STANFORD FIVE-ELEMENT INTERFEROMETER
OPERATING MANUAL
(preliminary)

prepared by the staff of the
Stanford Radio Astronomy Institute

edited by S. J. Wernecke

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1. INTRODUCTION

This operating manual has been written to acquaint the new user with operating procedures for the Stanford five-element interferometer. It is by no means a comprehensive discussion as the Stanford array is a sophisticated instrument not easily described in a few pages of text. Since a thorough understanding of the system is difficult to achieve in a short period of time, it is expected that the new user will increase his basic knowledge through operating experience.

Documentation on the Stanford array is contained in several volumes of in-house reports called glints. Glints cover a wide range of topics including antenna construction, electronic hardware, computer software, results of observations, and the use of interferometric data. Most glints have not been written as tutorials, and some may be difficult reading for those not familiar with local terminology. Certain glints are of interest to the new user. They are referenced in this manual and included in the appendix. Reference volumes of all glints can be found at the field site and at the office on campus. Extra copies of single glints can be obtained through the Institute secretary.

2. LICENSING PROCEDURE

Unlike the situation at some installations, the observer using the Stanford interferometer is also the operator; he controls the antenna drive system, the computer, and associated electronic hardware. The Institute staff is available to provide some assistance; however, this is generally limited to normal business hours. The night-time observer will find he is usually the only person at the field site. As improper use of the system poses a threat to personnel and equipment, new observers must demonstrate competence in operating the interferometer. Authority to operate the interferometer is granted only after the new user completes the licensing procedure described below.

(1) After reading the operating manual, the new user will be asked to complete a short (closed book) exam which covers aspects of the antenna drive system. This knowledge is essential for safe operation of the array. Questions are limited to the material presented in Section 4 of this manual.

(2) The successful examinee will be issued a learner's permit which allows him to operate the array in the presence of an Institute staff member. By assisting in actual observations and by participating in special training sessions, the trainee will gain experience with the antenna drive system, the electronic hardware, the computer, and methods of data collection and reduction.

(3) When the trainee feels ready, he will be asked to perform a short observation in the presence of (but unassisted by) a member of the Institute staff. The examinee will be required to:

(a) precess the source to the date of the examination
(b) run the on-line interferometer program
(c) set the antennas on the source
(d) take gain and local oscillator line length measurements
(e) take several integrations
(f) terminate the on-line program and stow the antennas.

After completion of these steps, the new user will be considered a license operator, although it should be clear to him that his training is far from complete and that it is his responsibility to continue to develop his understanding of the system.

3. OVERVIEW OF THE SYSTEM

A preliminary description of the Stanford interferometer is contained in the July, 1971 issue of Sky and Telescope. A more detailed report by Bracewell et al. is contained in Proceedings of the IEEE, September, 1973. The appendix includes copies of both papers. The new user is encouraged to read both papers. Institute staff members will be happy to discuss topics which are not covered adequately in these papers.

4. ANTENNA DRIVE SYSTEM

The procedure for driving the antennas has been described in detail by R. S. Colvin (Driving Instructions, glint 459). The new user is expected to have a good understanding of this material as it will be covered in the written pre-licensing examination. Supplemental information not included in this glint is given below.

In the control room, readouts give the nominal pointing of each antenna in declination, hour angle, and right ascension. Coding of these readouts is as follows:

Declination:

$$\text{DEC READOUT} = 3600.0 + \text{DECLINATION}$$

where DECLINATION is in minutes of arc

Hour angle:

$$\text{HA READOUT} = 50000.0 + \frac{\text{HOUR ANGLE}}{2}$$

where HOUR ANGLE is in seconds of time. One hour of motion corresponds to 1800 counts on the hour angle readout.

Right ascension:

The Right ascension readouts display the right ascension in in minutes and seconds of time modulo six hours.

EXAMPLE:

DEC READOUT = 4820.5

HA READOUT = 52300.0

RA READOUT = $320^m\ 45^s$

The antenna is pointed to a declination of 4820.5-3600=1220.5' which equals $20^\circ\ 20'\ 30''$.

The hour angle is $2\times(52300-50000)=4600^s = 1^h\ 16^m\ 40^s$.

The right ascension is $5^h\ 20^m\ 45^s$, $11^h\ 20^m\ 45^s$, $17^h\ 20^m\ 45^s$, or $23^h\ 20^m\ 45^s$. The reading of the sidereal clock and the antenna hour angle must be used to resolve the ambiguity.

To define a safe range of antenna motion, two levels of protective switches are installed on each antenna. Limit switches establish absolute bounds on antenna motion. They are set to be activated just before the rim hits the ground or the dish is driven into the pedestal (as when entering the stow position). It is impossible to drive an antenna past the limits without wiring changes. Boundary switches are activated before the limit swithces to provide a redundancy in protection. The boundary also defines the area of the sky for which accurate instrumental calibration is known. The region between the boundaries and the limits is called the danger zone. It is possible to operate the array in the danger zone; however, the benefits of danger zone operation are slight except for sources in the extreme south. Because of the extra risk involved, such operation is discouraged. Use of the danger zone is restricted to experienced operators. In all cases, the operator must be present at the control panel during any danger zone operation.

5. ELECTRONIC HARDWARE

Under normal circumstances, the user need only be concerned with the electronic hardware in the control room. It is possible that controls in the contactor and ground boxes will occasionally be found in abnormal positions; consequently, all users should know correct switch settings for all reasonably accessible controls. Figures 1-3 illustrate the layout of equipment in the control room racks. The contents of the contactor box are described in glint 459. The standard positions of controls related to the interferometer mode of operation are marked with red dots in the control room and are listed in Tables 1- . Certain non-standard positions are required for observations of the sun and for single dish observations. Users interested in these types of observations should consult with the Institute staff.

TABLES NOT PREPARED YET

6. COMPUTER HARDWARE

The computer hardware is described by R. S. Colvin and A. R. Thompson in glint 413. An addendum is provided at the end of that glint to reflect changes in the system since the glint was written.

7. COMPUTER SOFTWARE

The Institute uses a cassette operating system called SRAIOS (Stanford Radio Astronomy Institute Operating System) which is a

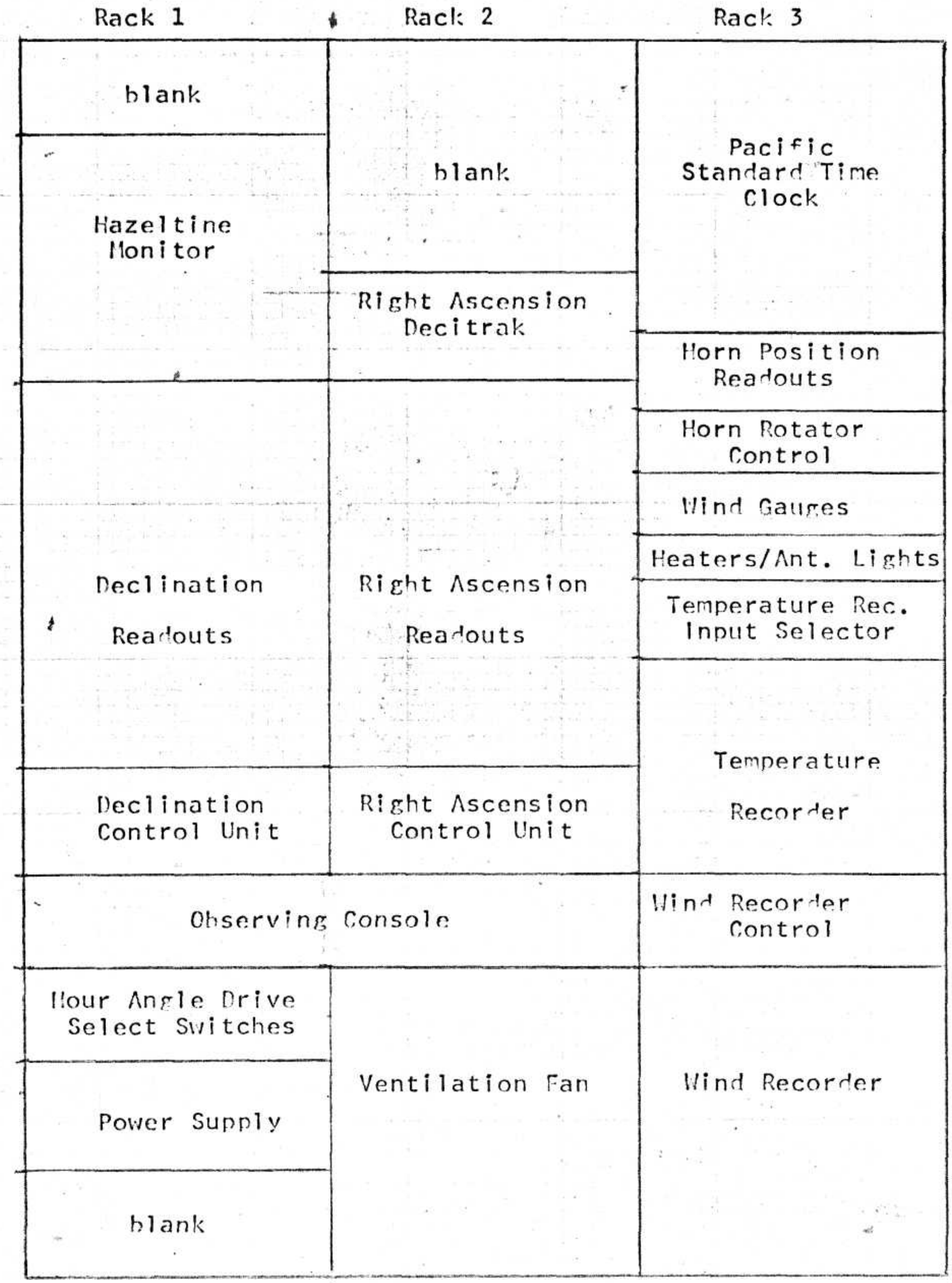


Fig. 1: Equipment Layout (Racks 1,2,3)

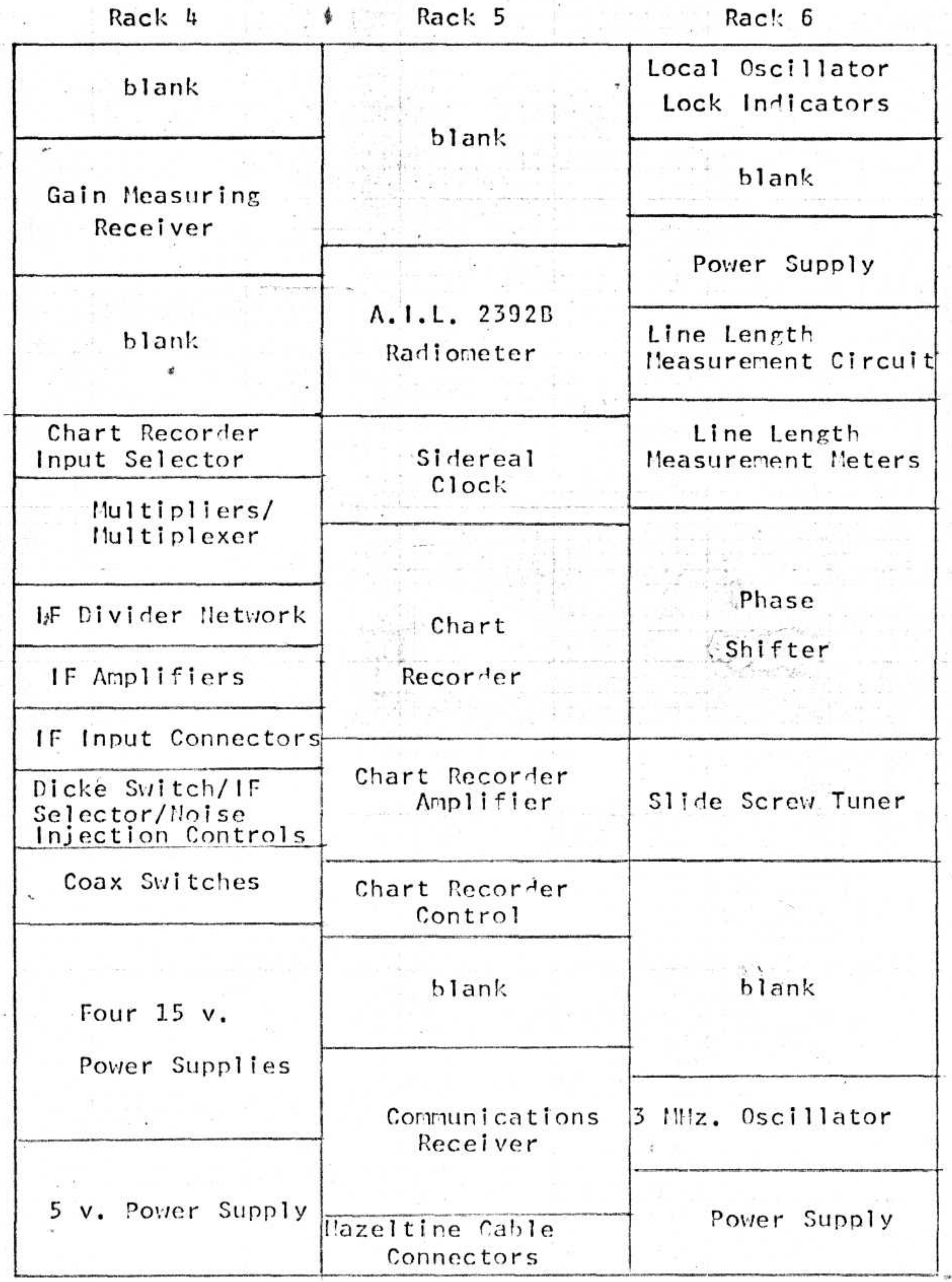
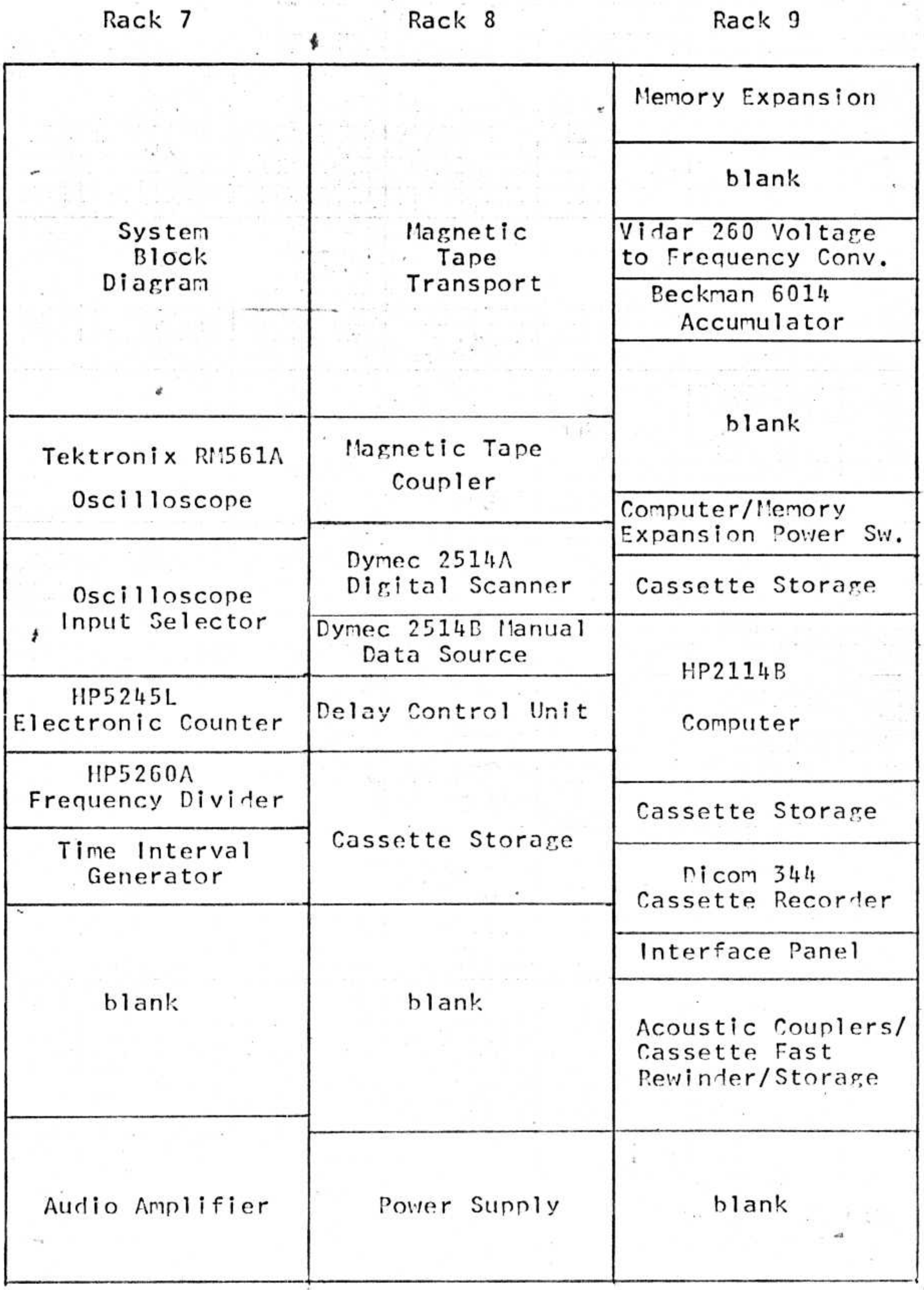


