VLA TEST MEMORANDUM NO. 128

Informal Notes on Using the VLA for VLBI

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I. Equipment and Documentation

a. Terminals: MK II cassette; MK III, available about March, 1981

b. Frequency Standard: Hydrogen Maser (VLG-10, P8 - on loan from SAO)

c. Timing: excellent reception of Loran C - West Coast chain station at Searchlight, Nevada (total delay: emission + propagation + receiver $\sim$ 44256 microseconds; period : 99400 microseconds)

d. Documentation:

i) proposals: NUG Newsletter August 1, 1980.

ii) phasing the array: "How to Use the VLA for VLB," Clark, August 27, 1980.

iii) local oscillator system: "Concerning the VLA Local Oscillator settings," Hunt, November 28, 1978.

II. Phasing the Array

N Antennas of the VLA can be connected to form a phased array for VLB use. Currently, this is accomplished by observing a source and running ANTSOL, a standard VLA program that calculates instrumental phases for each antenna. These phases are passed to the Modcomp computer which inserts the proper phase shift in each signal before summation. This procedure takes about 15 minutes and hence the array is phased on data that is at least this old. Clark plans to automate the system by December so that the array will phase itself based on the analysis of every 10-second block of data. (A 1 Jy source gives about 1° rms phase noise in 10 sec with a 50 MHz bandwidth at 6 cm wavelength.) The principal problems with phasing are: (1) the beam or field of view is small and (2) atmospheric delays over the array reduce the effective collecting area and may make calibration somewhat uncertain. The beam sizes of various subarray are listed in Table 1.

The calibration of the phased array should be done by running the FILLER program with a 5 minute averaging time. The VLA data can then be examined with the standard VLA program LISTER on the DEC-10 which gives a matrix of all the fringe visibilities among VLA elements and their vector sum. This vector sum is the desired calibration term for VLBI.

More tradition strip-chart radiometry can be done to insure that a properly phased signal is getting into the VLB terminal and to monitor the overall phase stability of the array. The signals from each telescope are shifted in frequency and time to refer them to the array center and then are clipped (3 levels). The preclipped band is 0-50 MHz. These clipped signals are summed to form a pseudo-analog signal. The VLB converter takesa part of this signal, say 10-12 MHz, reclips and records it. This narrow band signal also passes through a square law detector (see Figure 1). The detected signal can be used to measure the effective radio "T_A/T_R" for the array. The following analysis shows how to interpret this detector output.

The voltage from the i th antenna is

$$x_i(t) = s_i(t) + n_i(t)$$

where s(t) is the Gaussian random process due to the source and n(t) is the one due to the receiver in the ith telescope. Ignore gain constants and assume that

$$\langle s_i^2 \rangle = T_{A_i}$$

$$\langle n_i^2 \rangle = T_{R_i}$$

The clipped signal is $x_{c_i}(t)$ (1, 0, -1). The analog sum signal is, therefore,

$$y(t) = \sum_{i=1}^{N} x_{c_i}(t)$$

and the detector output is

$$\langle y^2 \rangle = \langle \left(\sum_i x_{c_i} \right)^2 \rangle$$

$$= \sum_{i,j} \langle x_{c_i} x_{c_j} \rangle$$

Now, <u>if there are no phase errors in phasing the array</u>

$$\langle X_{c_i} X_{c_j} \rangle = 1 \qquad i = j$$

$$= C \left[\frac{T_{A_i} T_{A_j}}{(T_{R_i} + T_{A_i})(T_{R_j} + T_{A_j})} \right]^{\frac{1}{2}}$$ i [redacted] j

where C is the clipping correction. C = 0.84 for 3 level clipping with complete multiplication (see Bowers and Klinger, A&A Suppl., 15, 373, 1974). Hence,

$$\langle y^2 \rangle = N + C \sum_{i \neq j} \left[\frac{T_{A_i} T_{A_j}}{(T_{R_i} + T_{A_i})(T_{R_j} + T_{A_j})} \right]^{\frac{1}{2}}$$

If all antennas have the same T_A and T_R then,

$$\langle y^2 \rangle = N + C N (N-1) \frac{T_A}{T_R + T_A}$$

By going on source to measure the deflection $\langle y^2 \rangle_{on}$ and off source to measure $\langle y^2 \rangle_{off}$ we can calculate the quantity (familiar to all spectroscopist who use digital correlators)

$$q \equiv \frac{\langle y^2 \rangle_{ON} - \langle y^2 \rangle_{OFF}}{\langle y^2 \rangle_{OFF}} = C (N-1) \frac{T_A}{T_R + T_A}$$

Notice that if N = 1, then q = 0, since the antenna voltage is clipped so there is no difference between on and off source power. Other pecularities are: firing a noise tube would produce no response when the array is off source; on source, firing a noise tube would reduce $\langle y^2 \rangle_{on}$ since the correlation coefficients are reduced!

The desired calibration constant is therefore

$$\frac{N T_A}{T_R + T_A} = \frac{1}{C} \left(\frac{N}{N-1} \right) q$$

The phasing will not be perfect and each antenna produces a signal with an undesired phase shift ψ_i. Hence,

$$\langle y^2 \rangle_{ON} = N + C \frac{T_A}{(T_R + T_A)} \sum_{i \neq j} \langle \cos(\psi_i - \psi_j) \rangle$$

If the ψ_i's are assumed to be independent, zero mean, gaussian random variables with variance σ^2 (not very good assumptions) then

$$\langle \cos(\psi_i - \psi_j) \rangle = \mathrm{Re} \{ \langle e^{i\psi_i} e^{i\psi_j} \rangle \}$$

$$= \mathrm{Re} \{ \langle e^{i\psi_i} \rangle^2 \} = \left(e^{-\frac{\sigma^2}{2}} \right)^2 = e^{-\sigma^2}$$

Hence

$$\langle y^2 \rangle_{ON} = N + C \frac{T_A}{(T_R + T_A)} N(N-1) e^{-\sigma^2}$$

and

$$q^* = c\,\frac{T_A}{(T_R+T_A)}(N-1)\,e^{-\sigma^2}$$

The phase noise can therefore be estimated by the equation

$$\sigma = \left\{ \ln \frac{(N-1)T_A}{(T_R+T_A)q} \right\}^{\frac{1}{2}}$$

or

$$\sigma = \left\{ \ln \frac{q}{q^*} \right\}^{\frac{1}{2}}$$

III. Phasing Tests

We took some data with the detected analog-sum signal on August 28, 1980, just before and after sunset on what might be called a late summer day - T ∿ 70°F scattered (∿0.4 coverage) nontowering cumulus clouds ∿ 1 km thick.

EXAMPLES

1. See Figure 2

Source = 3C345

λ = 6 cm

S = 7.41 Jy

$T_A \approx 7.41/10 = 0.74$ K

$T_R = 53$ K

N = 15

(expect) $(N-1)\frac{T_A}{T_R} = 14\,\frac{0.74}{53} = 0.20$

(measured) $q = \frac{208-174}{174} = 0.20 \Rightarrow \frac{q}{c} = 0.24$

The flux has either increased to 9.1 Jy or possible C = 1. In any event the phasing is excellent and very stable.

2. <u>See Figure 3</u>

Phase noise is clearly a problem

Source = W49 (Maser)

λ = 1.3 cm

time = 03:15 - 04:15 GMT (sunset $\sim$ 1:30 GMT)

$T_R \sim 400$ K

$T_A \sim 400$ K

N = 15

$$\frac{(N-1)\ T_A}{T_R+T_A} \approx 14\ \frac{400}{800} \sim 7$$

Assume that the peak response occurs when the phase errors are all zero. Then

$$q = \frac{215-27}{27} \sim 6.9 \Rightarrow \frac{q}{c} = 8.3$$

The amplitude about 30 minutes after phasing gives

$$q^* = \frac{150-28}{28} = 4.4$$

Hence

$$\sigma = [\ln \frac{6.9}{4.4}]^{\frac{1}{2}} = 0.67 \text{ rad} = 38°$$

3. See Figure 4

Source W49 (Maser)

Time = 00:15 - 01:15 GMT

$$q^* = \frac{110-35}{35} = 2.1$$

$$\sigma = [\ln \frac{6.9}{2.1}]^{\frac{1}{2}} \sim 1.1 \text{ rad} \sim 62°$$

The expected phase noise at 6 cm during this time would be about 14°. Hence the signal loss due to phase noise is only ($e^{-\sigma^2}$ $\sim$ 0.94) about 6 percent. Hence the smooth trace in Figure 2. At 6 cm the VLA should probably have the effective area of 25 antennas much of the time.

4. See Figure 5

Source = 3C345

λ = 1.3 cm

Time = 05 GMT

q^*= 0.018

As is well known and dramatically illustrated here, the phase noise decreases greatly a few hours after sunset!

IV. VLBI

A VLBI experiment was run during the same period that the phasing tests were performed. The other station was Haystack (manned by Schneps and Haschick). The VLBI data were processed by Craig Walker. The instrumental delay was about 6 microseconds. Walker gives a preliminary baseline of:

Bx = -3093522 meters

By = 584703 meters

Bz = -742003 meters

Figure 6 shows the video bandpass of both stations. At the VLA the input to the VLB converter was 10-12 MHz with the VLA bandpass set to 12.5 MHz. The VLA lowpass filter appears to have its 3 db point at 11.5 MHz. Hence, in future experiments the 25 MHz bandpass should be used if a 10-12 MHz IF is desired.

