with the imaginary tending to be slightly (on the order of .1%) larger than the real. The difference between the real and imaginary difference RMS's was smaller, but the imaginary still tended to be greater than the real. Some correlation was apparent between different times and between different bandwidths. The errors in the various bands behaved more specifically as follows:

L BAND - The RMS of differences was much higher than in the other two bands. Mapping revealed confusing sources in the field (see fig. 5) which are responsible for most of the high noise level, and thus the higher errors.

C BAND - There was apparent correlation between similar observations (same band, bandwidth) at different times. Over short times (hours) the difference RMS's were on the order of .3%. Over days, they went up to ≈.9%, but the error did not appear to change systematically with the number of days. Less correlation was seen between bandwidths with difference RMS's of of about .6%. The errors were greater for the 6.25 MHz bandwidth than for the other three. Observations done with bandwidths of 50, 25, and 12.5 MHz had closure error distributions with RMS's of about 1% whereas the error root mean squares for observations done at 6.25 MHz were often 0.5% greater. Correspondingly, the difference distribution RMS's were also greater, ≈1.3%. Between different frequencies and bands, the RMS's of the error differences ranged from 1.5% to 3%, not indicating as much correlation.

U BAND - Here, as in C band, the errors appeared to be correlated over time with a slightly better correlation over short (hour) timescales. The RMS of differences over hours tended to be on the order of .7% (twice that of C band), and they rose to about .9% for differences over days. This also held true for observations of 3C273 done by Cornwell and Owen on February 26, 1985. Differences between bandwidths behaved the same as in C band (≈.6% to .8%). However, between different bands the root mean squares of the differences were significantly smaller: .8% to 1.6% and ≈.9% respectively.

Detailed listings of the errors and the differences are available from A. O'Donoghue. The errors as calculated by BCAL1 and listings of the differences have been written to tape and are available on volume v3833 in the VLA tape library. The flies are named for the quantity being differenced and give the band and bandwidth. For example, [AOD.MAR25]WIDTHL.01 is the file of differences between observations at two different bandwidths, 50 MHz and 25 MHz in L band on March 25.

DISCUSSION

In the first part, the approximate equality of the real and imaginary errors does not agree with any of the simple pictures presented by Thompson and D'Addario in 1982. They suggest that comparable phase and amplitude errors may arise from combinations of effects. It is indicated by the smaller errors on the BD side than on the AC side that the samplers may be involved since they had to be adjusted on the BD side in late 1984 and the phase errors are more notably smaller on that side in early 1985 than in the late summer of 1984.

In the second part, the time-dependent behavior is confusing, but some simple questions and conclusions can be presented: It is not clear why the closure errors in C band should be smaller than in U band. There seems to be a slow decorrelation in the closure errors which on time scales of hours. On timescales of days to weeks, no further degradation seems to occur.

Results were comparable on different sources ranging from 2 Jy to 30 Jy so the effect is clearly multiplicative.

While this project has by no means solved the closure error problem, it has, we hope, clarified and quantified some of the problems. Further work will doubtlessly be needed if we are to solve the problem.

We are grateful to Durgadas Bagri, Barry Clark, Tim Cornwell, Fred Schwab, Ken Sowinski, Craig Walker, and all those at the Test/Coordinations meetings for helpful discussions.

TABLE 1

RESIDUAL DISPERSIONS

DATABASE	CH.	BAND	AVERAGE	DISPERSION	
				PHASE(deg)	AMPLITUDE(%)
AUG 01	1	6cm	1 min	.55	.0080
	6	6cm	1 min	.5	.0070
SEP 05	1	6cm	1 min	.65	.0110
	6	6cm	1 min	.50	.0080
	1	20cm	1 min	.65	.0090
	6	20cm	1 min	.60	.0070
JAN 30	1	6cm	1 min	.6	.0100
	6	6cm	1 min	.4	.00975
FEB 19	1	6cm	1 min	.6	.01075
	6	6cm	1 min	.35	.00725
FEB 20	1	6cm	scan	.6	.0100
	6	6cm	scan	.3	.0095
	1	20cm	scan	.6	.0125
	6	20cm	scan	.5	.0090
MAR 13	1	6cm	1 min	.6	.0095
	6	6cm	1 min	.3	.00975
MAR 19	1	6cm	1 min	.625	.0120
	6	6cm	1 min	.45	.00625