Fig. 2: Equipment Layout (Racks 4,5,6)



Rack 7

- System Block Diagram
- Tektronix RM561A Oscilloscope
- Oscilloscope Input Selector
- HP5245L Electronic Counter
- HP5260A Frequency Divider
- Time Interval Generator
- blank
- Audio Amplifier

Rack 8

- Magnetic Tape Transport
- Magnetic Tape Coupler
- Dymec 2514A Digital Scanner
- Dymec 2514B Manual Data Source
- Delay Control Unit
- Cassette Storage
- blank
- Power Supply

Rack 9

- Memory Expansion
- blank
- Vidar 260 Voltage to Frequency Conv.
- Beckman 6014 Accumulator
- blank
- Computer/Memory Expansion Power Sw.
- Cassette Storage
- HP2114B Computer
- Cassette Storage
- Dicom 344 Cassette Recorder
- Interface Panel
- Acoustic Couplers/ Cassette Fast Rewinder/Storage
- blank

Fig. 3: Equipment Layout (Racks 7,8,9)

modification of the CMTOS system supplied by Dicom. Certain aspects of SRAIOS are described by C. J. Grebenkemper in glints 431 and 432. Compilers available include Hewlett-Packard versions of FORTRAN, ALGOL, BASIC, and ASSEMBLER. Descriptions of these languages can be found in Hewlett-Packard literature at the field site, and all but ALGOL are described in A Pocket Guide to HP Computers. FORTRAN users will be interested in glint 410 by L. R. D'Addario which explains the use of the load-go option available in our system.

Programs and subroutines used at the field site fall into three categories. First, system software includes SRAIOS and various routines supplied by Hewlett-Packard and Dicom. Second, supported software includes those programs which have been written by the Institute staff and are essential to the operation of the interferometer. These programs are used by all observers and have been subject to extensive debugging. The program authors are responsible for correcting any errors that may be discovered. ~~Four~~ FIVE programs are currently in the supported category. The programs are:

STIM: SETTING / CHECKING SIDEREAL CLOCK IS ALSO SUPPORTED

*

PREC (glint 524; author S. J. Wernecke) is the program which performs source precession. The 1950.0 positions are entered through the Hazeltine keyboard or they can be read from cassette tape. A list of standard calibrators can be found on the PARAMETERS tape. This catalog is precessed weekly by the Institute staff. Sources not in this catalog must be precessed by the observer before using NELI.

NELI (glints 475, 525; author L. R. D'Addario) is the on-line program used while making interferometer observations. NELI handles data acquisition from the ten interferometer channels and outputs estimated visibilities to an output tape and to the line printer. NELI also controls delay line settings and continuously updates the Hazeltine display to reflect changes in the correct pointing of each antenna. If a calibrator has been observed before the source of interest, NELI can produce on-line plots of line integrated brightness. The computation required to produce the plots is performed concurrently with data acquisition so that no observing time is lost.

NOTE (glints 505, 528; author S. J. Wernecke) is the editor of NELI output tapes. The user can specify any combination of replace, delete, and insert functions. NOTE is particuliarly useful for correcting gain or line length measurements which were entered incorrectly, deleting bad data records, and inserting additional comments into the EDITED NELI output FILE. NOTE should be used when copying files from the archives observing tapes to user cassettes. NOTE check for errors on the observing tape and prompts the user for corrections if any are found.

CORN (glint ; author C. J. Grebenkemper) is the program which corrects the visibility data for measurable instrumental effects. These effects include changes in receiver gain or local oscillator line lengths, clock errors, phase parameter errors, S-band frequency errors, phase shift and attenuation due to the multipliers, and gain changes due to shadowing and dish deflections. The output of CORN is a corrected data tape which is ready for calibration.

The third category, contributed software, consists of programs written by Institute staff members and observers and donated for public use. The programmer offers no guarantee that the program is error-free, and a user who discovers bugs (or has other complaints about program operation) must modify the program for his own use. Most of the software available at the field site is of a contributed nature, including many subroutines in the library and a number of programs on the SRAIOS system tapes. The user of contributed software should obtain a source listing of the routine to check that the program performs the desired task. Listings of all subroutines in the library and of all programs on SRAIOS system tapes are contained in binders at the field site. Another binder contains additional program documentation which explains program input and output and the calculations performed.

8. DATA REDUCTION SOFTWARE

Sufficient software (supported and contributed) exists so that an observer can obtain a one or two dimensional map without doing any programming. Development of software in the mapping and analysis stages of data reduction is continuing. The structure of existing data reduction programs is shown in Figure 4. The user should refer to program listings and to the program documentation binder for a discussion of the options and algorithms available in each program.

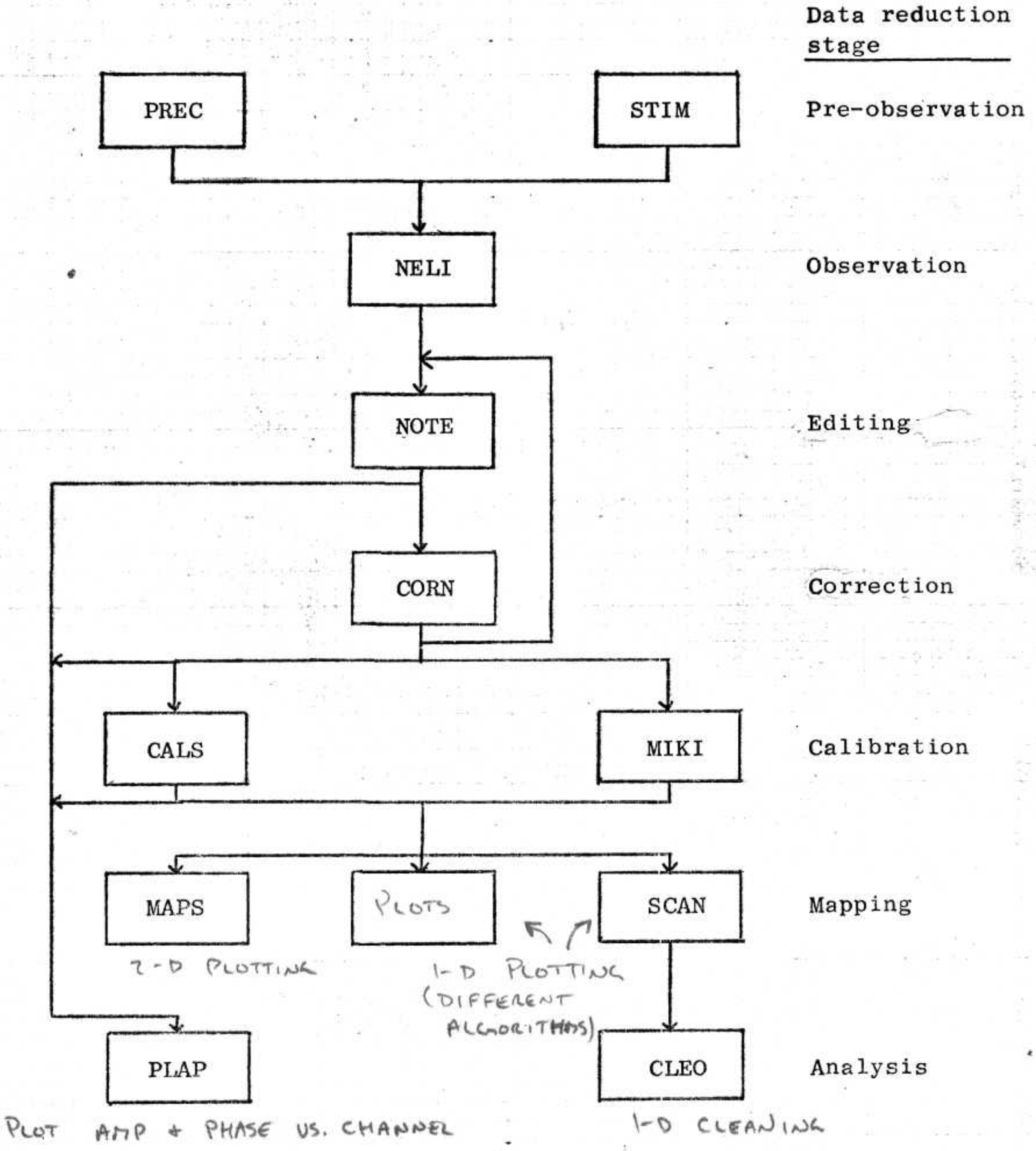


Figure 4: Structure of Data Reduction Software

9. GAIN MEASUREMENTS

L. R. D'Addario describes the gain measuring hardware in glint . The procedure for making gain measurements is explained below. As gain measurements interfere with the interferometer operation, they should not be made while an integration is in progress.

1) Ensure that the gain measuring radiometer (rack 3) is turned on and that the chart recorder input selector (rack 4) is set to 12. Turn on the chart recorder control (rack 5). Set full scale voltage on the chart recorder amplifier (rack 5) to 1 volt.

2) With IF amplifiers (rack 4) set to manual, adjust the lower potentiometer on each amplifier so that meter readings are the same in both ALC and manual positions. The upper potentiometers control the ALC level and should not be adjusted once observations have started.

3) With the IF selector (rack 3) set to LOAD, adjust the chart recorder offset (rack 5) so the chart recorder (rack 5) reads 0.

4) With IF amplifiers (rack 4) set to manual, switch the IF selector (rack 3) to each amplifier in turn and record the deflection registered on the chart recorder (rack 5). These readings are input to the on-line program using the GA command.

5) Turn IF amplifiers (rack 4) to ALC. Turn chart recorder (rack 5) off if no more measurements are required. Resume observations.

OBSOLETE

10. LOCAL OSCILLATOR LINE LENGTH MEASUREMENTS

The local oscillator system and the line length measurement technique are described by A. R. Thompson in glints 285 and 358, respectively. During observations, it is necessary to measure the electrical lengths of the S-band distribution lines to each antenna as differential path length changes cause correctable phase errors in the estimated visibilities. Ordinarily, measurements are made at half hour or hour intervals although more frequent measurements may be desirable around sunrise and sunset WHEN ~~since~~ line length changes ARE ~~are typically~~ GREATEST ~~greater then~~ . The following procedure should be used to make line length measurements. These measurements do not interfere with interferometer operation and can be made while integrating.