3C345 was observed well after sundown in the period 04:30 - 05:30 UT when the atmosphere has settled down (see Figure 5 and Section III, example 4). The cross correlation functions, averaged for two minutes, are shown in Figure 7 for 2 cases: (bottom) Haystack vs. VLA (Antenna 25); and (top) Haystack vs. VLA (phased). The fringe visibility is a factor of 2.2 bigger when using the phased array than when using the best antenna. Hence, at

1.35 cm, the phased array has 5.0 times the SNR of the single best antenna. This seems reasonable since the system temperatures ranged from 300 to 1000 K. If all the system temperatures were 300 K, we would have expected an SRN improvement of 15.

We made VLB observations of W49 using the phased array from 0^h until 4^h UT. The fringe amplitude and phase for a 3000 second run ending at 01^h, with 5 second integration period, are shown in Figures 8 and 9. Note that the amplitude drops to as low as ~20 percent of its peak value as the VLA becomes dephased. The time scale of significant changes in the phasing is about one minute (compare Figure 4).

The amplitude and phase of a second run on W49 ending at 04^h UT are shown in Figures 10 and 11. The mean fringe amplitude has increased by a factory of 1.7 over the earlier run. Note the monotonic decrease in fringe amplitude from 1.75 to 1.3 as the VLA slowly dephased over a 40 minute period (compare with Figure 3).

The coherence time and rms phase noise functions are plotted versus integration time in Figure 12. The coherence, C(τ), is defined as

$$C(\tau) = \left< \left| \frac{1}{\tau} \int_0^\tau e^{i\phi(t)} \, e^{i\omega t} \, dt \right| \right>$$

where ϕ is the interferometer phase and w is a frequency adjusted to maximize $C(\tau)$, i.e. to remove the linear phase drift.

At 4^h UT the coherence time of the interferometer was about 3 times longer than at 1^h UT. The coherence time at 4^h UT ($C(\tau) = 0.5$ at $\tau \sim 2000$ seconds) is comparable to that normally obtained at K band on other VLBI experiments.

V. Things to remember doing VLBI with the VLA.

1. Any single antenna can be used for VLBI simply by tapping the video signal on the T5 module. Do not forget to suppress the LO phase switching.
2. When using the phased array there is an extra delay of 163 microseconds due to the delay line system.

VI. VLBI in September & December 1980

The recommended setup for 6 cm is shown in Figure 13 and for 1.3 cm (spectral line) is shown in Figure 14.

VII. MK III Frequencies

The VLA frequency conversion scheme is rigid and sets constraints on MK III operation. Most of the IF bands are 50MHz wide and a full bandwidth of 50 MHz can be achieved only by observing a certain discrete frequencies (see Figure 15). A reasonable set of MK III center frequencies are 1665, 4985, and 23785 MHz.

TABLE 1

RESOLUTION OF VARIOUS SUBARRAYS

OF THE VLA FOR PHASED-ARRAY OPERATION

ARRAY	ANTENNAS	L[(1)] (m)	MAXIMUM RESOLUTION[(2)] (18cm)	(6cm)	(2cm)	(1.3cm)
A	27	21000	1"0	0"3	0"11	0"08
A-1	24	17157	1.2	0.4	0.14	0.09
A-2	21	13644	1.6	0.5	0.18	0.12
A-3	18	10473	2.0	0.7	0.22	0.15
A-4	15	7659	2.8	0.9	0.31	0.21
A-5	12	5223	4.1	1.4	0.46	0.31
A-6	9	3188	6.7	2.2	0.74	0.51
A-7	6	1590	13.5	4.5	1.50	1.01
B	27	6393	3.3	1.1	0.37	0.25
B-1	24	5223	4.1	1.4	0.45	0.31
B-2	21	4153	5.2	1.7	0.57	0.38
B-3	18	3188	6.7	2.2	0.74	0.51
B-4	15	2331	9.2	3.1	1.02	0.69
B-5	12	1590	13.5	4.5	1.50	1.01
C	27	1946	11.0	3.7	1.22	0.83
C-1	24	1590	13.5	4.5	1.50	1.01
C-2	21	1264	17.0	5.7	1.89	1.27
C-3	18	970	22.1	7.4	2.45	1.66
D	27	592	36.2	12.1	4.0	2.72
D-1	24	484	44.3	14.8	4.9	3.32

(1) Length of SW arm

(2) Minimum beamwidth of phased array $\equiv \lambda/(1.73L)$

Figure Captions

1. Schematic diagram of phased VLA and VLBI system.
2. Detected signal from phased array vs. time on 3C345 at 6 cm.
3. Detected signal from phased array vs. time on W49 at 1.3 cm from 03:00 - 04:00 UT.
4. Detected signal from phased array vs. time on W49 at 1.3 cm from 00:00 - 01:00 UT.
5. Detected signal from phased array vs. time on 3C345 at 1.3 cm from 05:00 - 05:20 UT.
6. Video bandpasses for Haystack (top) and VLA (bottom). Roll-off in VLA filter is due to 12.5 MHz VLA filter since the IF is 10-12 MHz.
7. Cross correlation functions from 2 minute segments of data on Haystack-VLA baseline at 1.3 cm. (Top) Haystack vs. 15 antenna phased array. (Bottom) Haystack vs. antenna 25.
8. Fringe amplitude vs. time for frequency channel 118, Haystack-phased VLA. Source, W49. Data from 00:07 UT until 00:57 UT, with averaging time of 15 seconds. Deep fades are due to changes in VLA phasing caused by atmospheric turbulence.
9. Fringe phase vs. time for observation in Figure 8.

10. Fringe amplitude vs. time for frequency channel 118, Haystack-phased VLA. Source, W49. Data from 03:16 UT until 03:49 UT.

11. Fringe phase vs. time for observation in Figure 12. The phase stability is much improved over 01^h run but there are still phase jumps (T = 1300 sec).

12. (Top) Phase coherence vs. integration time and (bottom) rms phase deviation vs. integration time for the 2 observations of the W49 maser at 1.3 cm. The coherence is about 3 times better for the late evening run compared to the "sunset" run.

13. Recommended LO setup for 6 cm in September 1980 for VLB Network run.

14. LO setup for August 1980 VLBI test. This system is recommended for future H_2O VLBI runs with bandwidth = 25 MHz as shown.

15. Possible MK III frequencies that will allow as much of the 56 MHz record bandwidth to be used.

FIGURE 1

ANALOG-SUM & VLBI SYSTEM

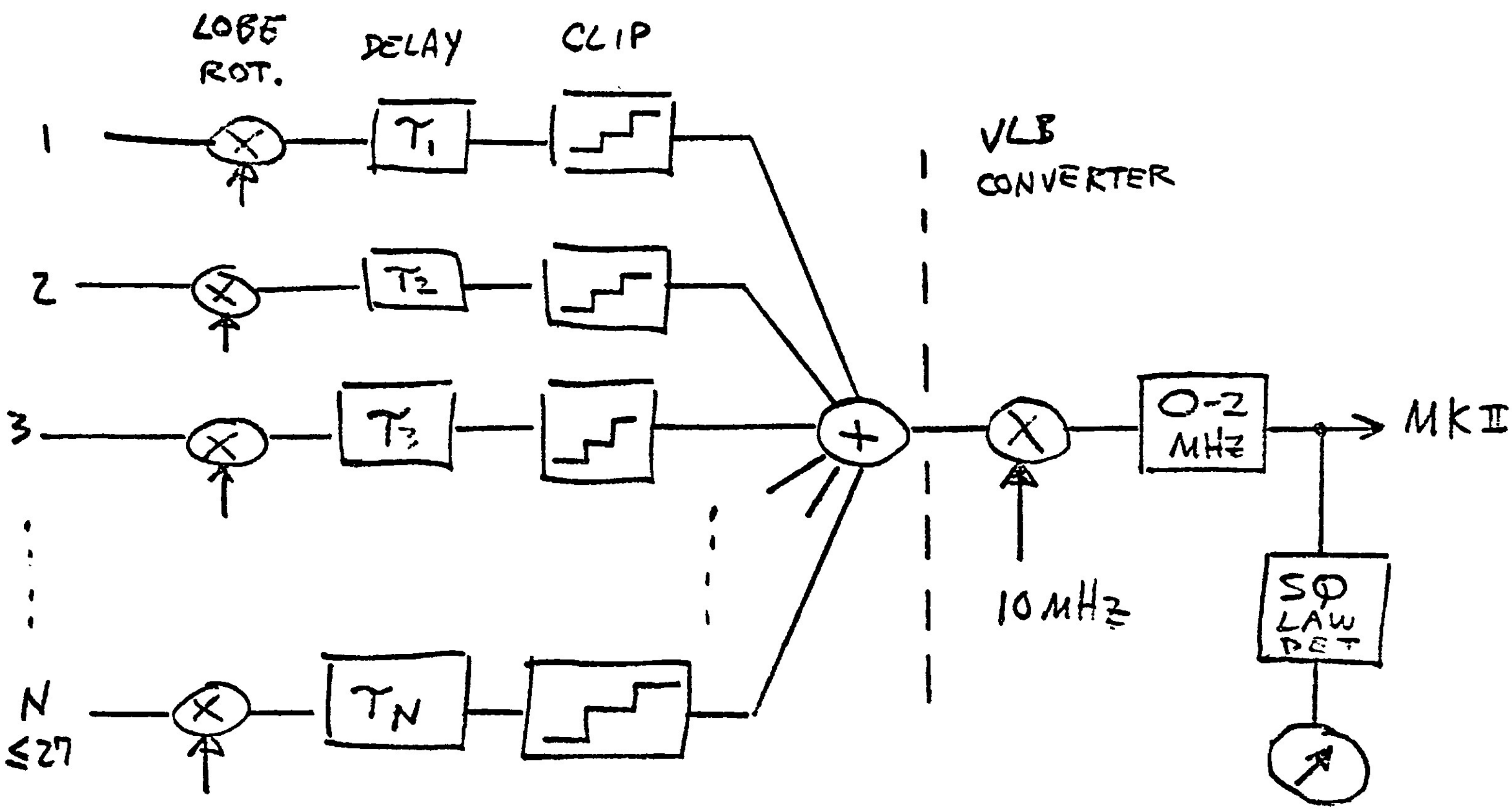


FIGURE 2

3C345

8/29/80

02:31 UT

C ARRAY (N=15)