TABLE 2

EXPECTED THERMAL NOISE

The theoretical rms of the amplitude noise fluctuations for a single antenna pair is given by Hjellming (1982) as

$$\Delta_{\mathrm{noise}}(\mathrm{theoretical}) = C(50/\Delta\nu_{\mathrm{MHz}})(10/t_{\mathrm{sec}})^{1/2}\ \mathrm{Jy}$$

where the constant C depends on the band as follows:

L BAND: C = 0.026
C BAND: C = 0.017
U BAND: C = 0.043

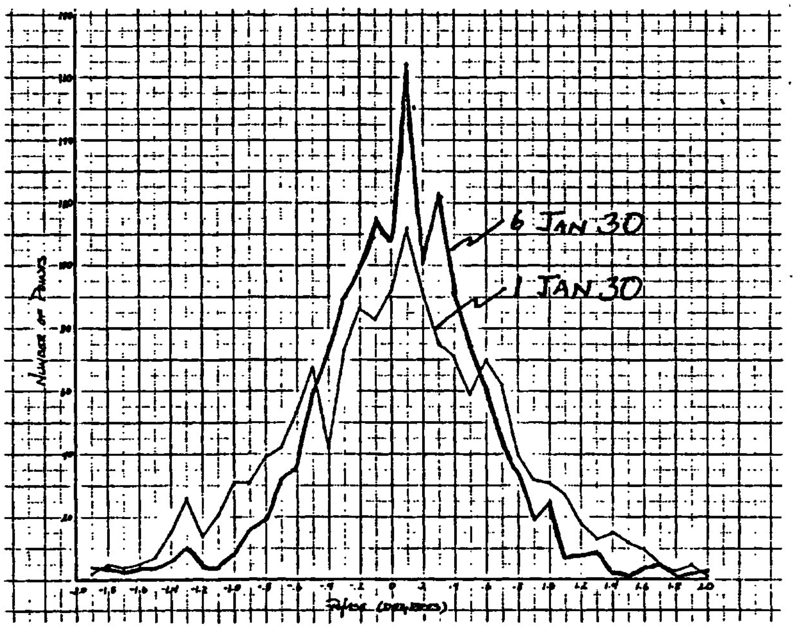
The values for OJ287 for the various bands, bandwidths and integration times are:

L BAND	1.6 Jy	50 MHz,	5.5 min	.28%
		25 MHz,	11.5 min	.28%
		12.5 MHz,	11.5 min	.39%
C BAND	2.3 Jy	50 MHz,	5.5 min	.13%
		25 MHz,	11.5 min	.13%
		12.5 MHz,	11.5 min	.18%
		6.25 MHz,	30.0 min	.16%
U BAND	6.0 Jy	50 MHz	5.5 min	.12%
		25 MHz	11.5 min	.12%
		12.5 MHz	11.5 min	.17%

FIGURE 1

RESIDUALS: 6cm (January 30, 1985)