1) Turn on SWR meter (rack 6). Set rotary switch (rack 6) to TUNE LINE.

2) Adjust slide screw tuner (rack 6) to obtain an SWR meter reading in the left half scale on the 60 db. range.

3) Set the rotary switch (rack 6) to antenna 1. Adjust the coaxial phase shifter (rack 6) for a null (with SWR meter set to 60 db.) on the Simpson microammeter (rack 6). There is slight backlash in the phase shifter mechanism; consequently, measurements should be taken using a consistent technique. The convention adopted by Institute staff members is to record the phase shifter reading for the first positive going null encountered (starting from a phase shifter reading of zero) and to approach the null turning the phase shifter knob clockwise.

4) Repeat step 3 for all antennas and input the phase shifter readings to the on-line program using the LO command. All readings should be between 0 and 135.

5) Return the rotary switch (rack 6) to the TUNE LINE position and turn down the SWR meter sensitivity. Turn off SWR meter when the last measurement of an observing session is completed.

11. THE SIDEREAL CLOCK

The sidereal clock is set to record mean sidereal time. Since the apparent position of sources and the apparent sidereal time are relevant to observations, the following PROCEDURE convention is established.

When the source right ascension is input to NELI ~~the on-line program,~~ it should be input as the apparent right ascension ~~minus the equation of equinoxes for the~~ day of the observation. The equation of equinoxes can be obtained from the Ephemeris. This has the effect of converting the sidereal clock to one which records apparent sidereal time rather than mean sidreal time. The subtraction is performed for the observer using PREC to precess sources. The observer should remember to do this subtraction for sources precessed by other programs or for sources for which apparent positions are obtained from the Ephemeris, i.e. planets.

NELI NOW DOES THIS SUBTRACTION

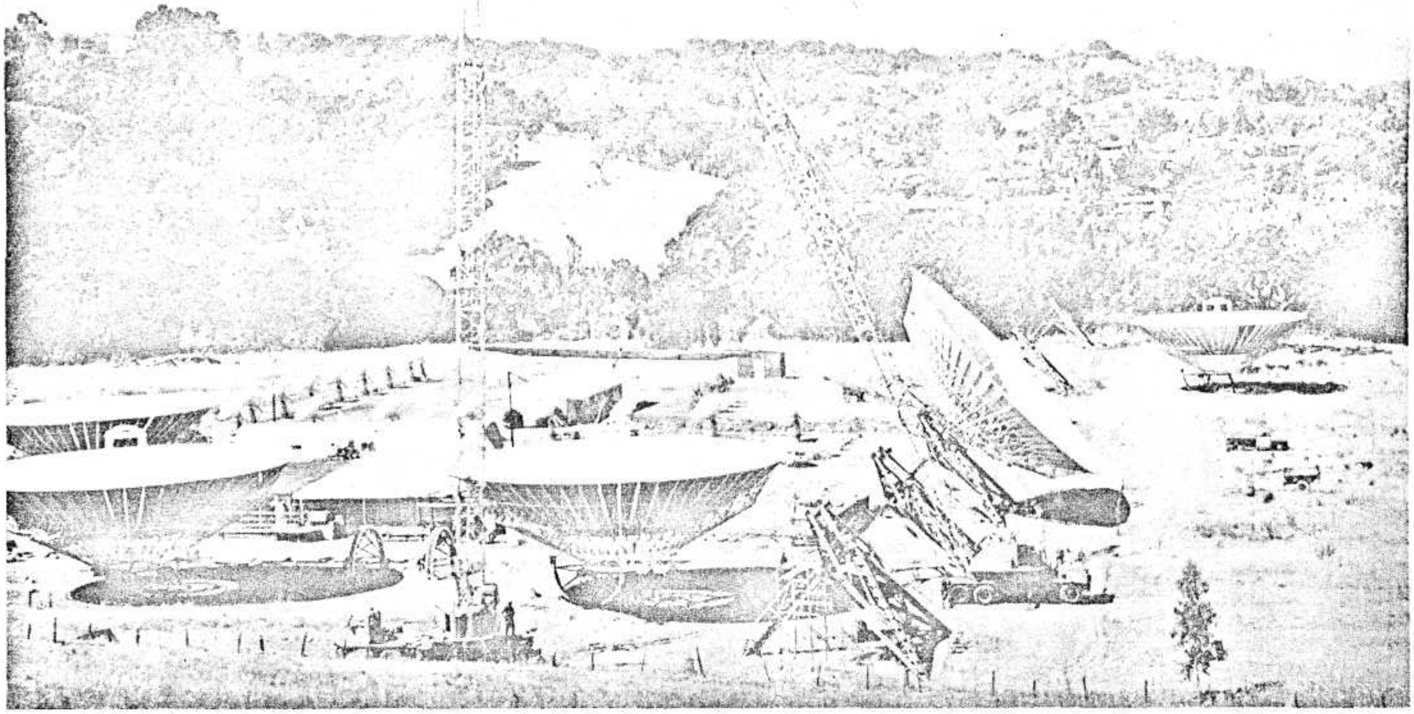
The sidereal clock is reset weekly by the Institute staff. Normal drift in that period is less than 50 msec. Since data can be corrected for the effect of small clock errors, the observer may wish to check the clock error before beginning observations. L. R. D'Addario describes the procedure to be used in checking the clock in glint 461. It is requested that users refrain from resetting the clock except in the event of a power failure (power fail indicator light is off). In view of the regular maintenance, large clock errors not caused by a power failure are most likely due to an error made in checking the clock. An entry should be made in the sidereal clock log in the control room after any checking or resetting activities.

12. IN THE EVENT OF DIFFICULTY

Weekly maintenance sessions are scheduled to ensure the reliability of the interferometer. In spite of this attention, some failures are inevitable. In view of the complexity of the system, it is impractical to supply new users with a COMPREHENSIVE trouble shooting guide. ~~SOME SUGGESTIONS ARE~~ MADE * ~~In general,~~ the proper response ~~in the event of difficulty~~ is to carefully document the problem using one of the Trouble Report forms available at the field site. This report should be given to one of the members of the technical staff.

Equipment repair should only be performed by the technical staff; observers are discouraged from attempting makeshift remedies as incorrect "cures" can easily do more harm than good. It is difficult to write a concise definition that distinguishes equipment repair from less complicated tasks which might be easily and safely performed by an observer. Certainly, setting switches to the proper positions is not considered repair work nor is correcting obviously misconnected (or disconnected) cables on the various front patch panels. As a rule of thumb, any action which requires an observer to go into the racks ~~of~~ OR to disassemble equipment should not be performed unless an emergency arises (a fire, for example). Under no circumstances should antenna safety switches be jumpered or wiring modified. In all instances, corrective activities must be carefully documented. ~~(see problems~~

Some of the most common difficulties ~~difficulties~~ and operator errors are described at the end of this section; however, if the problem can not be resolved using this checklist...

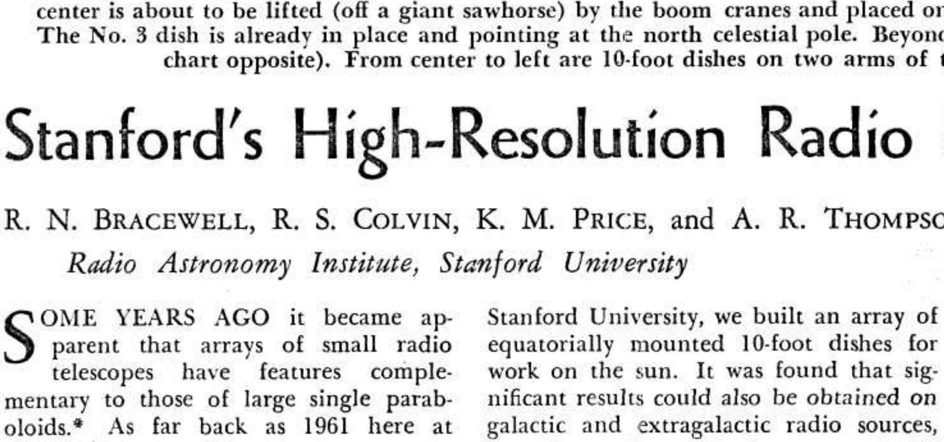


A view from the east showing all five antennas of the Stanford array in various stages of construction. The dish below center is about to be lifted (off a giant sawhorse) by the boom cranes and placed on the No. 1 tripod base (right foreground). The No. 3 dish is already in place and pointing at the north celestial pole. Beyond it are the tripods for Nos. 7 and 10 (see chart opposite). From center to left are 10-foot dishes on two arms of the solar-cross interferometer.

Stanford's High-Resolution Radio Interferometer

R. N. BRACEWELL, R. S. COLVIN, K. M. PRICE, and A. R. THOMPSON
Radio Astronomy Institute, Stanford University

SOME YEARS AGO it became apparent that arrays of small radio telescopes have features complementary to those of large single paraboloids.* As far back as 1961 here at Stanford University, we built an array of equatorially mounted 10-foot dishes for work on the sun. It was found that significant results could also be obtained on galactic and extragalactic radio sources, but the modest collecting area of this array (a cross of 32 dishes each 10 feet in diameter) limited us to a handful of the known radio sources.



Participants in the interferometer project included (left to right) authors Price and Bracewell and W. S. Scott, Stanford Linear Accelerator Center.

A few years ago we began planning for a larger instrument, confident that our experience in achieving resolution of less than a minute of arc with the first array could result in 20-second-of-arc resolution with a larger one. By going to a relatively short wavelength of 2.8 centimeters (10,690 megahertz), and by using a *minimum-redundancy* array, we could avoid moving large antennas on rails yet obtain a fast interferometer with resolution up to an order of magnitude better than that of most large paraboloids. We should be able to observe at centimeter wavelengths the sources in the extensive catalogues that have been compiled by existing survey instruments, such as the Cambridge 3C interferometer.

This should all be possible with five 60-foot paraboloids, equatorially mounted and spaced as explained below along a 675-foot east-west base line (corresponding to 7,336 wavelengths). They would form a minimum-redundancy interferometer which, when pointed at the meridian, would have a very narrow response peak in hour angle, while resolution in declination would be obtained by observing over a wide range of hour angles, a technique known as earth-rotation synthesis. This takes advantage of the rotation of the earth to change the position angle of the

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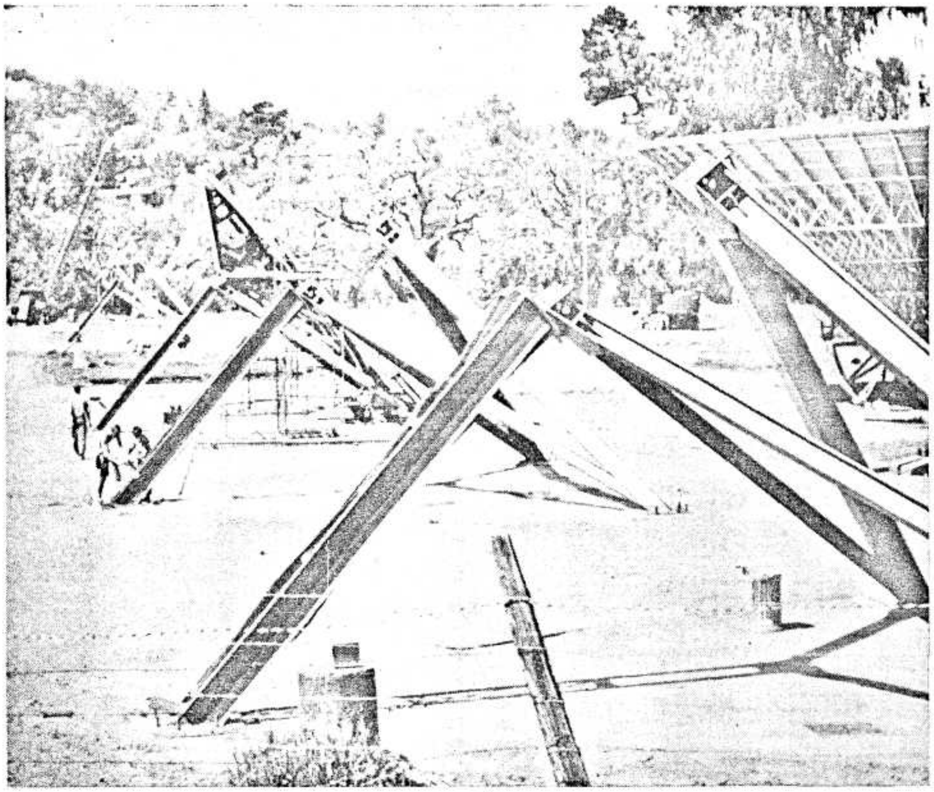
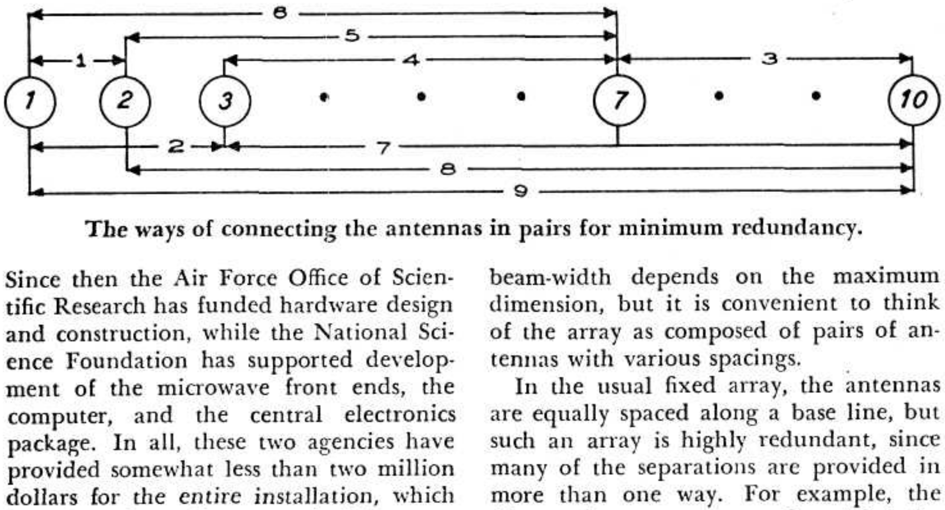
*For example, the Bonn 100-meter and the Illinois 120-foot dishes, described in SKY AND TELESCOPE for December, 1970, page 339, and March, 1971, page 132.