$\nu = 5\,\mathrm{GHz}$

15 cm/hr

$S = 7.41$

$T_R = 53$

$T_A = \frac{7.41}{10}$

$(N-1)\,\frac{T_A}{T_R} = 0.20$

$\frac{\mathrm{ON-OFF}}{\mathrm{OFF}} = 0.20$

RMS ~ 0.2 Jy

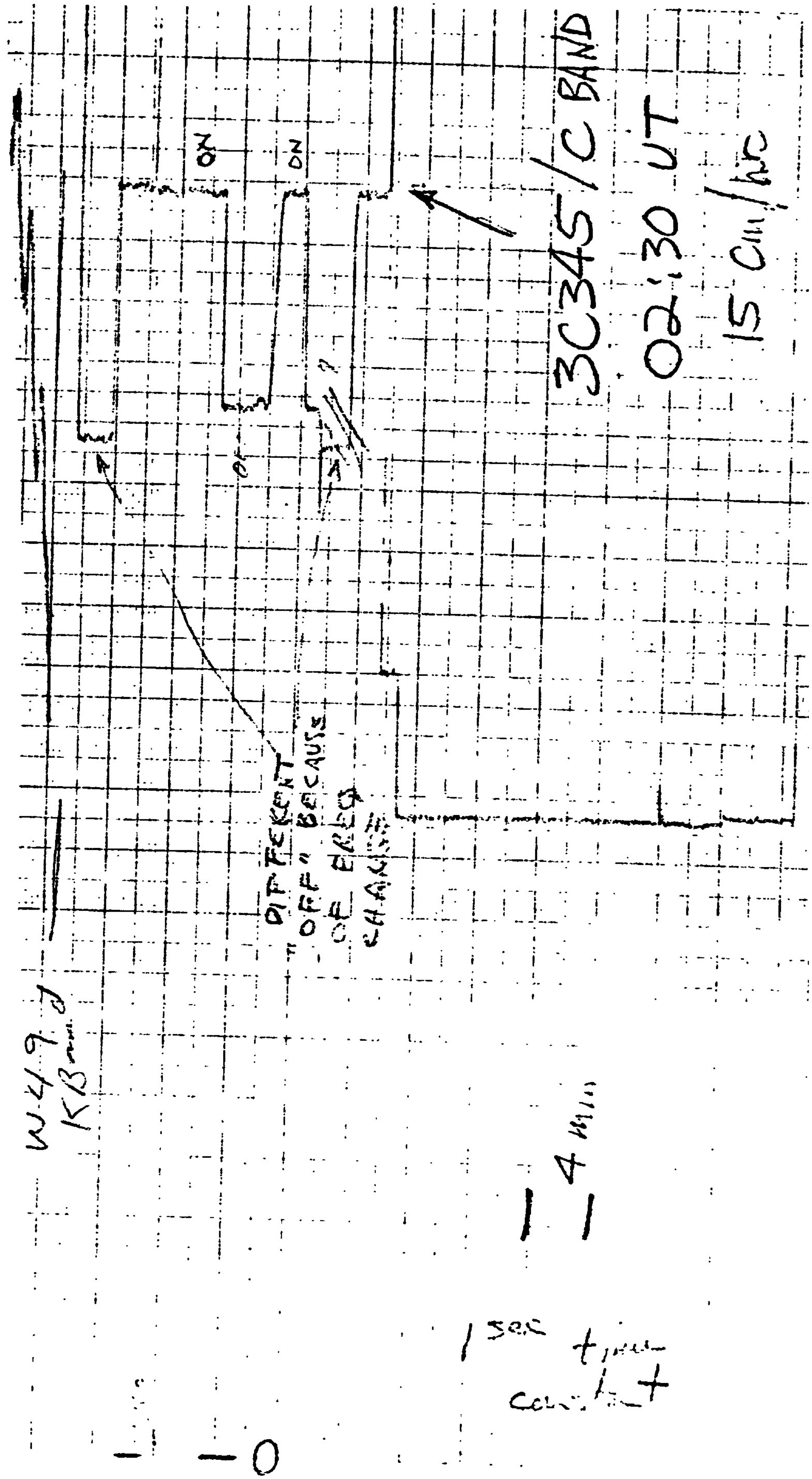
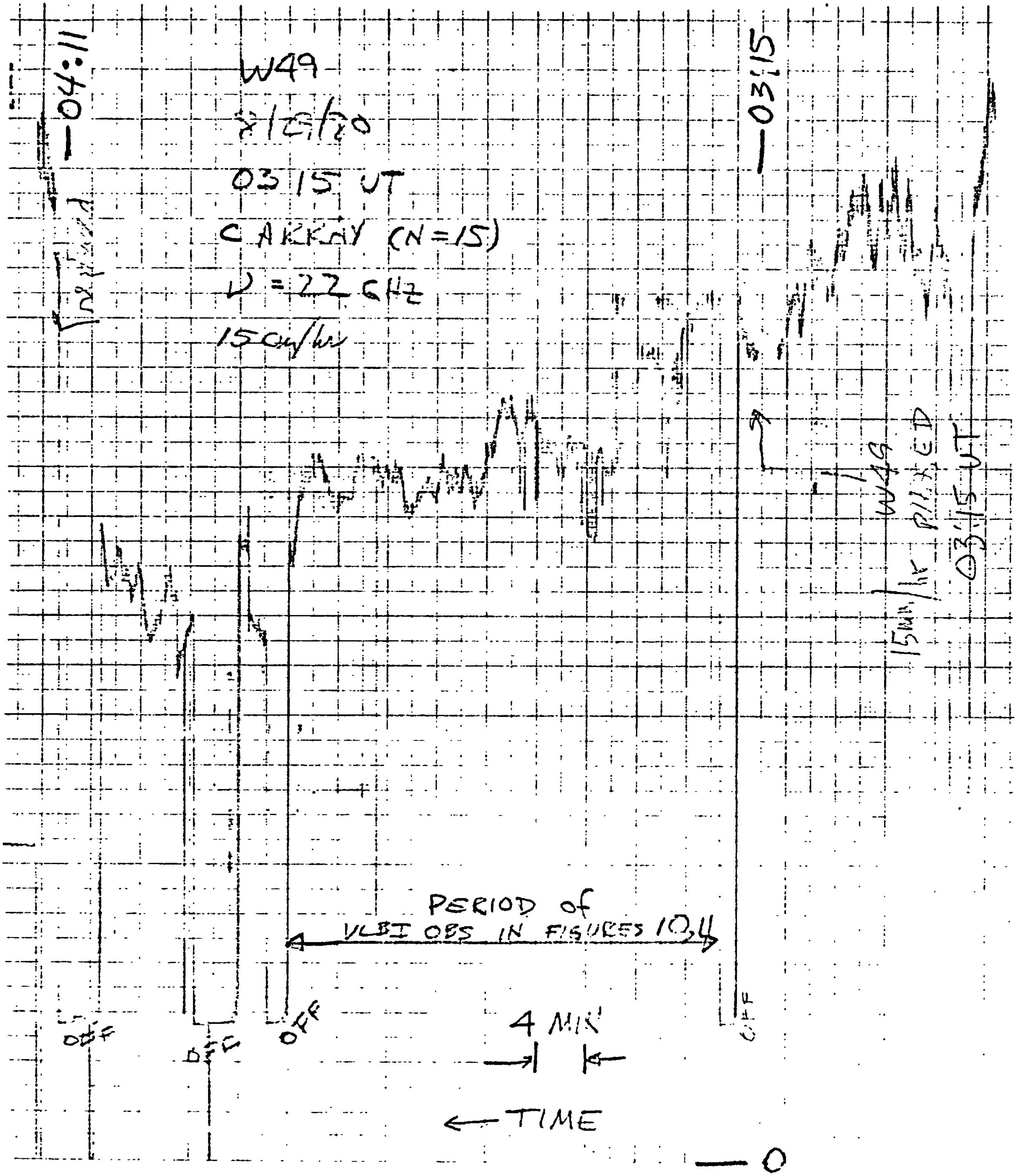


FIGURE 3


W49
03 15 UT
C ARRAY (N=15)
ν = 22 GHz
15 cm/hr
04:11
03:15
OFF
OFF
OFF
OFF
PERIOD of
VLBI OBS IN FIGURES 10,11
4 MIN
← TIME
0
W49
03:15 UT

