VLB ARRAY MEMO No. 49

STUDIES OF ARRAY DYNAMIC RANGES

I. INTRODUCTION

During December 1981 I did some simulations of source-mapping with a 10-station VLBI Array. In all of these simulations, I used

1) VLB:FAKE to produce data with random (and, in some cases, systematic) errors

2) The standard Caltech mapping package, involving AMPHI (when relevant), INVERT, and CLEAN

3) Array 13 (HSTK, IOWA, LRDO, BLDR, BOISE, SALEM, GSTN, OVRO, ANCH, and HNLU)

4) DECLINATION 64^{o}
(This allowed different results to be more easily compared, and also eased the computational requirements, as discussed in the Appendix)

The bulk of the simulations used DAISY as a test source, but I also did some mapping with a new test source. CEREBRUM (see Table 1 and Figure 1).

II. RESULTS

The dynamic ranges of the maps I made are displayed in Table 2. The variation of dynamic range with S/N for the full phase, perfect calibration case (row 1 of Table 1) can be qualitatively understood. Below ~1 Jy source strength, the dynamic range increases rapidly with increasing source strength; the S/N ratio is the main limitation to the dynamic range. Above ~1 Jy source strength, the dynamic range increases only slowly with increasing source strength. This happens because holes in the u-v coverage are the main limitation to the dynamic range in this regime.

Row 2 of Table 2 shows the results obtained when one goes to 24 hour tracks (a δ=64 source is circumpolar at 7 of the 10 stations). The increase in dynamic range is greatest for strong sources, for which the dynamic range is limited by u-v coverage, rather than by S/N.

Row 3 of Table 2 gives the dynamic range obtained with perfectly calibrated amplitudes, but random phases (i.e. only closure phases available). The degradation in dynamic range caused by the loss of full phase information is ~10%, except for the lowest S/N case, where it is 20% (closure phases are on average $\sqrt{3}$ times noisier than phases; this is an important effect at low S/N). The loss of phases reduces the amount of data (45 amplitudes + 45 phases) by 9, or 10%. The fact that this is mirrored so closely in the measured values of dynamic range is strong evidence that 1) software limitations are not significant at the 0.3% level in these simulations, and 2) the RMS measurement of dynamic range is a meaningful one.

Note that a point source starting model was used for all the hybrid mapping that went into Table 2.

The results for cases involving amplitude calibration errors are less satisfying. Rows 5 and 6 of Table 2 give results where small, systematic amplitude errors were introduced, in an attempt to simulate 10 GHz data. These errors are of three kinds

1) Station-dependent errors, correlated on a timescale of ~30 minutes. They simulated bad weather and pointing problems. For most stations, values of 0-2% were used, but they were a bit larger for HSTK and HNLU, and ranged from 0-10% for LRDO (corresponding to quite bad weather there).

2) Station GAIN errors of 0-2% (the same throughout the track)

3) Baseline errors of 0-.4% (simulating the errors of some future, well-understood correlator)

When a hybrid map was made from this data, letting AMPHI adjust the phases but not the amplitudes, a dynamic range of 168 (for S=20 Jy) resulted. When AMPHI was allowed to adjust the amplitudes as well as the phases, a much cleaner looking map resulted (i.e. the largest spurious features visible on the map were several times smaller than in the previous case). However, the relative fluxes of various features were wrong by several percent (in particular, the core was ~6% too strong), and a simple measurement of D.R. was not possible. When the D.R. was measured in the usual way, it came out to be 158. When the core flux was allowed to vary relative to the rest of the source, the D.R. increased to 207. I feel that even this is an underestimate of the quality of the map, but I see no reasonably objective way to vary component fluxes outside the core. My feeling is that for most purposes (one usually does not wish to know component fluxes to 5%), small amplitude errors have only a minor effect on the useful information that can be obtained with 10 station data. For weak (<~.5 Jy) sources, the effect should be negligible.