The polar axle and hour wheel of each antenna will slip into the gap formed by the double legs on the north (right) side of its tripod. Two men at the left edge of this picture are installing the baseplate for the polar-alignment theodolite on the No. 2 antenna (see diagram on page 4).

beam with respect to the source. Such a versatile instrument would be very useful for galactic, extragalactic, planetary, lunar and solar work, but it would require a computer and also costly phase-stable electronics.

Much of the development has been done "in house," beginning with panel design for a 60-foot reflector in 1965. Since then the Air Force Office of Scientific Research has funded hardware design and construction, while the National Science Foundation has supported development of the microwave front ends, the computer, and the central electronics package. In all, these two agencies have provided somewhat less than two million dollars for the entire installation, which has taken about 4½ years to build.



The ways of connecting the antennas in pairs for minimum redundancy.

MINIMUM REDUNDANCY

An array of antennas can be thought of as having a beam that maps out a distant source of radiation by scanning its different parts. We can also understand what the array is doing by thinking of the source as producing a complicated radiation field in the neighborhood of the observer. By exploring the field with our antennas, we can reconstruct the image of the source.

The first way of thinking corresponds to what happens when a single paraboloid is pointed to different parts of a source long enough to map out its characteristics. The beam-width can be reduced by increasing the diameter of the dish. Similarly, in an interferometer array the beam-width depends on the maximum dimension, but it is convenient to think of the array as composed of pairs of antennas with various spacings.

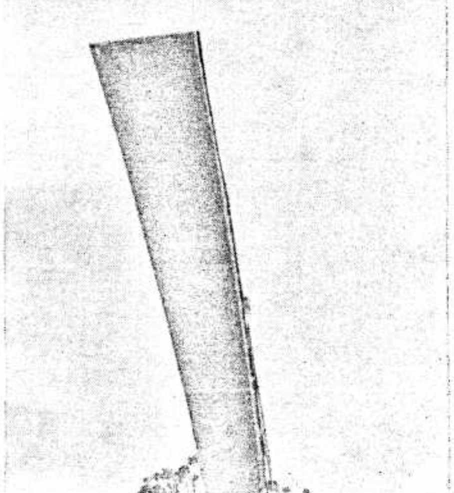
In the usual fixed array, the antennas are equally spaced along a base line, but such an array is highly redundant, since many of the separations are provided in more than one way. For example, the distance between antennas 1 and 3 is the same as between 2 and 4. Yet the maximum separation can be produced in one way only.

When the data are properly processed, we need only one pair of antennas for each separation, and to reduce the redundancy some elements of the uniformly spaced array can be left out. The omission either saves money and maintenance or permits the use of larger antennas to increase the overall instrument sensitivity.

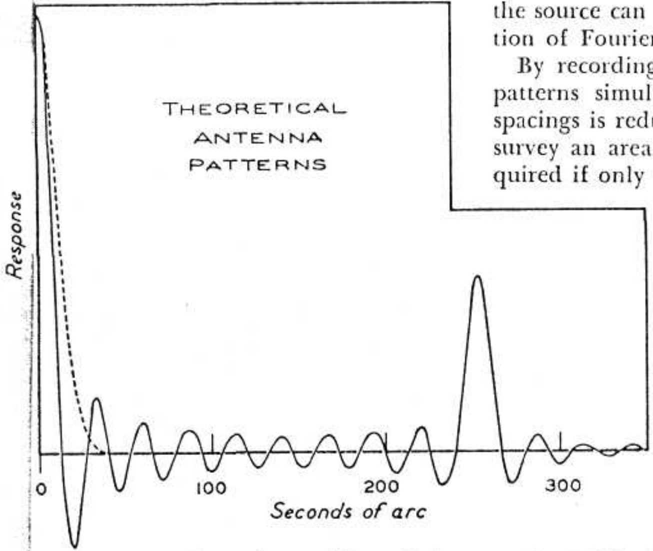
To visualize our array, first consider 10 paraboloids equally spaced 75 feet apart on an east-west line, and then remove the 4th, 5th, 6th, 8th, and 9th. The chart at left below shows how the remaining five paraboloids can be paired to produce every separation from one unit of 75 feet up to nine units. All the information that can be extracted from an electromagnetic field by the full 10-antenna array can be found by this five-element array. Only for the single-unit separation is there redundancy (1-2 and 2-3), which cannot be avoided with this number of antennas.

However, if this array is connected up by simply adding the five signals received, it will have a poor reception pattern, with strong side lobes. Therefore, we operate the 10 different antenna pairs as separate two-element interferometers and record their outputs simultaneously but separately. The signals received at each antenna are first divided four ways and combined in 10 voltage multipliers in such a way as to produce 10 two-element interferometer responses. These are sinusoidal and analogous to the sinusoidal optical interference fringes produced by a two-pinhole Young's interferometer.

Because of the earth's rotation, the output from every multiplier rises and falls with a period of about two to 20 seconds or more, depending on the separation of



Some four years ago, C. C. Lee, R. N. Bracewell, and a sheet-metal expert completed this first dish panel. Set horizontally, it was tested by loading with sandbags until it broke.

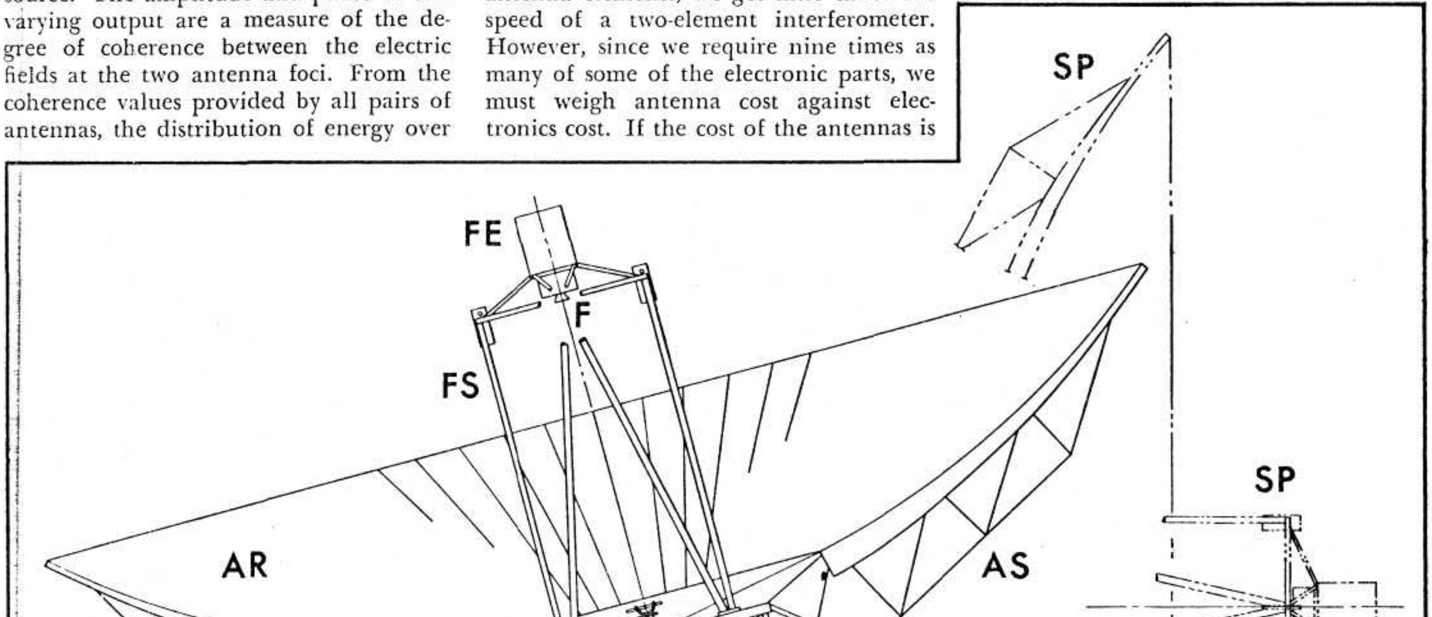


In the array's antenna pattern, the "grating response" peak is some 253 seconds of arc from the main beam. The oscillatory side lobes can be eliminated by combining the fringes from the nine channels with suitable weighting coefficients, resulting in the dashed curve.

the antennas and on the position of the source. The amplitude and phase of this varying output are a measure of the degree of coherence between the electric fields at the two antenna foci. From the coherence values provided by all pairs of antennas, the distribution of energy over the source can be computed — an application of Fourier transforms.

By recording nine independent fringe patterns simultaneously (one of the 10 spacings is redundant), the time taken to survey an area is only one-ninth that required if only one pair of antennas were used. With 2½ times the number of antenna elements, we get nine times the speed of a two-element interferometer. However, since we require nine times as many of some of the electronic parts, we must weigh antenna cost against electronics cost. If the cost of the antennas is significantly greater than that of the electronics, the advantage is clear, especially for antennas more costly than ours.

The pattern of the array is shown in the graph, and we see that there is a main beam 17 seconds of arc wide. In addition, a response is seen 4.2 minutes of arc away, which results from the fact that the array is made up of discrete antennas, the collecting surface not being continuous as in a single large paraboloid. This feature corresponds to the 1st-order fringe of an optical diffraction grating and for this reason is known as a grating response. The beam-width of the single antennas, approximately seven minutes of arc, sets a limit to the field of view, but in practice we are generally limited to 4.2 minutes, because otherwise main beam and grating lobe responses overlap and interpretation of the observing record is complicated.



A scale drawing of a 60-foot reflector with the following principal parts labeled: *AR*, aluminum reflector; *AS*, aluminum structure; *DD*, declination drive; *DW*, declination wheel (steel); *F*, focus; *FE*, front-end box; *FS*, feed support (steel); *HA*, hour-angle drive; *NP*, north-pole-pointing (stow) position; *OH*, octagonal hub (steel); *PA*, polar axis; *SP*, service position; *SL*, south leg; *TS*, theodolite stand (for polar alignment). Stanford Radio Astronomy Institute diagram.

EQUIVALENCE TO ANALOGUE IMAGES

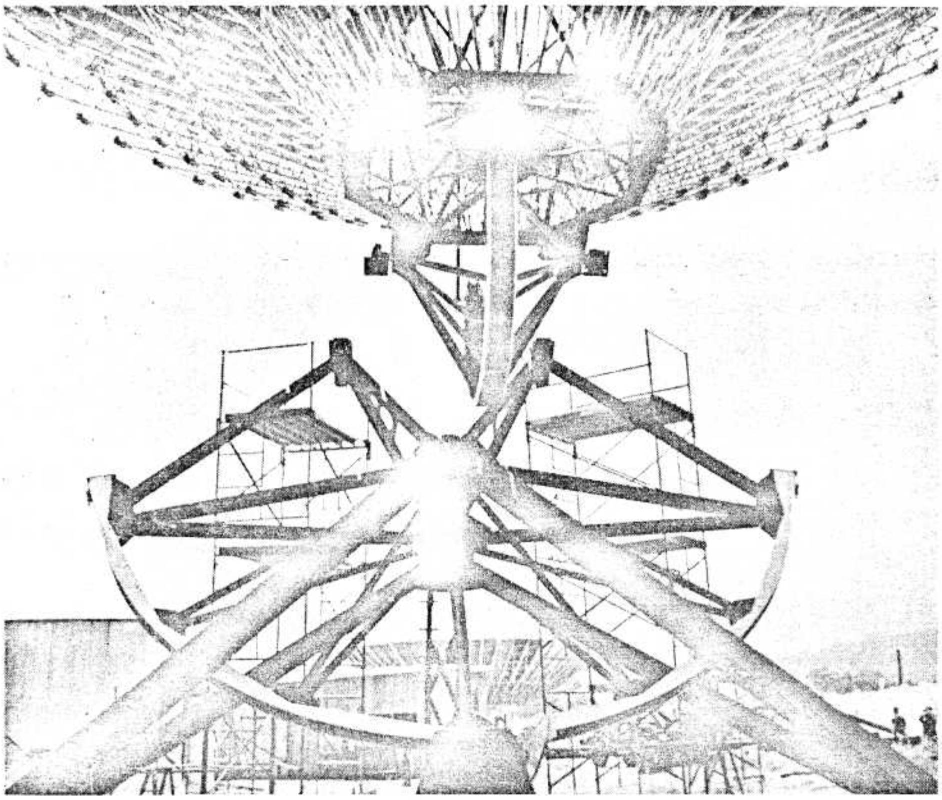
As with an optical telescope, a conventional paraboloid radio telescope forms an image of the source in the focal plane, but only part of this image can be picked up by a feed horn placed on-axis at the focus. If we wish to collect the information elsewhere in the focal plane, we must point the dish to each part of the source sequentially.

Hypothetically, if we had a 675-foot dish (diameter equal to our base line), we could place other horns in the focal plane and observe a number of parts of the source simultaneously, at least in principle. But in practice, difficulties would arise from the proximity of the horns to each other and from aberrations in the image-forming properties of paraboloids.