SUNSET ~ 01:30 UT FIGURE 4

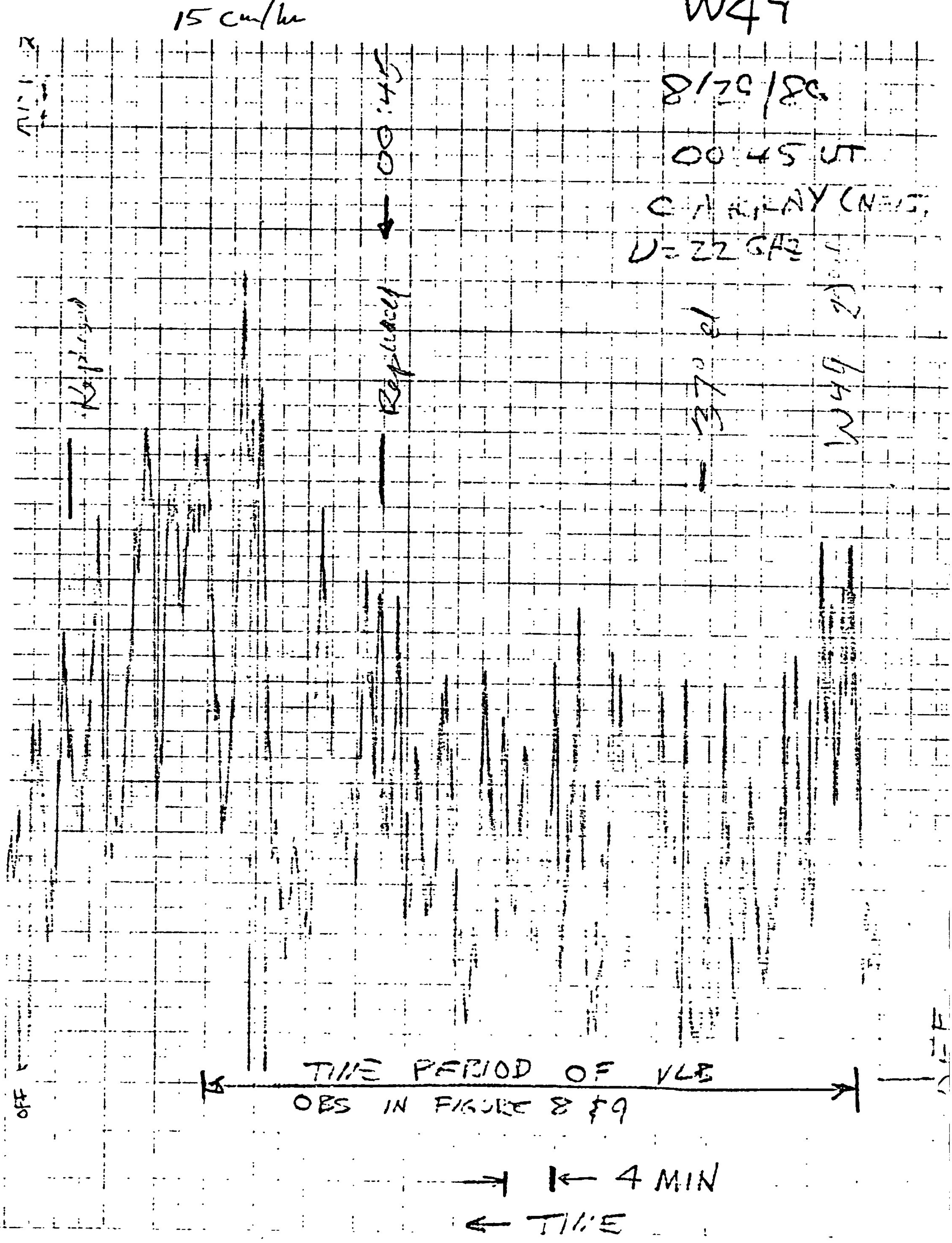
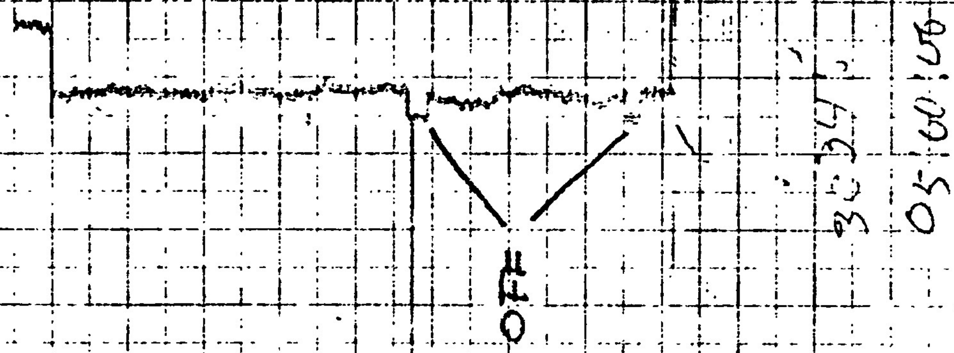


FIGURE 2



3C345

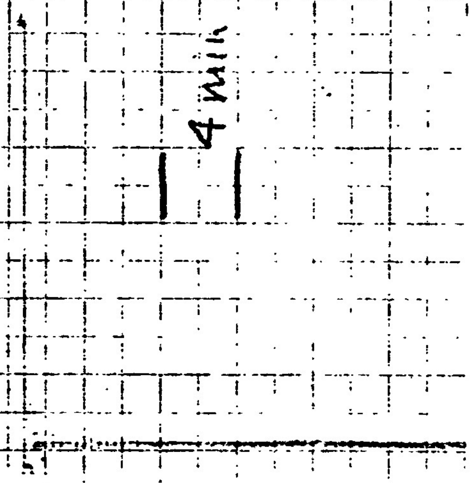
8/25/20

05^h UT

C ARRAY (N=15)

ν = 22 GHz

15 cm/hr



S = 7.1 Jy

$T_A \sim \frac{7.1}{12}$

$T_R \sim 400$

$(N-1)\frac{T_A}{T_R} = 0.020$

$\frac{ON - OFF}{OFF} = \frac{4}{225} = 0.018$

FIGURE 6

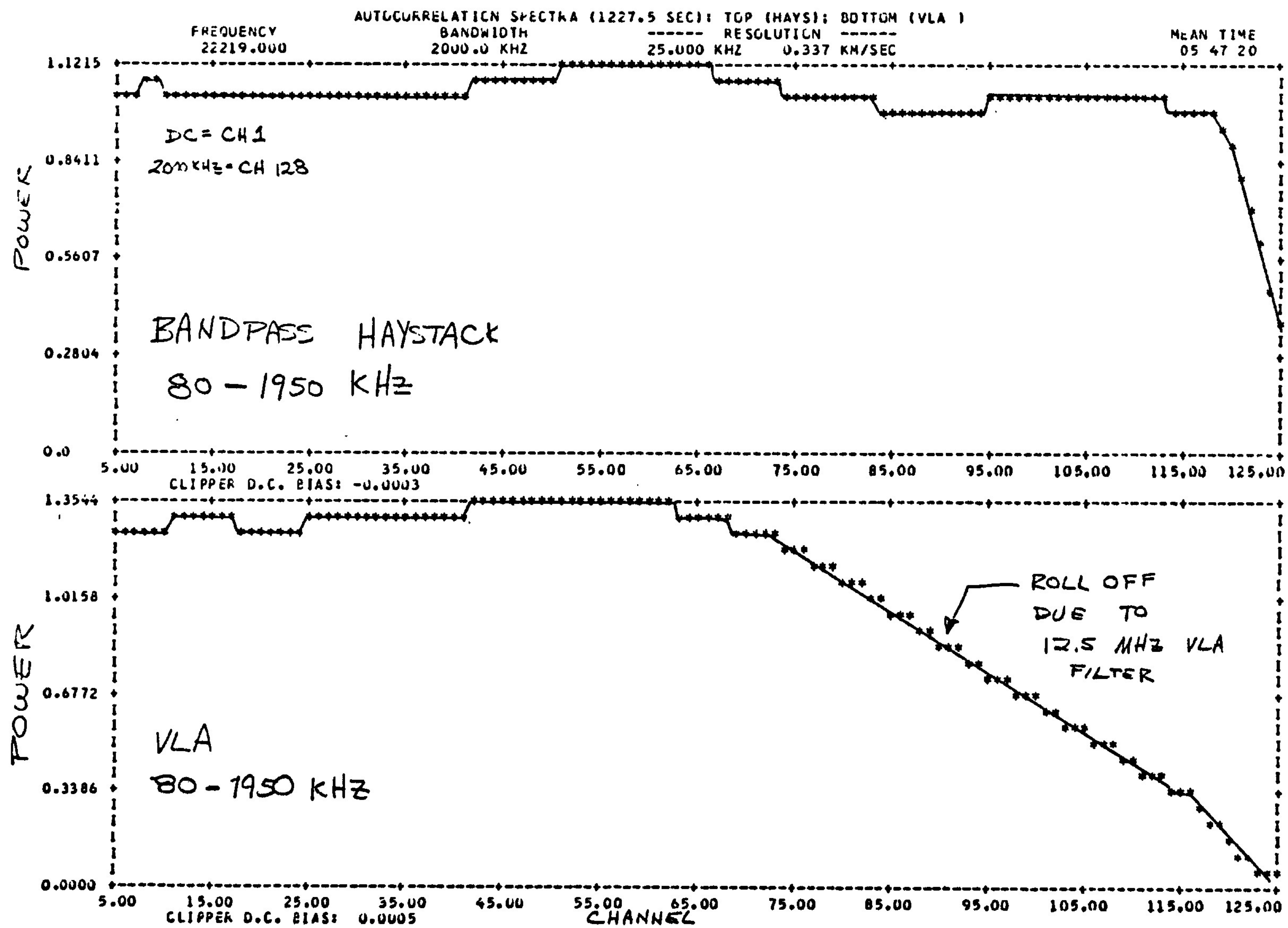

HAYS --> VLA
2420600 (1)
M33 (CN)
AUTOCORRELATION SPECTRA (1227.5 SEC): TOP (HAYS): BOTTOM (VLA)
FREQUENCY 22219.000
BANDWIDTH 2000.0 KHZ
------ RESOLUTION ------
25.000 KHZ 0.337 KM/SEC
MEAN TIME 05 47 20
DC = CH 1
2000 KHz = CH 128
BANDPASS HAYSTACK
80 – 1950 KHz
POWER
CLIPPER D.C. BIAS: -0.0003
VLA
80 - 1950 KHz
ROLL OFF DUE TO 12.5 MHz VLA FILTER
CLIPPER D.C. BIAS: 0.0005
CHANNEL