The bottom row in Table 2 gives the results when large systematic errors are introduced by FAKE, to simulate data at high (~20-40 GHz) frequencies. (I put in time-varying errors that at times reached 50% for the worst stations, and station GAIN errors of 0-10%). Hybrid mapping converged quickly (4 Iterations for a 20 Jy source; 2 Iterations for a .5 Jy source) from a point source starting model to a poor map, with DR~48 independent of source strength. This value of D.R. is a good measure of the quality of these maps, as there are (relatively) large, spurious features.

In this case, hybrid mapping has failed, as the resulting maps did not produce a good fit to the closure amplitudes. A better starting model is needed. Unfortunately, producing a good starting model is difficult when there are large amplitude errors. I think that mapping sources using data with large calibration errors will be a major problem, even with AMPHI and 10 stations. More work on this problem is needed.

OTHER TEST SOURCES

Hybrid mapping works well on DAISY (and presumable AMOEBA as well), since both are dominated by a bright, compact core. A point source works well as a starting model. Many, but by no means all, sources observed with VLBI are indeed dominated by a bright core. The values for D.R. measured for DAISY (and AMOEBA) are therefore relevant, but they do not tell the whole story. I therefore made up the test source CEREBRUM (Table 1 and Figure 1), with a complexity akin to that of 3C 84.

The full phase, perfect calibration case for CEREBRUM is illustrated in Table 3. The values are comparable to those with DAISY, but with a much steeper falloff with decreasing S/N. I do not know the reason for this difference.

I had time for only one test of hybrid mapping on CEREBRUM, and even it was not completed when I left (the files are in my disk area if someone wishes to continue the process). I started out with a point source, and ran 6 iterations. At that point, the dynamic range was only ~40, with the ratios of the two brightest features wrong by 10%. The map was converging slowly in the right direction, and with a suffient number (100?) of iterations, might have reached the correct solution. However, I chose to help the process along, by the following procedure.

I looked at the output map from the sixth iteration, picked the top 6 features, measured approximate dimensions and fluxes from the map, and made up a model of 6 Gaussian components. I then let VLBFIT adjust the component fluxes, shapes, etc. to optimize the fit. The resulting model was used as input to hybrid mapping. I think that my knowledge of the source did not influence me greatly in this procedure, but the fact that CEREBRUM is composed of Gaussians means that the procedure worked better than it would for a real source. (A large amount of effort with model fitting could make up for the non-Gaussian nature of a real source)

I then ran 11 iterations of hybrid mapping, until I ran out of time (each iteration required 70 minutes of CPU time). The map got better with each iteration; the dynamic range increased by 20-30 each time, and was 267 on the eleventh iteration. I leave it to the reader to guess how high a D.R. could ultimately be achieved. Hybrid mapping seems to converge much more rapidly when the source is dominated by a bright core.

The enormous computing requirements for producing high dynamic range hybrid maps provides a strong incentive for investigating other techniques (e.g. maximum entropy) for producing maps. Reliability tests of MEM mapping programs would be very useful.

APPENDIX: METHODS

I first investigated the dependence of D.R. on CLEAN parameters (NITER, LOOPGAIN, map size). I found that for $\delta=64^\circ$, 128x128 maps had as large a D.R. as 256x256 maps(This is not true for $\delta<=18^\circ$). I finally decided on NITER=4000, LOOPGAIN=.2 as producing the best maps (a smaller value of NITER, or a larger value of LOOPGAIN definitely gave poorer results). For CEREBRUM, which has large areas of low surface brightness, I needed to remove 8000 delta functions (NITER=8000, LOOPGAIN=.2). I used a CLEAN window 20 mas on a side, and then excluded a strip 2 mas wide around the border, as this contained large ridges of emission which I believe to be caused by the interaction of the regular features in DAISY with the software (a real source would have less regular structure, and the problem would not arise).