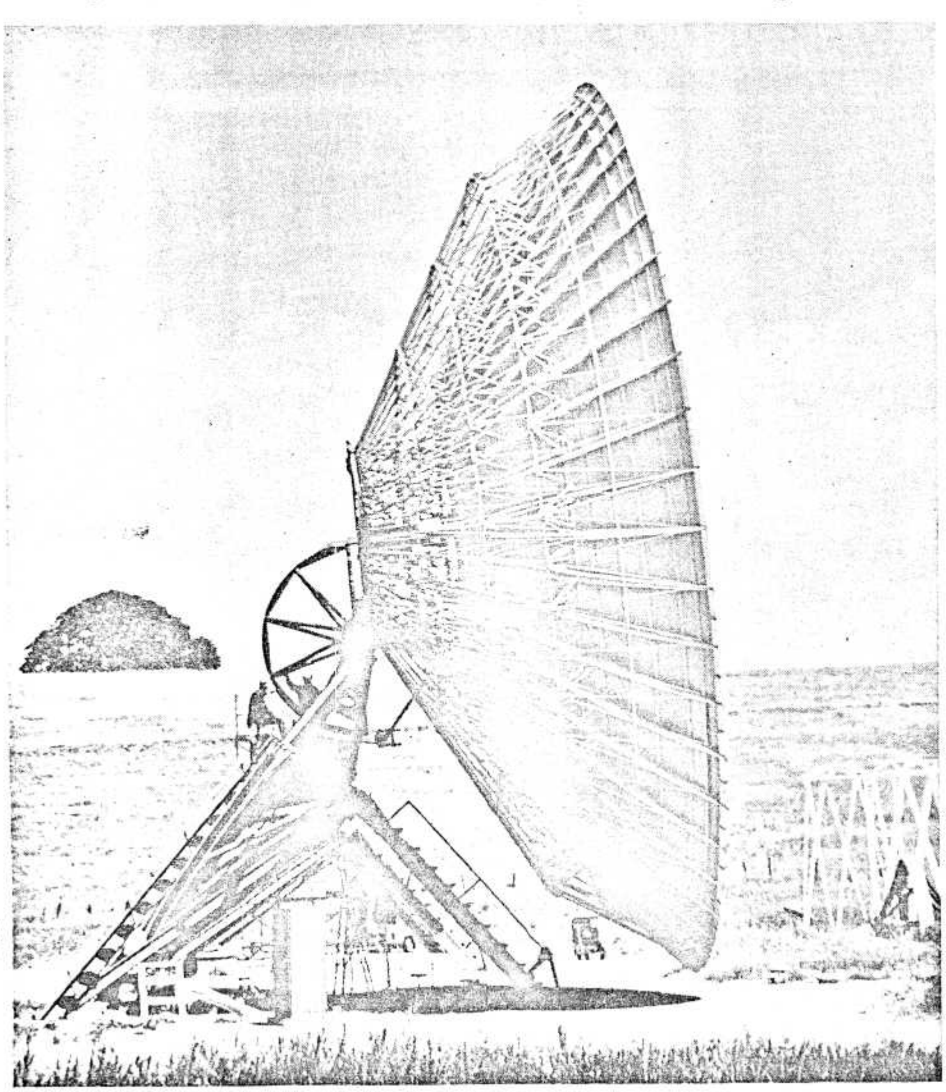
With our minimum-redundancy array, such practical difficulties are avoided, for the analogue image formation results from the way in which the signals are processed in the computer.

THE 60-FOOT REFLECTORS

A great advantage of an interferometer employing dishes of moderate size is that they can be equatorially driven to follow a source across the sky. In our case the coverage is for 10 hours, from five hours east of the meridian to five west of it. Our range in declination is from the north celestial pole to the southern horizon (−52°), covering the entire sky visible from our latitude.



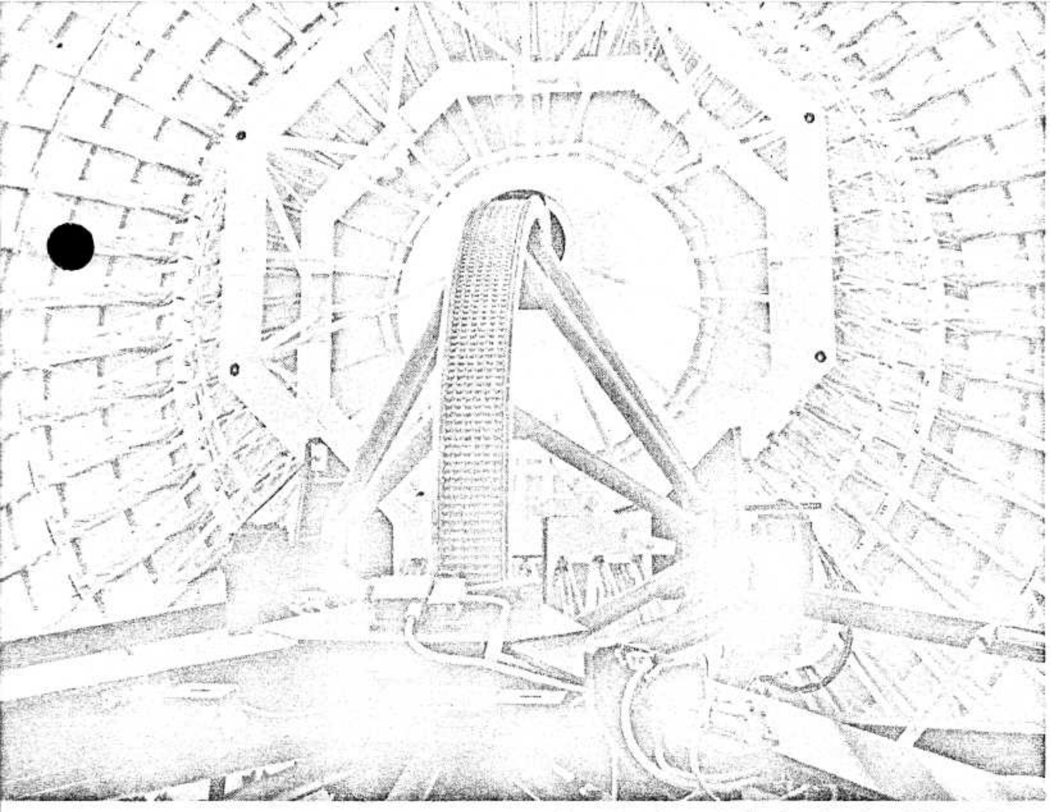
Above, in a view from the north, the yoke and hour wheel are already installed on a base frame, while the dish and declination wheel are being lowered into place. Below, a view from the west shows how offsetting the hub permits the dish to clear the ground when turned fully south for servicing.



The diagram gives a north-south cross section of one of our 60-foot reflectors. The base tripod has one leg due south, the other two widely split toward the north. As shown on page 3, each of the latter is double, to form the upper and lower supports of the stubby polar axis. This is already installed in the picture of the dish with the declination assembly attached (above) being lowered into place.

In each case, motion about the axis is by means of a large half-wheel around which a roller chain wraps. The hour-angle wheel is 30 feet in diameter and the declination wheel 15 feet. The chain passes over two idler sprockets and a drive sprocket to which a motor is connected through a gear reducer. Walter S. Scott designed the drives and C. C. Lee supervised the mechanical construction up to mid-1969.

The dish construction is seen in several photographs and in the drawing. Its framework is cantilevered from a central octagonal steel box frame that also carries the supports for the antenna-feed assembly at the focus of the paraboloid. Note particularly that the dish is offset half the width of the box frame to the north of the declination pivots. This permits lowering the declination axis by about six feet, yet the reflector does not strike the ground when it is turned to the fully vertical position for servicing (pointing due south). Were the reflector center-mounted on the box frame, a much taller,



The central hub (light tone) is seen in this view of the back of a dish. The six-strand chain of the declination drive is about 10 inches wide.

more massive tripod would be required. The weight of the reflector and parts that move with it is 21,000 pounds, but counterweights were omitted on the grounds that drive, bearings and structure all must accept wind loads that considerably exceed the dead load.

An eight-legged structure similar to the tube of some optical telescopes supports the feed. This permits the feet to stand on the steel octagon, whereas the more usual three or four-legged support would require the feet to be well out in the flimsier aluminum panel structure. However, the greater number of legs means more loss of signal by shadowing. The focal length is 18 feet and the focal ratio is 0.3.

ANTENNA FEED AND ELECTRONICS

Each antenna has a feed horn that is rotatable to permit polarization studies. Receiving equipment is located in a front-end box mounted immediately behind the feed horn and also in a ground box at the foot of the south leg of each antenna.

The front-end box contains a tunnel diode preamplifier, a mixer and IF preamplifier, the local oscillator and noise calibration components. In addition, it is possible to throw a wave-guide switch in the front-end box that brings into operation a Dicke switch, so that the antenna can be operated as a single unit for pointing corrections and other adjustments. The local oscillator signals at each antenna are derived from a master oscillator (2673.25 MHz) in the control room, thus assuring that the signals from all antennas will be in synchronism. An automatic phase-lock system is used to assure this.

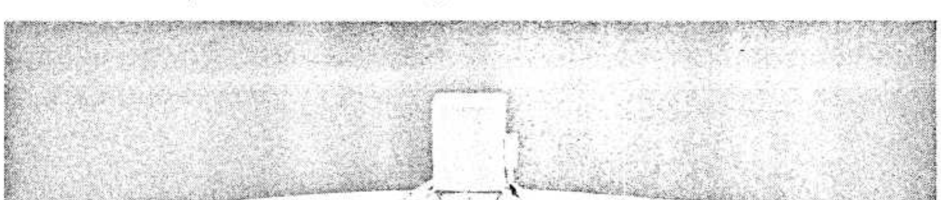
The X-band signals are converted in the mixer to an intermediate frequency band of 10 to 70 MHz. Because of this wide bandwidth (for increased sensitivity), compensation is needed for the antennas being at different distances from a given source. This is done by switching into each circuit varying lengths of cable, which act as delay lines. As the earth rotates, the relative distances change, so the delays have to be adjusted. For each antenna there are 512 possible values.

A small on-line computer calculates when it is necessary to change the delays and selects the appropriate values. It also samples the 10 multiplier outputs and performs an initial averaging of the data. Data is read into the computer 50 times per second, stepping sequentially from one multiplier to the next. Every five minutes the computer records on magnetic tape the average values of the amplitude and phase of the 10 fringe patterns. Thus 15,000 data samples are compressed into 20 values, greatly decreasing the cost of subsequent processing.

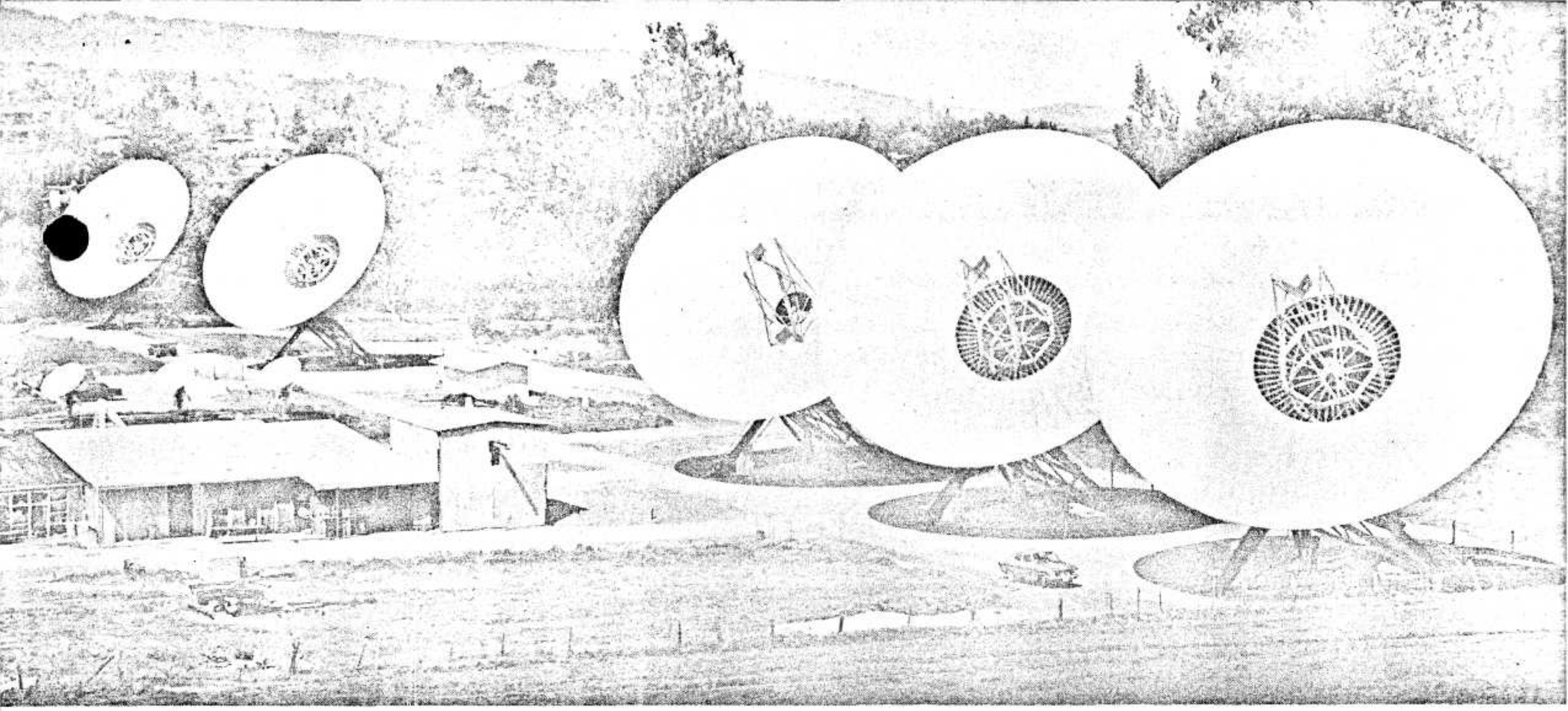
The antennas are driven in declination by independently controlled motors, but the hour-angle drive motors are connected to operate the array as a single unit. The antenna readouts and controls are located in the observing room and the latter are interconnected with a system of boundary and limit switches.