FIGURE 7

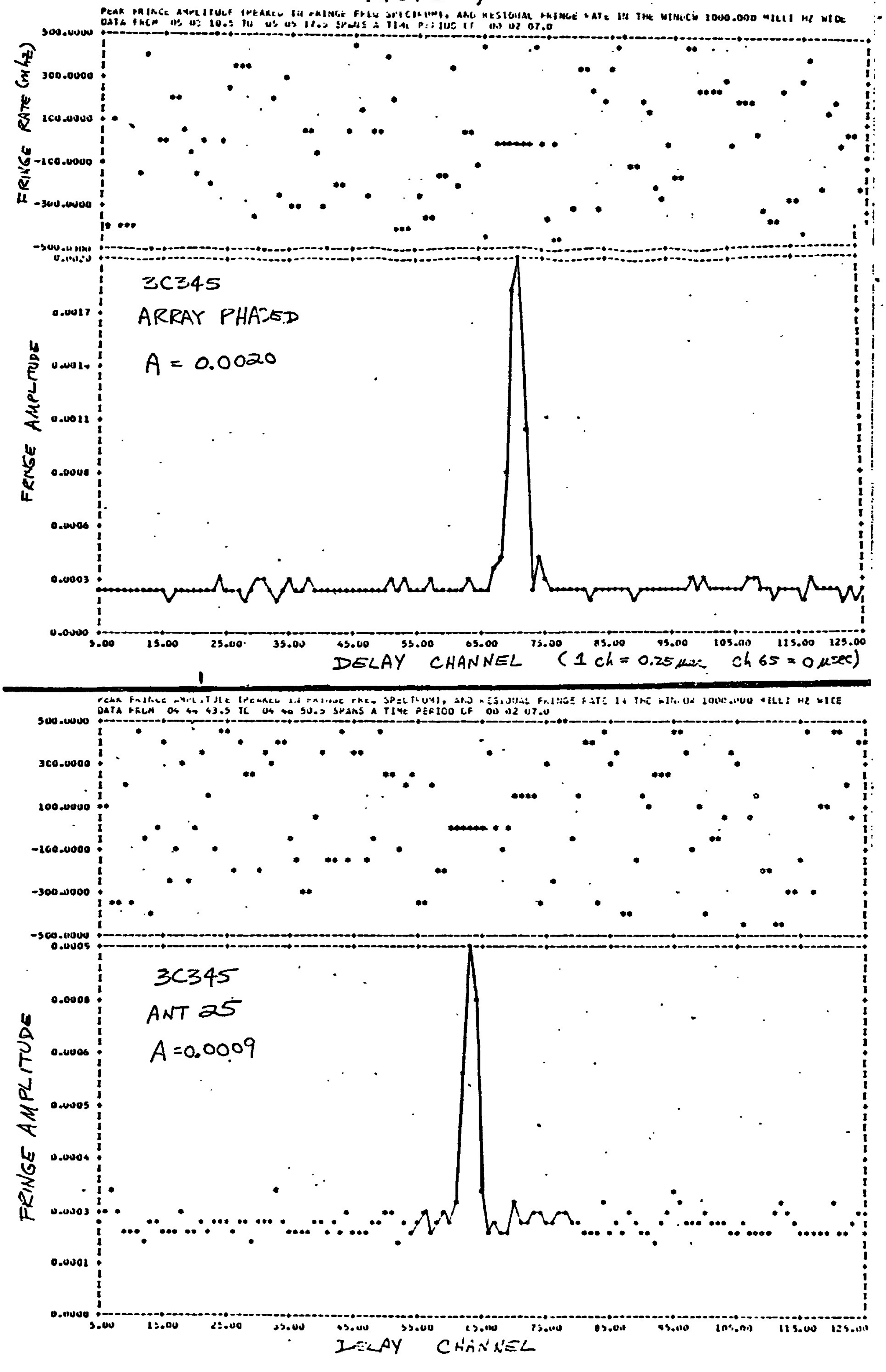

PEAK FRINGE AMPLITUDE (PEAKED IN FRINGE FREQ SPECTRUM), AND RESIDUAL FRINGE RATE IN THE WINDOW 1000.000 MILLI HZ WIDE
DATA FROM 05 03 10.5 TO 05 05 17.5 SPANS A TIME PERIOD OF 00 02 07.0
FRINGE RATE (mHz)
500.0000
300.0000
100.0000
-100.0000
-300.0000
-500.0000
FRINGE AMPLITUDE
3C345
ARRAY PHASED