Phase Residuals



Amplitude Residuals

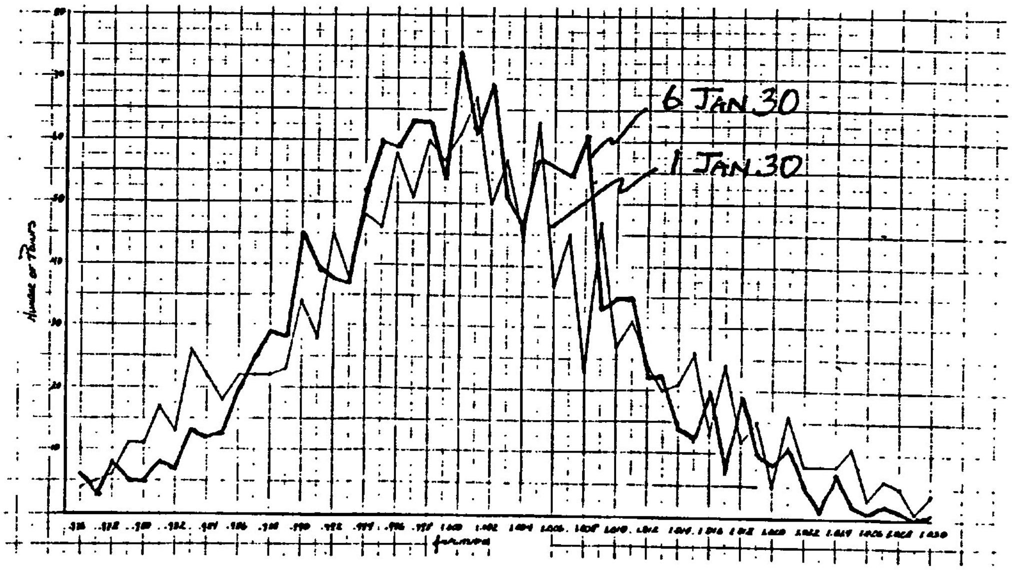
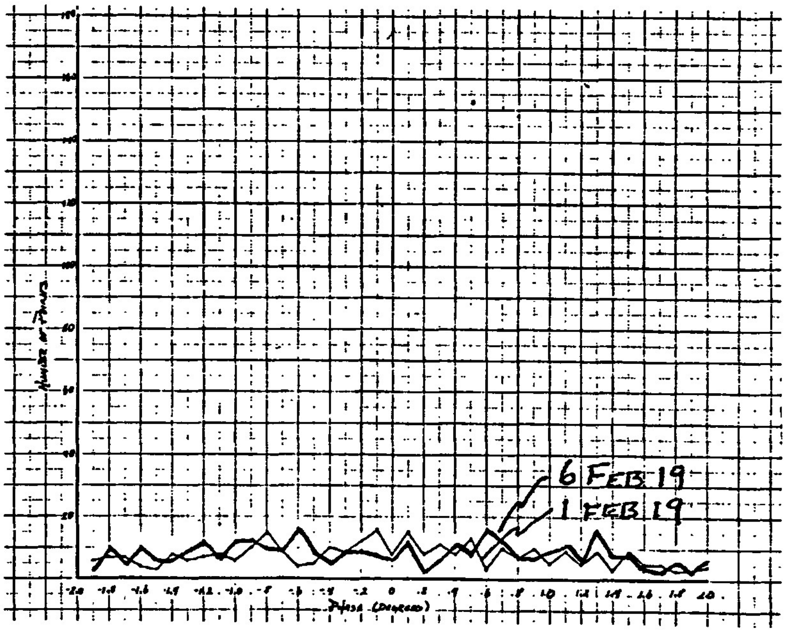


FIGURE 2

RESIDUALS: 1.3cm (February 19, 1985)