THE OBSERVING PROGRAM

Testing of the antennas is now under way. It includes correcting the readout indicators and resurveying of each reflector's surface. Phase measurements of



The feed box at the focus of a dish is reached by a ladder on the supporting truss. Each of the 56 panels contains about 100 accurately placed 1/16-inch holes, which are targets for a theodolite set up on the little platform at the dish center. The holes form tiny spots of light that must align properly as the theodolite scans them to check the figure of the paraboloid.



A view with the dishes pointing high in the southeast. Some of them have unfilled central sections, to allow convenient access for men and materials, but they will be filled in for regular observing.

the entire transmission system have begun, and the computer-controlled variable delays have been tested under automatic operating conditions with two antennas connected as a two-element interferometer. Both the readouts and the delay lines were designed by Alec G. Little. Since we are working to an accuracy of about one millimeter, we expect to find that corrections will be needed for ambient temperature changes, antenna position, and other effects.

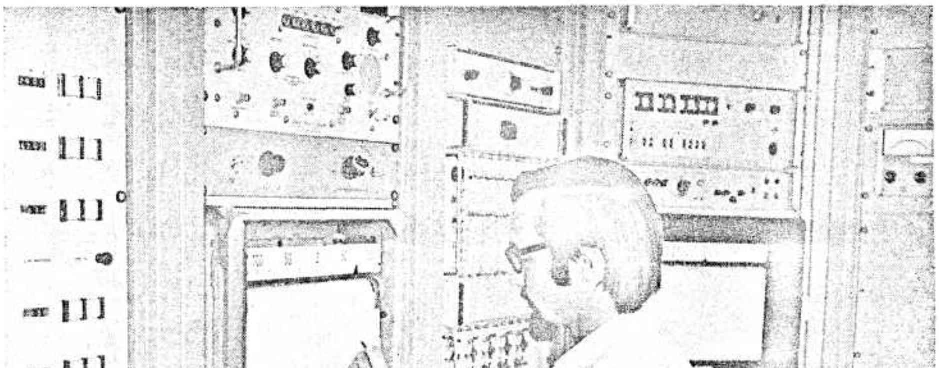
When all the two-element channels are working satisfactorily, the entire system will be operated in the rotation-synthesis survey mode for which it is intended. As we gain experience, a gradual transition will be made to observational programs, but the system is very complex and must b brought into adjustment with care.

The astronomical program will cover a variety of objects. We wish to study the structure of H II regions in the galaxy and planetary nebulae, and to compare the profiles of the latter with optical observations. Our array will be capable of detecting and measuring positions of small unresolved sources down to a flux density of a few hundredths of a flux unit; therefore the array will be more suitable than large single reflectors for surveying large numbers of small nebulae in search of radio emission.

We shall also work on the mapping of nonthermal supernova remnants and radio galaxies. These observations are time-consuming if done by movable-baseline interferometry, but are well suited to a fast, narrow-beam instrument such as ours.

The sun and moon will receive attention. It is possible that active solar regions can be internally resolved and solar radio bursts localized with respect to previously mapped components of an active region. There is also the outstanding question of solar limb brightening at different wavelengths. The immediate availability of our two-dimensional maps of the sun at a wavelength of 9.1 centimeters should furnish a good basis for special observations at our new wavelength of 2.8 centimeters.

Lunar observations for a full lunation might indicate features on the moon possessing unusual thermal properties or surface texture, especially in connection with radar maps. This subject is well developed theoretically, and observations of higher resolution are needed. In our case, there is the technical difficulty that the grating lobes of the interferometer (which limit the field of view) have a separation less than the moon's diameter (see graph on page 4). This problem is less acute with the sun, because of its changing appearance with time.



Graduate student Larry D'Addario, in the control room, checks pointing corrections for the No. 3 dish. Above the chart is a standard Airborne Instruments radiometer, and at left mechanical-counter readouts. Beyond his head is a bank of 10 multipliers, and at upper right a sidereal clock.

The Stanford Five-Element Radio Telescope

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C. JOHN GREBENKEMPER, KENT M. PRICE, AND ANTHONY RICHARD THOMPSON

Abstract—The Stanford radio telescope array is a fast image-[illegible]ing interferometer using earth rotation synthesis to produce a brightness map of the continuum radiation from a portion of the sky using data obtained in one 10-h observation. The array consists of five 18.3-m diam paraboloid antennas mounted on an east–west line in such a way that pairs of antennas span all spacings from 1 to 9 times the unit spacing of 22.9 m. At the operating wavelength of 2.8 cm (10 690 MHz) the half-peak beamwidth is 18.8″ and the grating-lobe spacing is 4.2′, both in the east-west direction. The antennas, which were constructed at Stanford, are equatorially mounted and have a range of motion in declination from the south horizon to the north pole and in hour angle from horizon to horizon or ±5 h, whichever is less. Both hour angle and declination motions are controlled by chain-drive mechanisms. The electronic receiving systems includes tunnel-diode preamplifiers followed by mixers and an IF system with a passband from 10 to 70 MHz; both upper and lower sidebands are accepted. The local oscillators at the antennas are phase locked to a reference signal which is distributed from a centrally located oscillator. A system for monitoring variations in the electrical lengths of the reference-signal cables is incorporated using modulated reflectors at the five antennas. The IF signals from the antennas pass through 9-b variable delay lines and the signals from each of the ten possible antenna pairs are then fed into ten analog multipliers. An on-line computer samples the output waveform of each multiplier five times per second and digitally filters the data to estimate the complex correlation of the signals averaged over any desired time interval. The computer also sets the delays, monitors various equipment, and controls the data recording and operator displays. In addition, it can be used off-line to perform the Fourier transformation or similar processing required to derive a map of a radio source. The sensitivity with the tunnel diode preamplifiers gives a signal-to-noise ratio of 5 to 1 for a point source of flux density 4×10^{-26} W $\cdot$m^{-2} Hz^{-1}; this assumes a system noise temperature of 1000 K, an antenna aperture efficiency of 30 percent, and an observing time of [illegible]h. An increase in sensitivity by a factor of 10 will be obtained by the use of uncooled degenerate parametric amplifiers.

INTRODUCTION

BY 1962 the techniques for constructing interferometers with fan beams narrower than a minute of arc had been demonstrated, for example by Swarup, Thompson, and Bracewell [1] and the method of earth-rotation synthesis using fan beams had already been demonstrated by Christiansen and Warburton [2] and analyzed theoretically by Bracewell [3]. In addition, the notion of supersynthesis, a combination of movable antennas and earth rotation had been introduced by Ryle [4], so the time was ripe for the design of new radio telescope systems. Some details of the projects originating about that time are given in Table I.

The high frequency of 10 690 MHz (approximately 2.8 cm) was chosen for the Stanford project, in spite of difficulties that would have to be faced with mechanical precision, because it would be specially suited to studies of the planets, sun, and moon and because, in the case of galactic and extragalactic objects, it would be complementary to the lower frequencies of the instruments being contemplated elsewhere.

The concept of minimum redundancy, which was in the air at the time, was also incorporated, leading to an east–west array of five 18.3-m diam equatorially mounted paraboloids situated at the locations indicated by the numbers as follows, east being on the right.

10 · · 7 · · · 3 2 1.

It will be seen that all interelement spacings from one through nine units are present and that unit spacing occurs twice. The basic design parameters, which were frozen by 1965, were described at the 15th General Assembly of the International Scientific Radio Union in Munich in 1966 [5] and are given in Table II. The general appearance of the array is shown in Fig. 1.

PRINCIPLE OF OPERATION

The signals from each antenna pair are correlated in the control room by a combination of analog and digital techniques to yield measurements proportional to complex visibility [6] after regular averaging intervals that may be varied but are typically 5 min. On the u–v plane [7], [8], which is the domain related by two-dimensional Fourier transformation to the source domain or "sky plane," nine concentric elliptical loci are traced out as time elapses [9] If the complex visibility were known everywhere in the u–v plane, Fourier transformation would yield the source distribution;[1] but because data are available only within a central island on the u–v plane, the resolution is limited in a way describable by the shape of the main beam of the instrument And because within this island only discrete loci are used, there is a further phenomenon of ringlobes surrounding the main beam in the full instrumental response pattern. The character of the main beamand ringlobes of east–west rotation-synthesis arrays has been studied by Bracewell and Thompson [9] with the result for the radial profile of the principal response pattern[2] shown in Fig. 2. The main beam is seen to be accompanied by oscillations which, if we take the squared amplitude, become the fringes that are customary in the intensity diffraction pattern of a circular (or elliptical) aperture. The first two of the series of ringlobes are also shown. Naturally the sidelobes may be reduced to any desired extent by data processing equivalent to the practice of aperture tapering, at the expense of a corresponding reduction in resolving power. The antenna pattern of a single element, which is also shown in this figure, acts to reduce the ringlobe response.

MECHANICAL SYSTEM

Each reflector comprises an octagonal steel hub and 56 identical 63-kg aluminum panels, which are made of welded and riveted tube 3.2 cm in diameter and a 1.5-mm reflecting skin. To minimize the amount of material, and hence the cost, the skin was made an integral load-bearing member; this design choice requires accurate and rigid structural work. A heavy optically aligned jig was built to impose the correct double curvature on the skin and fix its spatial relationship to the three points of attachment of the panel to the hub. The skin was formed by bending two 3.66 by 1.22-m sheets with permanent matt-white baked finish, the largest standard size available, over the jig. The sheets were not sheared to pie shapes but used as delivered; what would otherwise have been excess material was formed into flanges for rigidity and to

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[1] Corrections may need to be applied for asymmetry of an antenna pair and for the nonzero extent of the antennas since it is the complex degree of coherence of the field, rather than the complex visibility recorded by the apparatus, which is strictly the Fourier transform of the brightness distribution [6].

[2] The principal response pattern is only one of a range of possible patterns that may be synthesized [9].

eliminate gusset plates or connectors at the junctions of the tubes with the skin. Completed panels were cantilevered from their three support points and surveyed by automatic level and self-erecting leveling rods bearing fine scales and resting on conical points. Destruction and deflection tests were carried out by loading with sandbags; the joint design is thus known to be capable of withstanding a wind over 110 km/h blowing normally on the skin. (The rest of the structure was designed for 160 km/h allowing for the known wind loads on solid paraboloids variously oriented. A wind of 110 km/h at a height of 10 m is expected at the site once in 40 years.) The rms surface accuracy of the assembled reflectors after erection is approximately 2 mm, as determined with a theodolite on a built-in mount near the vertex; small target holes were drilled in identical known locations for this purpose while each panel was under construction on the jig.

The feed support is an octopod based on the octagonal steel hub to obtain more rigid support than would be available for the feet of a widely spread tripod or quadrupod. The octopod enables the legs to converge in the focal plane instead of beyond it and together with the low focal ratio (0.3) it leads to a short, light, and rigid feed support. A front-end box and a feed-rotator box are supported at the focus and may be reached for servicing by pointing the antenna to the south horizon. A 4.57-m diam declination wheel is attached to the hub and is driven by a 3-strand chain of 44.45-mm pitch that is held under pretension by compressed elastomers at each end. A conventional pinion-driven gear was considered but it was found to be about five times more costly. The declination wheels were assembled identically on a special jig that controlled the interrelationship of the declination bearings and the surface of the circular chainway. The welding was done in conjunction with theodolite observations from concrete mounts. The weight of the reflector and structure that moves with it is 9500 kg.

Attachment of the 56 identical aluminum panels to the welded steel hub had to cope with welding distortion of 5 to 10 mm. Machining of the weldment was considered but as it is approximately 4 m in diam and 2 m high heavy costs would have been incurred. They were circumvented by attaining the circular symmetry which, on smaller pieces, would most naturally be achieved on a lathe. The hub was fabricated on top of a rotating platform; then the panel connectors, which are the only parts demanding circularly symmetrical placement, were welded to the hub while being held rigidly in a jig fixed to the ground. The connecting devices are steel sleeves into which the three tubular panel members were plugged. After welding, the platform was rotated 1/56 of a turn and the operation was repeated. Each panel was then plugged in and adjusted with the aid of the theodolite mount near the vertex of the paraboloid. Tubular members interconnecting the panels were welded into place from a fixed platform with good use again being made of the rotating platform. Frequent theodolite monitoring controlled the sequence of operations and showed that the final adjustments and measurements must be carried out at night because, before the final structural bonds are made, thermal distortion due to sunlight exceeds the 1-mm tolerance desired.

The declination axis is offset by 2.02 m from the hub axis with the result that the lower rim of the reflector is near the ground both when the antenna is in its stowed position (pointing to the north pole) and when it is pointing to the south horizon at its other limit of travel. This feature avoids having to raise the pedestal on 2-m columns, which would more than double the amount of steel in the aready heavy pedestal, and simplifies every operation in which height is a consideration.

A steel yoke supports the reflector on roller bearings, carries the declination drive, and constitutes an hour-angle wheel 9.14 m in diameter around which a 6-strand chain of 38.1-mm pitch wraps. It weighs 17 000 kg including a 9000-kg counterweight, and is in turn supported by a pedestal so as to be able to rotate about a polar axis. The pedestal weighs 4970 kg and is attached to a reinforced concrete foundation consisting of three beams connecting the feet of the pedestal and three columns that descend between 3 and 4 m to firm gravel. Each pedestal has a built-in theodolite mount from which targets may be sighted in corresponding positions on the other pedestals and can also sight targets inside the polar axle and in the ends of the declination axle. An assembly drawing showing a view of a single antenna from the north is given in Fig. 3. Speeds and other details of the two drive systems are summarized in Fig. 4.

Hour angle and declination are indicated in the control room on mechanical counters driven by means of synchros with 18-tooth pinions engaging a fine-pitch (3.33 mm) rack rigidly attached to each chain-driven wheel. The surfaces against which the racks are mounted were built up with epoxy resin and then ground to a predetermined radius after the structures were erected by driving the antenna past grinding wheels fixed to the yoke or pedestal. Counterweights were not included in the original design because the drive motors had to be able to cope with wind loads much larger than the dead weight. For example, the wind load at 80 km/h normal to the reflector is 1.5 times the weight of the reflector. The yoke was, however, partially counterweighted with 9000 kg at a late stage to compenate for low gear-reducer efficiencies that would be encountered should sudden winds require the antennas to be slewed to stow from a cold start. The stow position, with the antennas pointing to the north pole, brings hard points of the steel hub of the reflector into close juxtaposition with the pedestal. The stow locks latch automatically as the antennas drive north on the meridian, forcing the hub down on elastomers on the pedestal.