A = 0.0020
5.00
15.00
25.00
35.00
45.00
55.00
65.00
75.00
85.00
95.00
105.00
115.00
125.00
DELAY CHANNEL (1 ch = 0.25 μsec ch 65 = 0 μsec)
DATA FROM 04 44 43.5 TO 04 46 50.5 SPANS A TIME PERIOD OF 00 02 07.0
FRINGE AMPLITUDE
3C345
ANT 25
A = 0.0009
DELAY CHANNEL

FIGURE 8

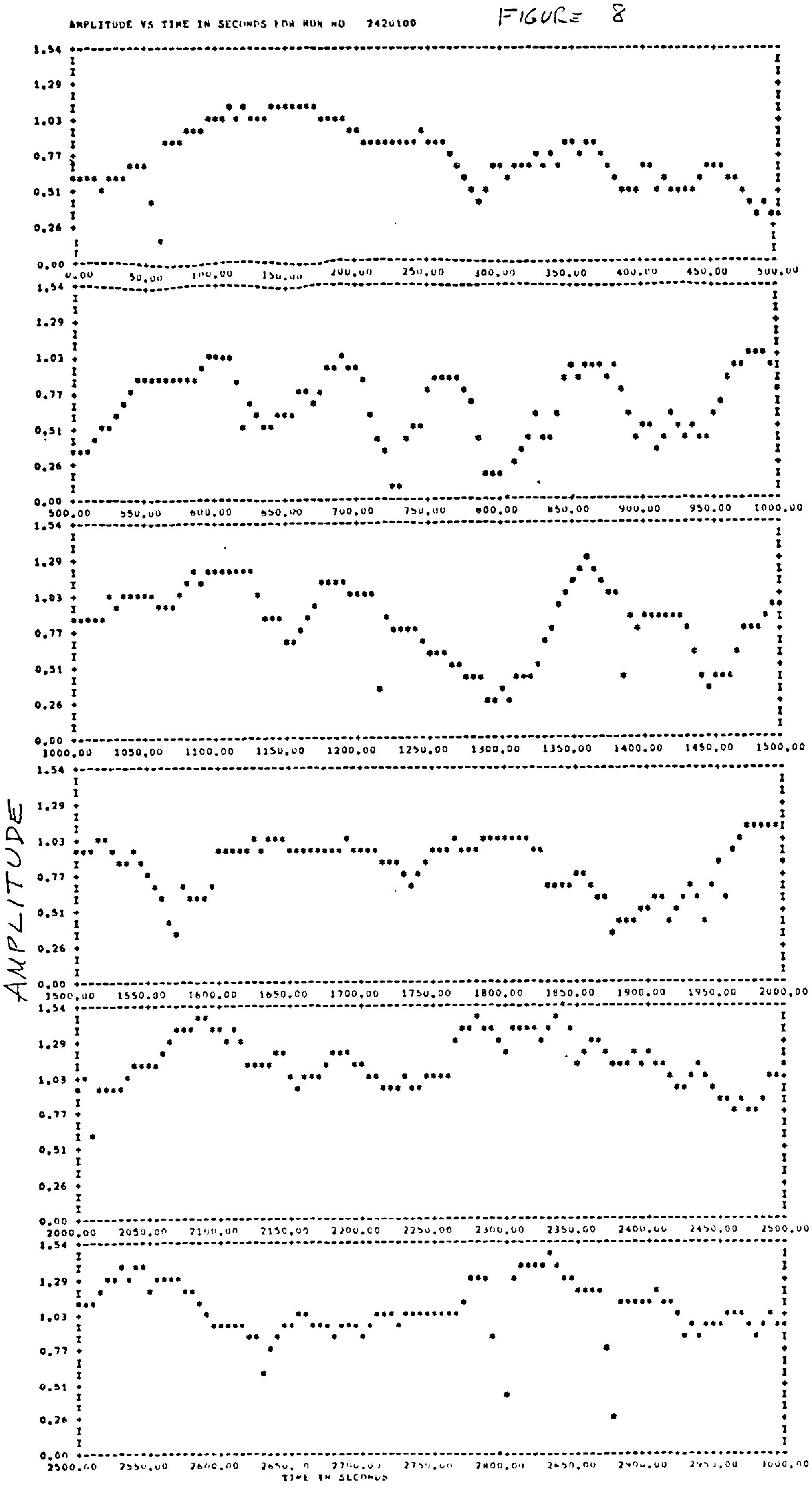
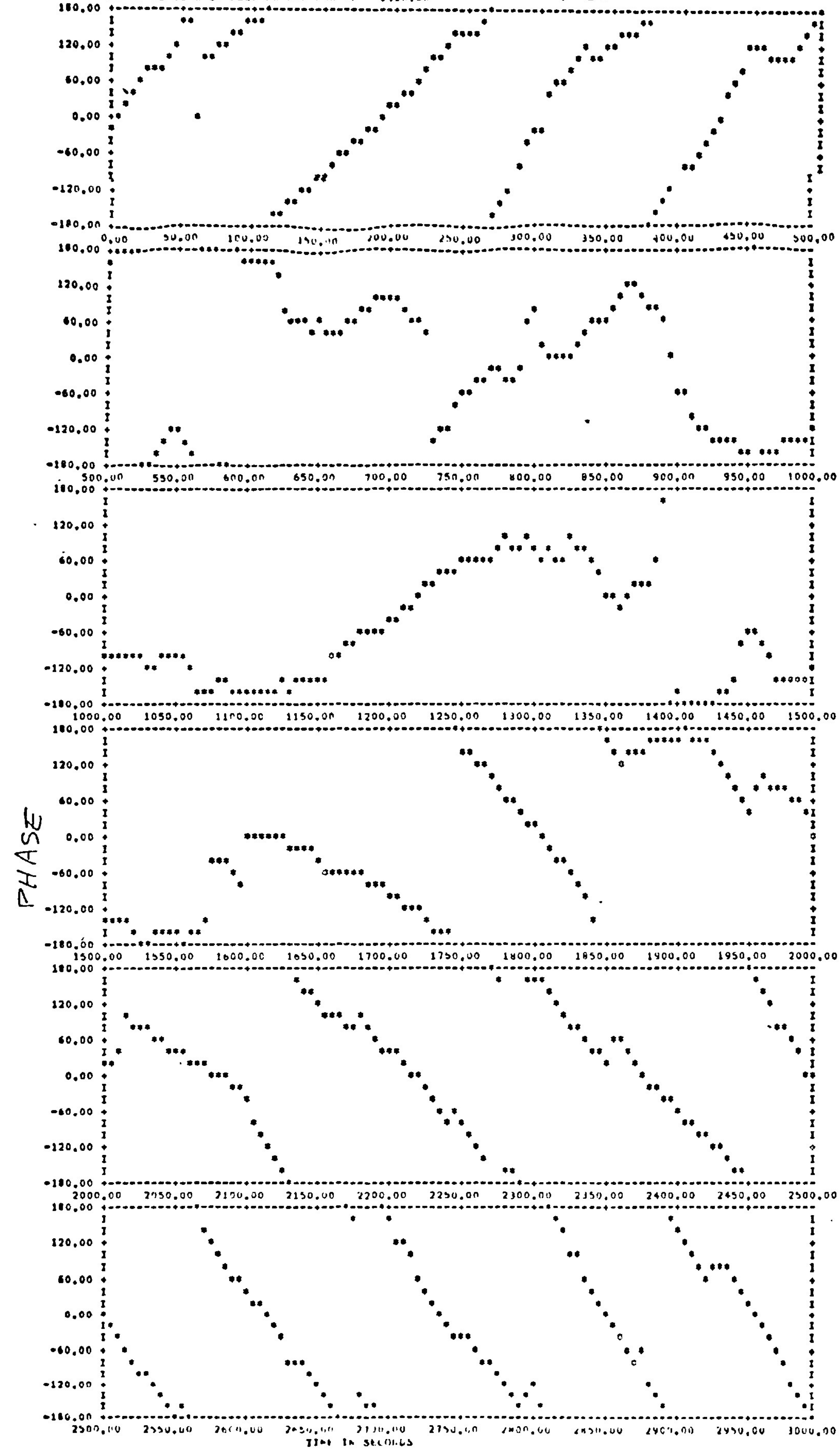