Phase Residuals



Amplitude Residuals

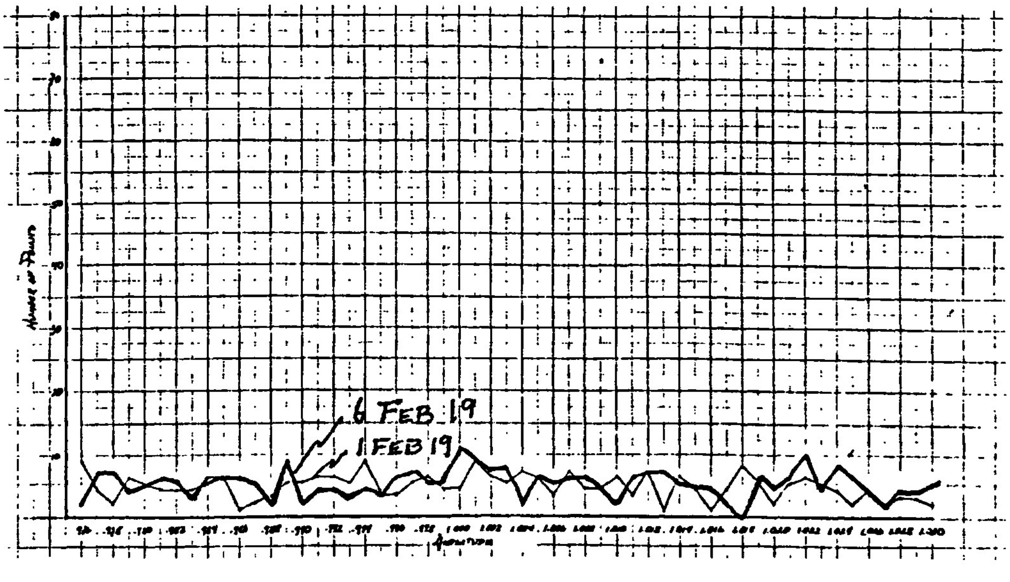
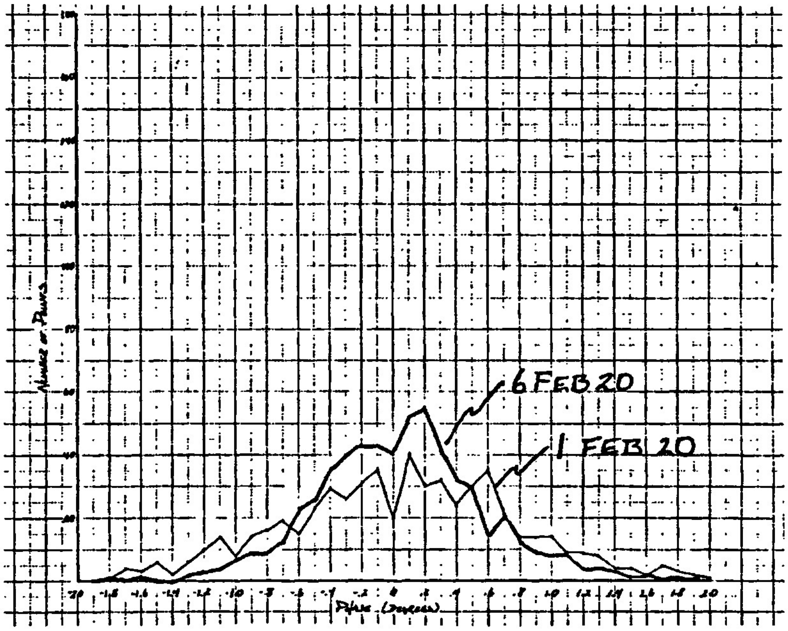


FIGURE 3

RESIDUALS: 20cm (February 20, 1985)