Subtracting the map from the FAKE source model produced a difference map. In the Caltech Array Report we defined the Dynamic Range as the ratio of map peak to the peak of the difference map (excluding small regions around the bright compact components). An alternative method is to take the ratio of the map peak to 5 times the RMS of the difference map (again excluding small regions around very bright components). I found that the two methods agreed fairly well, but I have used the RMS method here, because 1) it is more objective in the case where there are spurious features near, but not coincident with, bright map components 2) it varies more smoothly with source strength, and 3) it is less sensitive to the details of the noise in the data (see Table 4 and accompanying description).

For the D.R.'s quoted here, I measured the RMS in a +/-8 mas window centered on the source (see Richard Simon for details on how to do this). I then measured the RMS in a square box +/-0.6 mas wide, centered on the core, and did a weighted subtraction, to obtain a net RMS (I used 160 pixels for the +/-8 mas plot, and 12 pixels for the +/-0.6 mas plot). For CEREBRUM, I used two +/-0.6 mas boxes, one centered on each of the two brightest components. The quoted D.R. is the map peak divided by 5 times the net RMS.

In cases where full phase information was available, absolute position information was retained, and map registration was not a problem. For maps made with closure phase, registration is a problem. Substantial effects arise when the map and FAKE model are misaligned by as much as 0.001 mas. A prominent feature appears at the core of the resulting difference map, positive on one side, negative on the other. When alignment is perfect, there is an alternation of positive and negative features distributed along the long axis of the beam, within ~0.5 mas of the core. To correct the registration problem, I shifted the map until the difference map had the appearance of perfect alignment (the shift was typically 0.005-0.01 mas, and was in PA 45° for DAISY, PA -95° for

CEREBRUM). When the map is shifted correctly, the RMS of the difference map is nearly at a minimum (I did not adjust the shift to minimize the RMS, because this would introduce a degree of freedom not present when I measured the RMS of full phase maps).

For maps made with data possessing calibration errors, it was necessary to adjust the flux scales, as well as the positions. The simplest way of doing this is to multiply the map by a factor which sets the peak of the convolved map equal to the peak of the convolved FAKE model.

TABLE 1

CEREBRUM MODEL

3.000	1.000	180.000	0.300	0.800	17.000	1
3.000	2.767	49.558	1.700	0.600	70.000	1
0.400	3.820	-149.690	2.000	0.800	30.000	1
5.000	1.114	-37.889	5.000	0.700	10.000	1
1.000	2.236	116.565	3.000	0.100	100.000	1
3.000	2.000	0.000	0.500	1.000	0.000	1
2.000	2.324	56.050	6.000	0.500	40.000	1
1.000	0.657	-51.367	1.200	0.500	-20.000	1
0.600	1.000	180.000	4.000	1.000	0.000	1
1.000	1.993	174.990	8.000	0.950	6.000	1