AMPLITUDE VS TIME IN SECONDS FOR RUN NO 2420100
AMPLITUDE
TIME IN SECONDS

FIGURE 9

PHASE VS TIME IN SECONDS FOR RUN NO 2420100



AMPLITUDE VS TIME IN SECONDS FOR RUN NO 2420400

FIGURE 10

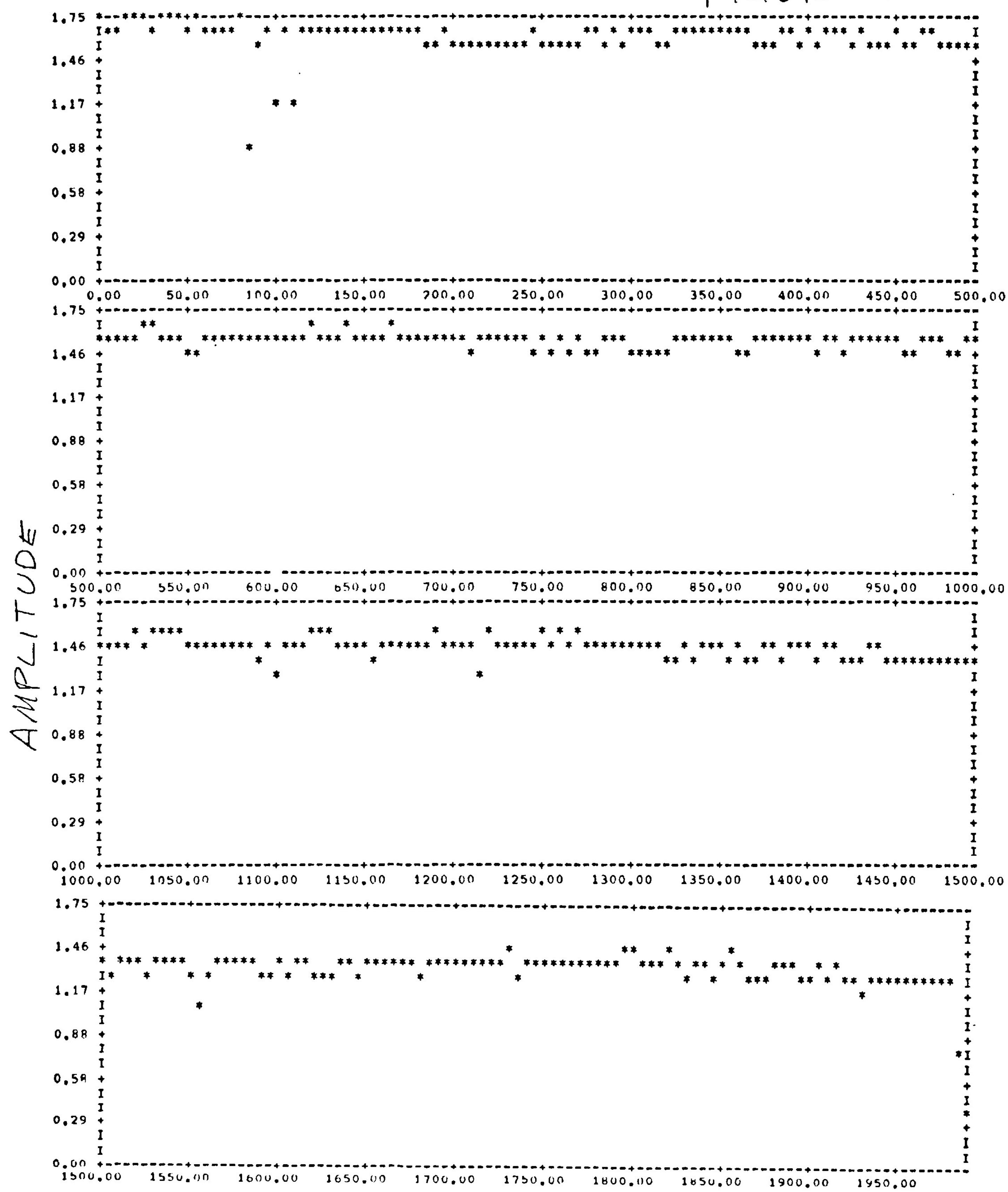


FIGURE 11

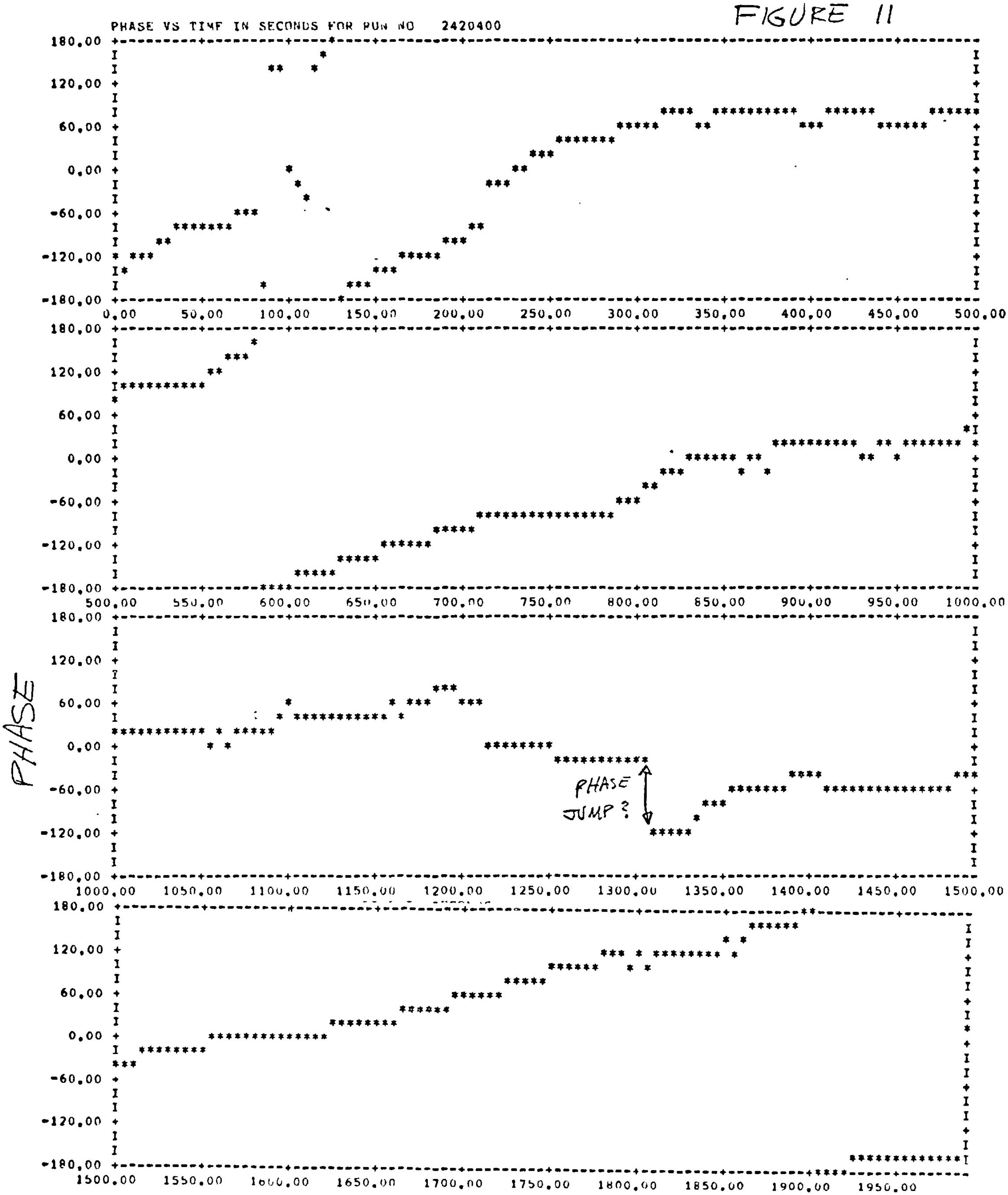
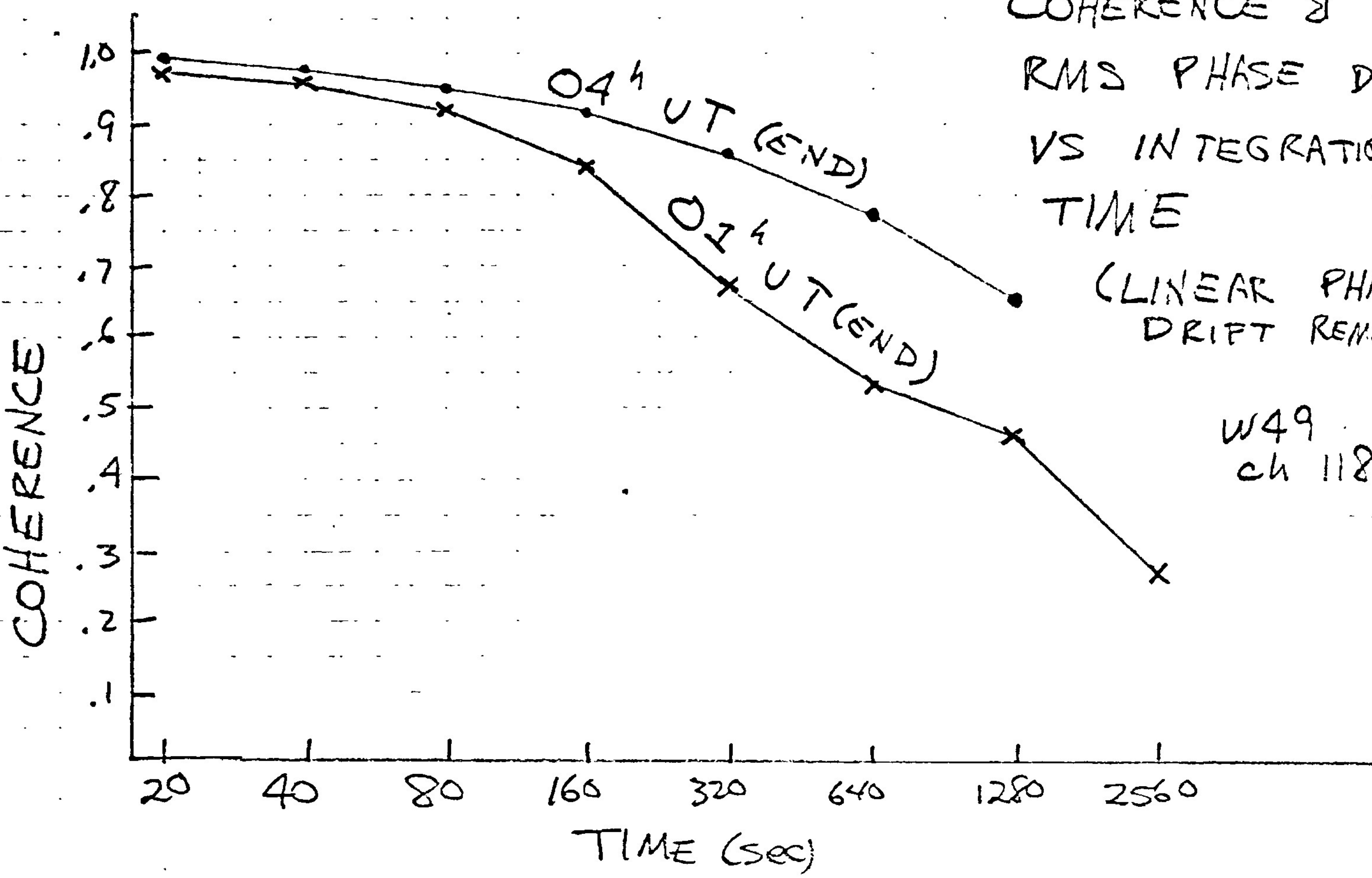

PHASE VS TIME IN SECONDS FOR RUN NO 2420400
PHASE
PHASE JUMP ?
180.00
120.00
60.00
0.00
-60.00
-120.00
-180.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400.00
450.00
500.00
550.00
600.00
650.00
700.00
750.00
800.00
850.00
900.00
950.00
1000.00
1050.00
1100.00
1150.00
1200.00
1250.00
1300.00
1350.00
1400.00
1450.00
1500.00
1550.00
1600.00
1650.00
1700.00
1750.00
1800.00
1850.00
1900.00
1950.00