Phase Residuals



Amplitude Residuals

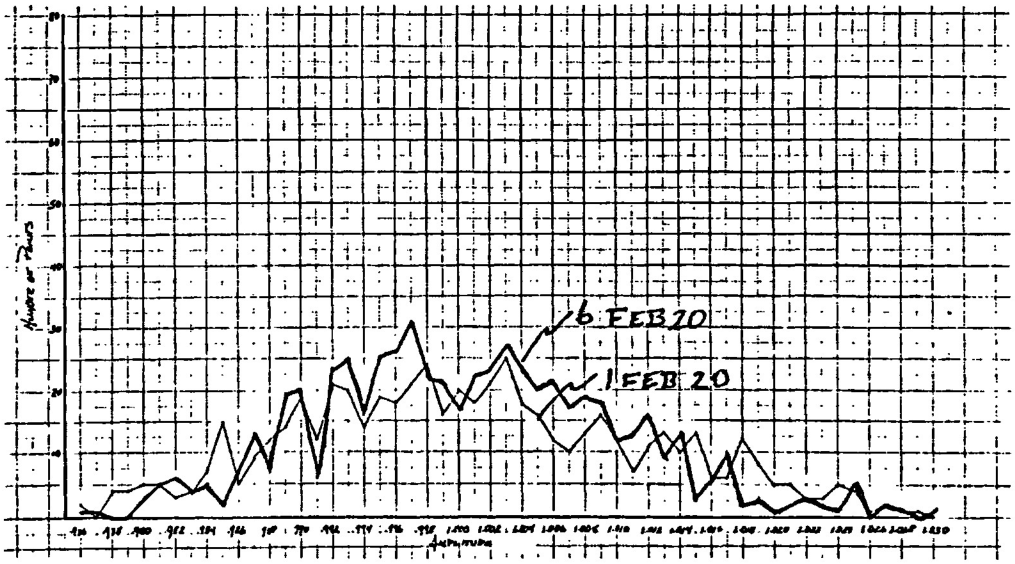
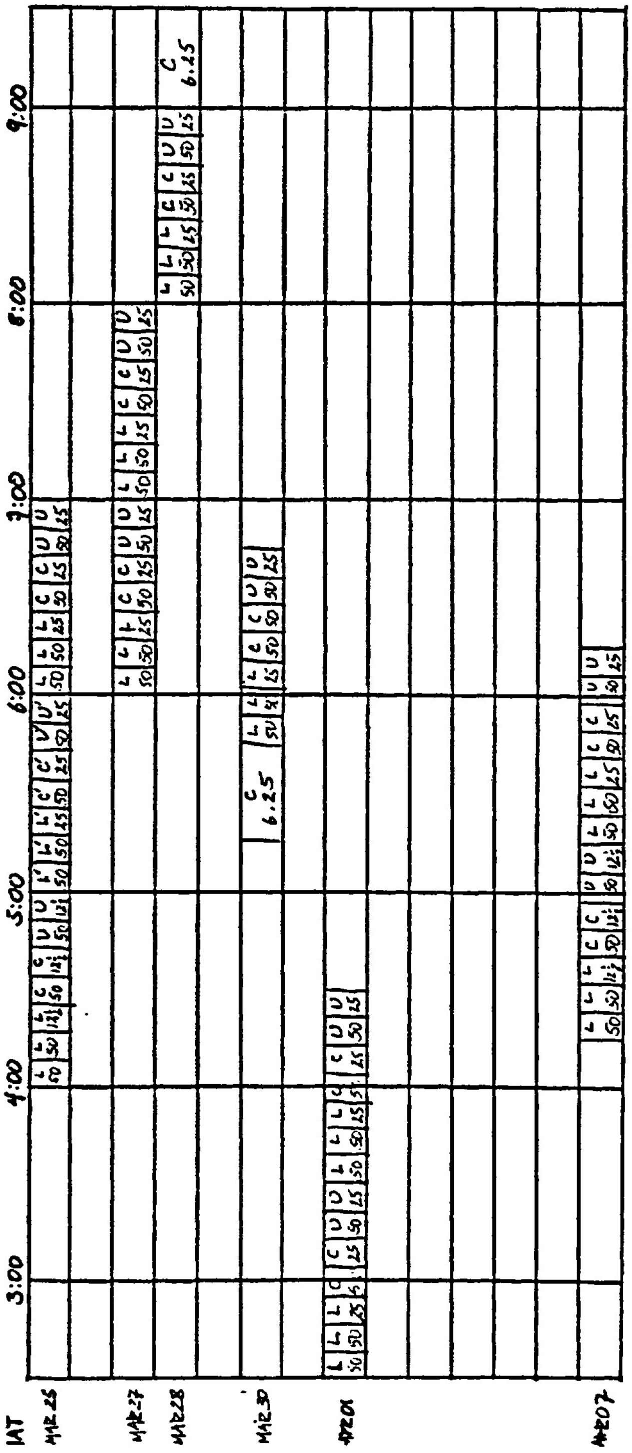


FIGURE 4

SCHEMATIC REPRESENTATION OF TEST OBSERVATIONS OF OJ287



The tests were done in March and April of 1985. The widths of the boxes do not indicate the scan durations, but simply the sequence of tests. Different scan durations and frequencies were used and are given below.

SCAN DURATIONS

50.0 Mhz	5:30 min
25.0 MHz	11:30 min
12.5 MHz	11:30 min
6.25 MHz	30:00 min

FREQUENCIES

L	1465, 1515 MHz
L'	1385, 1665 MHz
C	4885, 4835 MHz
C'	4735, 4785 MHz
U	14965, 14915 MHz
U'	15015, 15065 MHz

FIGURE 5

WIDE-FIELD MAP OF OJ287 IN L-BAND SHOWING CONFUSING SOURCES

The map was cleaned for 2000 itterations in MX on VAX 3. OJ287 is in the center. The confusing source in the bottom center of the field (at about 08 52 04 +20 11 00) was the most outstanding. Other possible confusing sources are indicated.