Figure 1
'CEREBRUM' test source

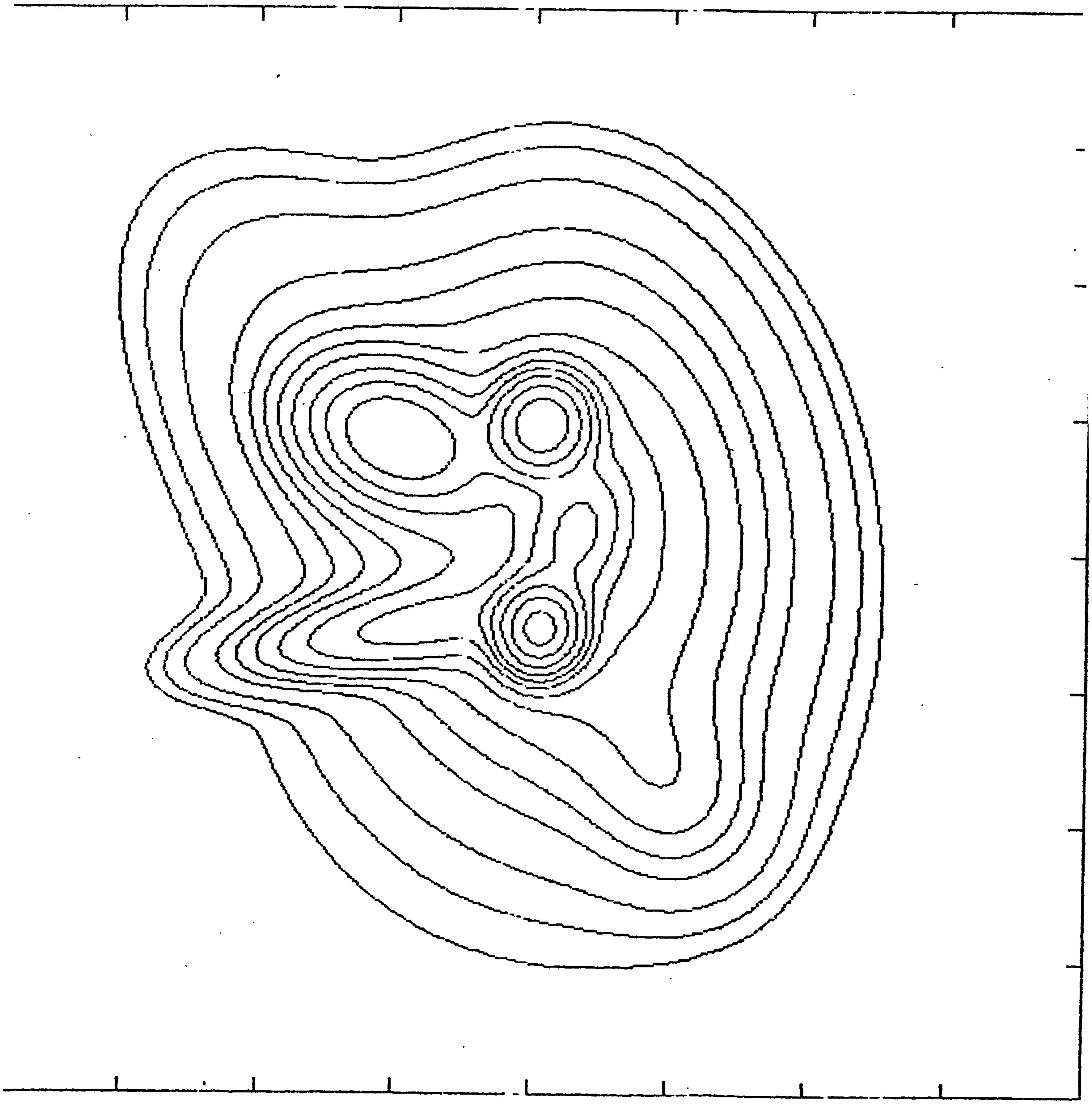

Table 2

RMS Dynamic Ranges for DAISY

	Source Strength (Jy)				
	20	2	.5	.2	.1
Full Phase 12 Hour Tracks	311	280	152	77	45
Full Phase 24 Hour Tracks	480	411	208	107	54
Closure Phase 12 Hour Tracks	278	251	137	69	36
Closure Phase 24 Hour Tracks			184		
Closure Phase Small Amp. errors (not corrected)	168				
Closure Phase Small Amp. errors (corrected by AMPHI)	158/207				
Closure Phase Large Amp. errors	47		48		

Table 3

RMS Dynamic Ranges for CEREBRUM

	Source Strength (Jy)				
	20	2	.5	.2	.1
Full Phase 12 Hour Tracks	434		126		29
Closure Phase 12 Hour Tracks	>267				

Table 4

Scatter in Dynamic Range Measurements

Dec. 64   12 Hour Tracks   Full Phase

DAISY

Source Flux (Jy)	D.R. (old)	D.R. (new)
2	270 ± 10 (4%)	279 ± 3 (1%)
.2	85 ± 6 (7%)	78 ± 2 (2.5%)

D.R. (old) is the old measure of dynamic range (map peak divided by peak of the difference map)

D.R. (new) is the RMS measure of dynamic range (map peak divided by 5 times the RMS of the difference map)

The scatter in dynamic ranges shown above were obtained from three independent reconstructions (FAKE, INVERT, and CLEAN) for each flux.