Expenditure during construction was 2 137 000 dollars made up of sarlaries 793 000 dollars, overhead and staff benefits 515 000 dollars, equipment, materials, services, and supplies 538 000 dollars, computing 46 000 dollars, other 245 000 dollars. Other programs were conducted at the same time; the cost of the array itself is estimated at 1 900 000 dollars.

All the mechanical and structural work was done on the site by the personnel of the Stanford Radio Astronomy Institute [10]. Photographs, drawings, and other details of the construction have been presented elsewehre [11]. Mechanical drawings and over 100 technical reports may be consulted at Stanford, and an index to the reports is available on request.

THE RECEIVING SYSTEM

A block diagram of the electronic receiving and data processing system is shown in Fig. 5. To follow the diagram note that the horizontal dashed lines separate the front-end box which is mounted near the focus, the ground box at the base of the antenna, the delay room, and the control room. The components in the front end and ground boxes are shown for one antenna only.

Front End

The signal is received at a linearly polarized feed horn, remotely rotatable to any desired angle of polarization, at the focus of each paraboloid. Modulated noise is added to the signal to permit measurement of the overall gain and then, in the normal mode of operation, it is directly connected to a tunnel-diode amplifier. An alternative mode can be selected by the waveguide switch so that the signal and a matched load at ambient temperatures are connected alternately to the amplifier at 35 Hz by a Dicke switch. This makes possible total-power measurements with a single antenna for calibration of pointing, aperture efficiency, etc. The amplifiers, which were obtained in the years 1967–1968, have a noise temperature of 900 K and were intended to provide a test system to be replaced by degenerate parametric amplifiers with noise temperatures around 90 K. Both sidebands of the amplifier signal are converted by a mixer to a band which extends from 10 to 70 MHz, and after further amplification the IF band is transmitted underground to the thermally stable delay room through a pressurized semi-air-spaced cable (1.27-cm Sprioline). The double-sideband system is appropriate for the future addition of degenerate parametric amplifiers and has the advantage that phase changes in the IF cables do not affect the phase of the multiplier output waveforms.

Synchronized Local Oscillator

The 10.690-GHz local oscillator at each antenna is a Gunn-diode unit phase locked to the 10.693-GHz fourth harmonic of a signal at 2673.25 MHz coming from a 0.5-W crystal-controlled oscillator in the control room. A 3.0-MHz reference signal is also distributed to each antenna for comparison with the difference frequency between the local oscillator and the fourth harmonic. The 2673.25-MHz transmission line is a pressurized 2.22-cm diam semi-air-spaced cable which is buried between the control room and the base of each antenna, and, on the exposed run from the ground to the focus, is covered by a sponge-rubber thermally insulating tube encased in an aluminum outer pipe.

Phase Monitoring

Thermal changes in the electrical lengths of the cables can be monitored using the system on the right-hand side of Fig. 5. A small modulated component of the 2673.25-MHz reference signal is reflected back down the line by a diode switch located in the front-end box and driven by a 400-Hz square wave. The reflected signal comes out of the lower port of the circulator where it is then mixed in a dectector with a sample of the outgoing signal, the phase of which can be varied by a calibrated phase shifter. The switch-frequency waveform from the detector output is amplified, synchronously detected, and displayed on a meter. When the phase shifter is set for zero output on the meter, the phase of the reference sample is in quadrature with the reflected component, and the setting of the phase shifter thus gives a measure of any variation in the round-trip path out to the reflector and back. A small component of the outgoing signal can also reach the detector through the reverse path in the circulator and could cause an error in the indicated phase. This component is canceled by adjustment of the tuner; before a phase measurement is made, the modulating square wave is switched to the diode switch at the lower port of the circulator, the connection between the phase shifter and the hybrid is opened, and the tuner is set for minimum reading of the phase detector output. Use of the phase-monitoring system does not disturb observations in progress and provides an accuracy equivalent to 3° of phase at the local-oscillator frequency. It has been found that line lengths vary only slowly in time, the total change in 10 h rarely exceeding 15°. The method was introduced by Swarup and Yang [12] for the Stanford microwave spectroheliograph.

Wide-Band Variable Delays

Because of the wide bandwidth, compensation has to be made for the fact that the antennas are at different distances from the source under study; otherwise there would be a loss in sensitivity from reduced correlation of the signals received from different antennas. Variable delay units equalize the time delays in the five signal paths from the source to the multipliers to within about 1 ns, which is 1/20 of the reciporcal IF bandwidth. A fixed delay is used for the antenna at position number seven, the nearest one to the center of the array, and an on-line computer controls the other four delays as a source is tracked across the sky. Each delay unit has 512 different possible delays obtained by switching in lengths of 1.27-cm semi-air-space dcable. Each length, when switched out, is replaced by a short piece of high-loss cable of equal attenuation. The cable lengths in each unit are proportional to the spacing of the corresponding antenna from number seven. All units are switched simultaneously by a reed-relay system designed by Little.

IF Amplifiers

The IF amplifiers in the control room provide 45 dB of gain to compesnate for losses in the delay units and IF transmission cables and their frequency response is adjusted to compensate partially for the difference in cable attenuation across the passband. Automatic level-control loops in the IF amplifiers hold their output levels constant, compensating for small attenuation changes which may occur when delay cables are switched. The overall gain of any of the five receiving channels may be measured at any time by switching a small portion of the IF amplifier output into a gain-monitoring receiver which measures the strength of the modulated noise injected at each front end; this is accomplished by a synchronous detector driven in phase with the modulation. Finally, each IF amplifier output is divided four ways, providing 20 inputs controlled at 20 mV rms for the ten analog multipliers.

Wide-Range Multipliers

In each of the multiplier units the multiplying element consists of two transistors with a common emitter resistor; the basic circuit, which has been described by Frater [13], was proposed for our use by Aitchison. In this application transistors were found to provide a higher dynamic range than diodes, an important consideration for observation of a strong source, such as the sun, for which a large fraction of the noise at the multiplier inputs is correlated. Within each multiplier unit one input signal is phase switched and the voltage from the multiplying transistors is amplified at the switching frequency and synchronously detected. The multiplier outputs are sampled by an analog multiplexer which is switched from one output to the next at a rate of 50 Hz. A resistance–capactiance filter at the output of each multiplier limits the noise bandwidth to about 2 Hz and samples are

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then taken at 5 Hz. The signals at this point are quasisinusoidal "fringes" with a minimum period of 1.87438 s, which is reached where the declination δ and hour angle h are both zero and then u is 9 units. In general, the nominal fringe period is 1.87438 $(9/u)$ sec δ sec h. A voltage-to-frequency converter and counter provide analog-to-digital conversion of the sampled voltages, which are then fed into the computer. The output of any one of the multipliers can also be displayed on a chart recorder for monitoring purposes.

[illegible]

THE ON-LINE COMPUTER

The computer is a Hewlett Packard Model 2114B, which is a 16-b machine with 8192 words of memory and a 2.0-μs cycle time. It performs four main tasks in on-line operation: control of the data sampling and reduction of the multiplier outputs to estimates of complex visibility; recording and display of the visibility data and system parameters; computation and display in real time of the desired antenna positions, taking into account calibrated pointing errors; and control of the delay lines. The first of these is the most complex, and will be discussed in more detail in what follows. The operator interacts with the system through a cathode-ray tube (CRT) terminal, from which he can enter data and can command without interrupting any ongoing data sampling. Other inputs to the computer include a digital sidereal clock and a multichannel scanner, the latter being used to monitor various equipment parameters. Mass storage is provided by a cassette-type magnetic tape unit with three transports. Final data reduction can be performed off line on the same computer or at the Stanford Computation Center to which data can be transmitted via telephone lines.

It can be shown that the output signal $s(t)$ from each multiplier, after low-pass filtering to a bandwidth much less than the IF bandwidth, may be expressed as

$$s(t) = V_R \cos(2\pi D/\lambda) + V_I \sin(2\pi D/\lambda) + n(t) \quad (1)$$

where V_R and V_I are the real and imaginary parts, respectively, of the quantity, proportional to complex visibility, measured by the corresponding antenna pair; $n(t)$ is a zero-mean Gaussian noise process; and D is the path difference for a reference direction r given by

$$D = r \cdot L + p_1(r) - p_2(r). \quad (2)$$

Here r is a unit vector, L is the spacing between two corresponding earth-fixed reference points at the two antennas, and $2\pi p_1/\lambda$ and $2\pi p_2/\lambda$ are the phase differences between the fields at each reference point due to waves coming from the direction r and the signals at the terminals of the corresponding antenna. If the reference points are chosen carefully, p_1 and p_2 will vary only slowly with r (further discussion of this is given in a later section). Rotation of the earth causes r (and consequently D) to vary with time in such a way that $s(t)$ may be described as quasisinusoidal with slowly changing frequency. Samples of $s(t)$ for each multiplier are digitized and read into the computer every $\Delta = 0.2$ s. The computer estimates V_R and V_I from a finite sequence of $M+1$ samples, $s(t_0), \cdots, s(t_M)$, $t_i = t_0 + i\Delta$. It is easy to show that if $D(t_M)/\lambda - D(t_0)/\lambda$ is aninteger (the samples span an integral number of "cycles" of $s(t)$), then the minimum mean-square error (mmse) estimates are

$$\hat{V}_R = \frac{1}{M+1} \sum_{i=0}^{M} s(t_i) \cos\left[2\pi D(t_i)/\lambda\right]$$

$$\hat{V}_I = \frac{1}{M+1} \sum_{i=0}^{M} s(t_i) \sin\left[2\pi D(t_i)/\lambda\right]. \quad (3)$$

If a nonintegral number of cycles is spanned, the mmse estimates are more complicated, and they have a somewhat larger variance per sample [14]. The variance increases rapidly if less than one cycle is spanned so the present on-line program ensures that the condition

[illegible]

$$D(t_M)/\lambda - D(t_0)/\lambda = \text{integer}$$

is satisfied; but otherwise M may be freely selected by the observer. The choice of M, or equivalently the "integrating period" $M\Delta$, is also governed by sampling considerations in the u–v plane; for a source whose diameter equals the ringlobe radius of 4.2′, the most widely spaced antenna pair samples an independent point in the Uv-plane every 25 min.

The program evaluates the sine and cosine of $2\pi D(t_i)/\lambda$ in real time, accumulating the sums in (3) separately for each multiplier. Stored information on L for each antenna pair and $p(r)$ for each antenna is used; the reference direction r is computed from the right ascension and declination of date for the center of the source (as entered by the operator) and from the current reading of the sidereal clock.[3] In addition, the quantities

$$\sum_{i=0}^{M} s(t_i) \qquad \text{and} \qquad \sum_{i=0}^{M} s^2(t_i)$$

are accumulated as a basis for monitoring the dc drift of the multipliers and the system noise, respectively. With ten multipliers, the processing of each sample must be completed in at most $\Delta/10 = 20$ ms. Careful programming was required to achieve this, since hardware multiply and divide instructions were not available. At present, about 65 percent of the available time is used. The computer's priority interrupt system is used to control the sampling, so that all of this processing normally takes place in the "background," while in the "foreground" other tasks are performed, using the remaining 35 percent of the machine's time. These tasks include recording and displaying the data from the preceding integrating period; computing the current desired antenna position settings and displaying them to the operator; monitoring the states of various equipment, and issuing warning messages in case of difficulty; accepting commands and data from the operator; and calibration of the previous integration, using data from an earlier observation of a calibration source, and recording and displaying the results. It is expected that additional capabilities will be added, including plotting of the one-dimensional brightness distribution estimated from calibrated data taken in the last integrating period.

The estimation of the two-dimensional brightness distribution from a 10-h observation must be performed off line because of the computer's limited memory. Programs are available for the 2114B to apply more precise corrections to the visibility data than is possible in the on-line program, taking

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[3] Local sidereal time at one end of the array differs from that at the other end by 0.56 s, which can be a nonnegligible fraction of a fringe period (minimum value 1.87 s), but this has no effect on the estimated phase provided r and all the L are referred to the same coordinate frame

into account the effects of atmospheric refraction, small errors in the sidereal clock's setting, etc.; to calibrate the visibility data using any available calibration source observations; to average the data in various ways; to plot estimates of the one-dimensional integrated brightness distribution; and to compute the two-dimensional brightness distribution by taking the direct Fourier transform. If a 5-min integrating time is used, about 1 h is required to complete all of the processing needed to compute the two-dimensional map.

CALIBRATION AND OBSERVATION PROCEDURES

Pointing Errors

Changing gravitational loads, as an antenna drives across the sky from boundary to boundary, results in movement of the beam through calibratable angles which, at extremes, may be 30′ greater than the drive wheel rotations which the readout system displays.

An observing technique which allows rapid precise measurement of the pointing errors has been developed. It involves tracking an unresolved source with the entire array pointed sequentially at four positions surrounding an initial guess at the correct pointing. All ten magnitudes $(\hat{V}_R^2+\hat{V}_I^2)^{1/2}$ are then recorded, and from the resulting 40 numbers it is possible to determine (with some redundancy) the five two-dimensional pointing errors. This is done by noting that

$$A_{ij} = \text{const} \times \left[g(\theta_i)g(\theta_j)\right]^{1/2}$$

where A_{ij} is the visibility magnitude for the channel involving antennas i and j; θ_i, θ_j are the magnitudes of corresponding pointing errors; and $g(\cdot)$ is the power pattern of an individual antenna (assumed known). After writing this set of equations for each of the four observing positions and taking ratios to eliminate the unknown constants, one obtains a nonlinear system which can easily be solved for each $g(\theta_i)$ and then for each θ_i provied $g(\cdot)$ is known.