FIGURE 12

COHERENCE & RMS PHASE DE[redacted] VS INTEGRATION TIME

(LINEAR PHAS[redacted] DRIFT REMOVED

W49 ch 118



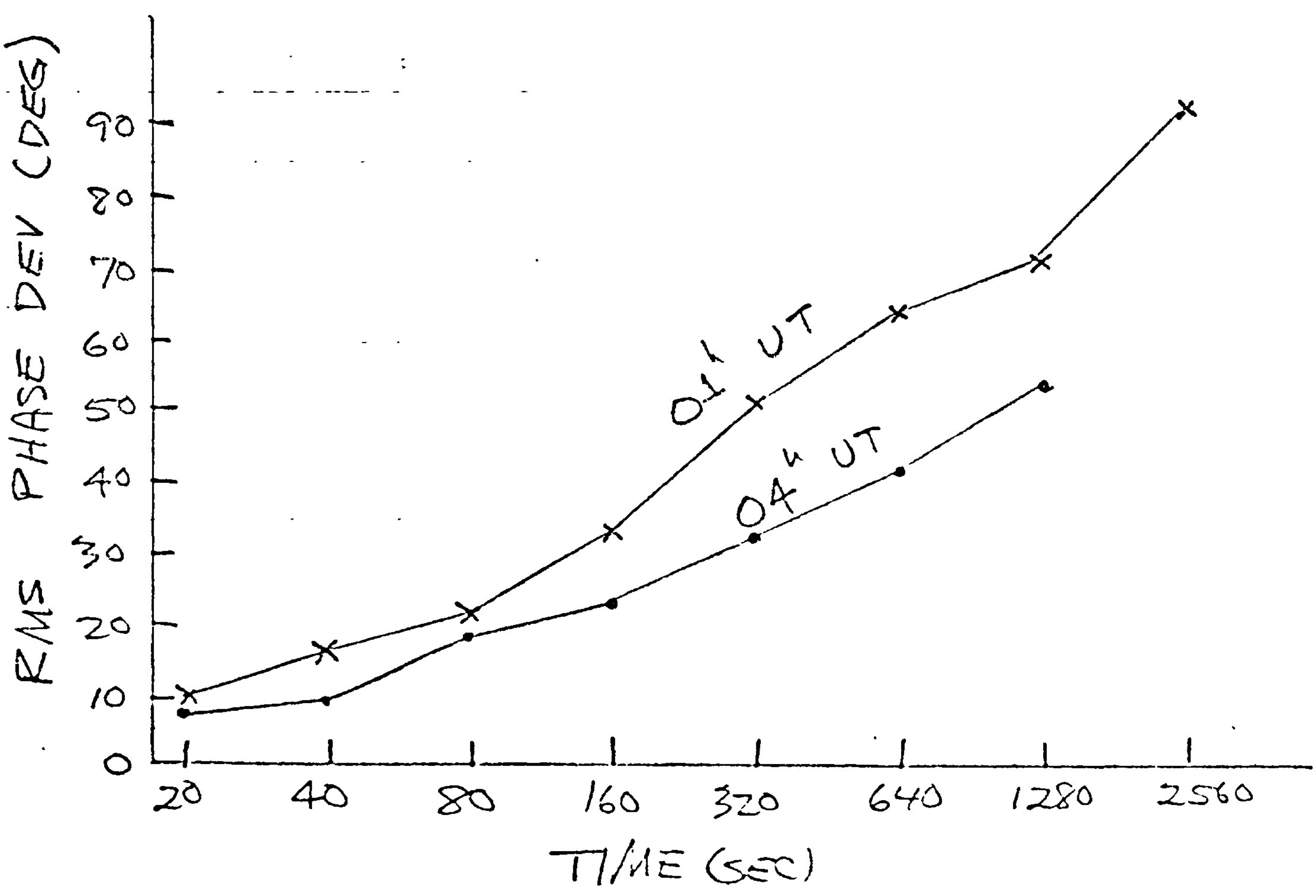
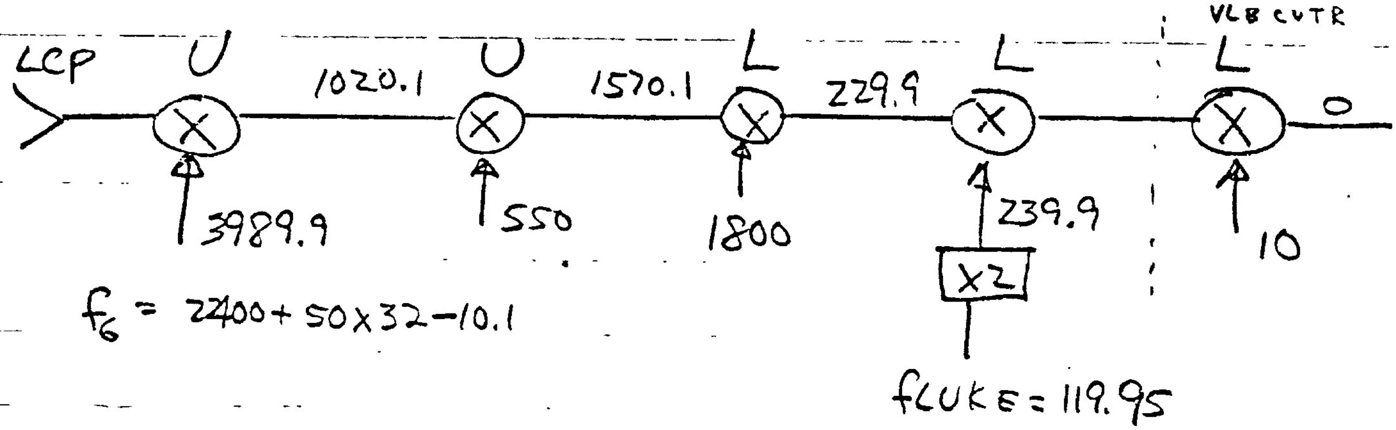


FIGURE 13

RECOMMENDED SETUP FOR 6 cm VLBI 9/80



f_6 = 2400 + 50 x 32 − 10.1

5010 − 5008 → 0 − 2 MHz

BASIC FREQUENCIES: f_6 = 3989.9 MHz
fLUKE = 119.95

<u>OBSERVE PARAMETERS</u> (check <u>LOSER</u>)

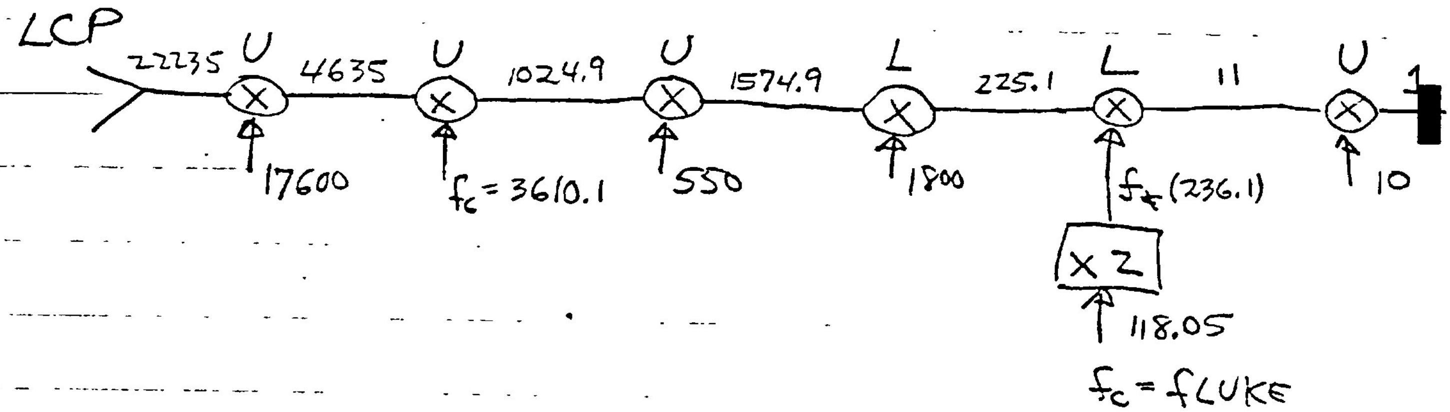
LO1AB = 0
LO1CD = 0
LOSYA = 3690
LOSYB = 3990
LOSYC = 3440
LOSYD = 3990

LOFIAC = 110.1
LOFIBD = 210.1

BAND = C, WIDTH = 1 (25 MHz)

FIGURE 14

CONFIGURATION FOR H_2O VLBI/MKII/LCP



NB f_{SKY} = RF BANDCENTER → 1 MHz

f_c = FLUKE = $f_*/2$ = $(22471.1 - f_{SKY})/2$

OBSERVE PARAMETERS

LO1AB=17.6

LO1CD = 17.6

LOSYA = 3310

LOSYB = 3610

LOSYC = 3060

LOSYD = 3610

NOTE A = B−300

C = B −550

D = B

LOFIAC = $350 - 2f_c$ = $f_{SKY} - 22121.1$

LOFIBC = $450 - 2f_c$ = $f_{SKY} - 22021.1$

BAND= K, WIDTH = 1 (25 MHz)

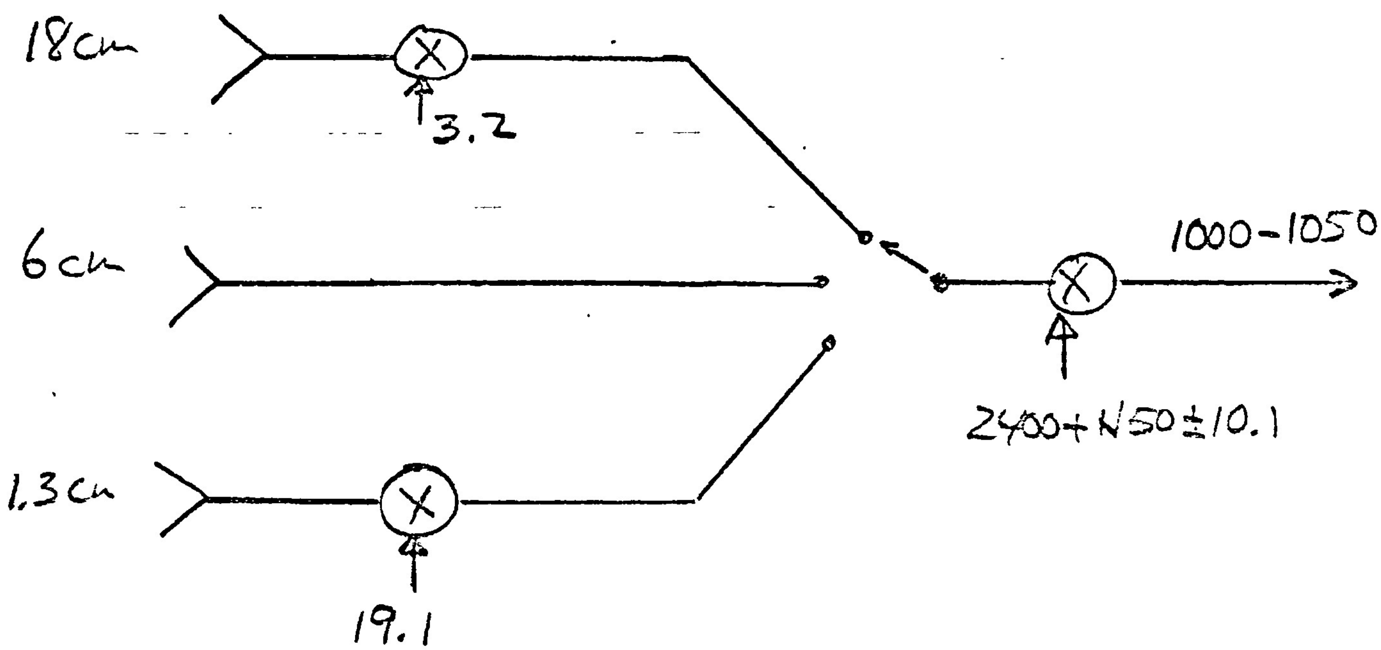
THIS CONFIGURATION WILL HANDLE

$22221 < f_{SKY} < 22259$

$f_* < 250$ ⟶ ↑ ↑ ⟵ IF BP LIMIT

FIGURE 15

MK III FREQUENCIES FOR FULL BANDWIDTH (56 MHz)



some possible frequencies

1415
1435

1635
1665
1685

4965
4985
5015

23765
23785 ← PROTECTED BAN
OFF H_2O