It is believed that most of the pointing error occurs in the mount structure rather than in the paraboloid or feed support With the result that, considering the lack of simple symmetries with respect to the local vertical, the pointing error for each antenna is a complicated function of direction in the sky. In order to allow real-time prediction of the desired pointing, the following formulas for Δh (indicated minus true hour angle) and $\Delta\delta$ (indicated minus true declination), which are based on structural analysis, were fitted to observational data obtained at numerous declinations.

$$\Delta h = a_1 + a_2 h + a_3 \sin h + a_4 \cos h + a_5 \sin h \sec \chi + a_6 \sin h \tan \delta + a_7 \cos h \tan \delta + a_8 \tan \delta$$

$$\Delta\delta = a_9 + a_{10}\delta + a_{11} \sin h + a_{12} \cos h + a_{16} Q + a_{13} Q \sec \chi$$

where δ is the declination, h is the hour angle, χ is the zenith distance, b is the latitude, $Q = \sin b \sec \delta - \cos \chi \tan \delta$, and the a_i are coefficients determined by a least mean-squares fit.

The coefficients are determined separately for each antenna, and are kept in the core memory of the computer during observations. These expressions maintain the residual pointing errors well within a small fraction of the 7′ beamwidth as shown in Fig. 6. Analysis of such data for a wide range of declinations reveals that systematic errors have been held to 1′ in the worst part of the sky and that random errors have an rms value of 0.5′ (or less, as much of the scatter such as that seen in Fig. 6 could be reduced by repeated observation). Although we regard these as negligible errors for most purposes, they will be reducible even further by refinement of the preceding formulas as we accumulate additional data, a virtue shared with all interferometers having fixed elements. A small pointing error θ reduces the single-element gain by about $\exp(-a\theta^2)$, which for $\theta = 1'$ equals 0.94 (in our case where $a = 0.057$). A random error with standard deviation σ can be shown to reduce the mean signal by a factor $(1+2\sigma^2 a)^{-1/2}$, which equals 0.99 for $\sigma = 0.5'$. This pointing accuracy shoud allow operation with the even narrower single-element beamwidth such as would result at a shorter wavelength of, say, 1 cm.

Focusing

The feed horn of each antenna is fixed at an optimum focus position that was determined by observing the response to a calibration source and using a remotely controlled focuser which was mounted on each antenna in turn.

Phase Calibration

The phase of the estimated complex quantity $\hat{V}_R + j\hat{V}_I$ depends, in accordance with (3), on knowledge of the path difference D. To know D it is necessary to know the relative positions of the reference points fixed with respect to the antenna pedestals, dimensional discrepancies between the two antenna structures such as differences in the distance between the declination and polar axes, and misalignments such as the polar axis not being parallel to the earth's axis. Great care was taken in the construction to make the five antennas as identical as possible and to harmonize the design with surveying requirements. Consequently, all the imperfections are small. Their effects have been analyzed for equatorial mounts such as ours by Wade [15], and the combined effect may be determined by radio source observations and may be expressed in terms of a set of phase parameters from which the path difference D, or phase function D/λ, may be evaluated in real time. As the antennas are permanent objects in permanent locations the parameters may be progressively refined by means of observations of known sources so that the on-line path difference is now accurate to 0.05 wavelengths over the whole sky. Even more precise corrections are possible with off-line computations for special cases.

Because the paraboloid axis does not intersect the declination axis, a path difference is introduced of 0.02 wavelengths per minute of arc differential setting error in declination. The antennas can easily be set to this accuracy. The phase shift in the distribution system of the local-oscillator reference signal is easily held constant to 0.01 cycles using the modulated-reflector phase-monitoring system previously described, thereby reducing the frequency with which calibration sources need be observed.

Observing Procedure

During the course of an observing session, one or more short measurements are made on calibration sources (unresolved sources at known positions, preferably with known flux densities) and these measurements are automatically ap-indicate brightness temperatures in the range 10^6 to 10^7 K at 2.8 cm and angular widths from 8″ to 25″ in agreement with the dimensions of associated sunspot umbras. A program of observations of Jupiter has begun with a view to studying the radiation belt and its time changes.

In addition to its performance in mapping, the array has a very useful capacity for observations of faint unresolved sources such as quasars, stars, and X-ray sources. It has also been used by D'Addario and Stull [19] to follow the decrease in the flux density of Cygnus X-3 from a value of 1.86×10^{-26} $\mathrm{W\cdot m^{-2}\ Hz^{-1}}$ when first observed after its outburst in September 1972, down to below a level of 0.2×10^{-26} $\mathrm{W\cdot m^{-2}\ Hz^{-1}}$. The array is clearly well suited to monitoring variations in sources with flux densities of $\sim10^{-26}$ $\mathrm{W\cdot m^{-2}\ Hz^{-1}}$, and since the addition of parametric amplifiers would increase the sensitivity by an order of magnitude, it is potentially a very useful instrument for variable-source studies. Addition of other wavelengths in the range 1 to 10 cm will allow analysis of Faraday rotation in different parts of extended sources and may lead to critical tests of models for extragalactic and galactic variable sources.

APPENDIX

LESS THAN TWELVE-HOUR TRACKING

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The hour angle notion of the existing structure is limited to ± h, and in addition, for southern declinations, the motion is further limited by the horizon, so we are led to consider the effect of missing sectors on the u–v plane. The effect is expressible in terms of a correction pattern $p_c(x, y)$ to be subtracted from the pattern shown in Fig. 2. It is easy to compute numerically for any given circumstances but an approximate analytic expression can also be given. Let the missing sectors on the u–v plane have a semivertical angle θ. Then replacing each missing arc by a straight line segment through the centroid of the arc, and retransforming, we obtain

$$p_c(x, y) = (90\pi)^{-1}\sum_{n=1}^{9} 4n\theta \,\mathrm{sinc}\,(2n\theta x)\cos(2\pi\eta n y)$$

where $\eta=(\sin\theta)/\theta$. For 10-h tracking ($\theta=\pi/12$) this expression accurately indicates the correction pattern. Its central value is then 1/6 of that of the 12-h pattern.

ACKNOWLEDGMENT

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are /

plied by the computer to determine the absolute phase and gain of each of the ten interferometer channels. Subsequent variations can be monitored using the modulated reflector and modulated noise source systems shown in Fig. 5. The on-line program can, at the option of the operator, apply corrections for the measured variations, apply the calibrator data, and display the results. Thus we have fully calibrated data available immediately at the end of an observing session. In addition, we record the uncorrected data in case the observer wishes to apply other corrections in the off-line processing.

SENSITIVITY

Consider the output sinusoid from any one multiplier when the array is observing a point source of flux density F. After an integrating time τ the estimated quantity $\hat V=\hat V_R+j\hat V_I$ has a standard deviation $\Delta V=\langle|\hat V-\langle\hat V\rangle|^2\rangle^{1/2}$, due to receiver noise given by

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$$\frac{\Delta V}{|\hat V|}=\frac{2kT_{\mathrm{sys}}}{AF(B\tau)^{1/2}}.$$

Here k is Boltzmann's constant, B is the effective bandwidth, and T_{sys} and A are the system noise temperature and the antenna collecting area, which are assumed to be the same for each antenna. Discussions of the signal and noise levels in a multiplying radiometer from which the above formula may be derived are given by Tiuri (see [16], [17]). If N antenna pairs are available simultaneously, the sensitivity is increased by a factor $\sqrt{N}$ since for a point source in the reference direction the visibility is the same for all antenna pairs whereas the errors are independent. If we follow the convention that the minimum observable flux density $F_{\min}$ corresponds to a signal-to-noise ratio[4] of 5

$$F_{\min}=\frac{5/2T_{\mathrm{sys}}}{A(NB_\tau)^{1/2}}.$$

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For the present array $T_{\mathrm{sys}}=10^3$ K, $B=60$ MHz, $\tau=10$ h, $N=10$, and $A=79$ m² (aperture efficiency = 30 percent) and we obtain $F_{\min}=0.03\times10^{-26}$ $\mathrm{W\cdot m^{-2}\ Hz^{-1}}$. For an extended source an approximate indication of the minimum strength for useful mapping is obtained by requiring a flux density $F_{\min}$ from each area of the source that subtends a solid angle equal to that of the synthesized beam.

FIELDS OF APPLICATION

From the above figures we estimate that there are about 50 extragalactic sources with measurable structures which can be investigated with the original tunnel-diode amplifiers. Many of these have been mapped at longer wavelengths and interesting studies of the variation of the spectral index should be possible.

The short operating wavelength of the array is also particularly well suited to observations of thermal sources and a program to search for compact components in over 200 H II regions was completed in the summer of 1972 by Felli, Tofani, and D'Addario [20]. The observations were made near meridian transit, providing one-dimensional strip-integrated profiles in only 5 to 10 min of observing time per source. Mapping of galactic and extragalactic sources is continuing, as are observations of the structure of active solar regions. Preliminary solar studies by Grebenkemper and Rust [18]

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[4] The term signal-to-noise ratio is commonly applied to the quasi-sinusoidal output of a multiplying interferometer to mean $S/\Delta S$, where "fringe amplitude" S is expressible in terms of the computable quantities $\hat V_R$ and $\hat V_I$ by $S=(\hat V_R^2+\hat V_I^2)^{1/2}=|\hat V|$ and ΔS is the rms multiplier output averaged for time τ in the absence of signal. It can be shown that, when $S/\Delta S\gg1$, $\Delta v/|\hat V|=\sqrt{2}\,\Delta S\gg S$.

Solulu.

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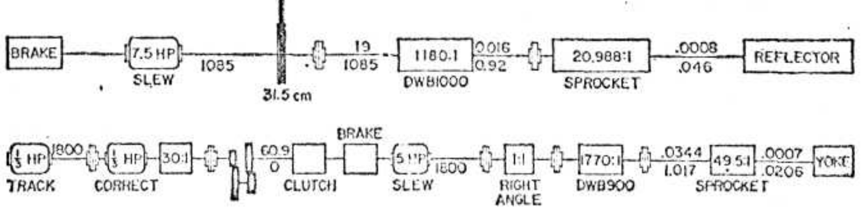

Fig. 4. Drive systems for declination (above) and hour angle (below). Gear ratios are shown in the boxes and shaft speeds in revolutions per minute are shown on the shafts.

TABLE I

CENTIMETER-WAVELENGTH EARTH ROTATION SYNTHESIS ARRAYS

Location	f (MHz)	Elements (total	movable)	Diameter (m)	Element Spacing (m)	Maximal Spacing (m)	Beam width	Imaging Time[a] (h)	lobe Radius	Beam o Elemen
Stanford, Calif.	10690	5	0	18	23	206	19″	10	4′.2	7′
Cambridge, England	5000	8	4	13	40	4560	2″	192[a]	5′	6′
Green Bank	2695	3	2	26	100 and 300	2700	8″	108[a]	4^{a}	20′
W. Va. [21]	8085						3″		1′	7′
Big Pine, Calif.	1420	3	3	27 and 40	30.5	1080	7″		24′	33′
Fleurs, Australia [22, 23]	1415	68	0	5.7 and 13.6	12.2	800	40″	12	1°	3°
Westerbork,	610	12	2	25	144	1600	56″	12	23′	83′
	1415						24″		10′	36′
The Netherlands [24]	4995						68″		28′	11′
Cambridge,	408	3	1	18	12	1550	80″	768[a]	None	3°
England [4], [25]	1407						23″			1°

[a] Excluding time taken to move antennas

TABLE II

BASIC PARAMETERS

Latitude[a]	+37°23′55.0″
Longitude[a]	+8h 08m 45.44s
Elevation	70 m
Wavelength in vacuo	2.80441 cm
Frequency	10,690 MHz
IF band	10–70 MHz
Reflector diameter	18.3 m
Element spacing	22.860 m(= 815.146 λ)
Extreme spacing	205.740 m (= 7336 λ)
East–west width of fan beam to half peak[b]	16.1″
East–west width of synthesized beam[b]	18.8″
Beamwidth of single reflector	7′
East–west ringlobe radius[b]	4.2′
Declination axis to polar axis	2.5908 m
Declination axis to paraboloid axis	2.02 m
Declination wheel readout radius	2.0864 m
Hour wheel readout radius	4.633 m

[a] The position given is the intersection of the meridian through the USCGS bench mark RATEL and the parallel, 13.1 m north of the bench mark, passing through the theodolite seats built into the pedestals. The midpoint of the array is 17.2 m west. The observatory location quoted in the American Ephemeris is the center of the adjacent microwave spectroheliograph cross array.

[b] North-south values are larger by the cosecant of the declination.

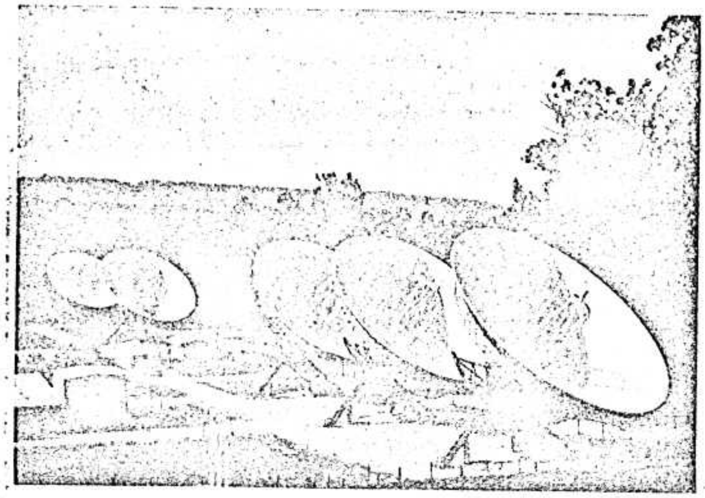

Fig. 1. A photograph of the radio telescope from the south-east.

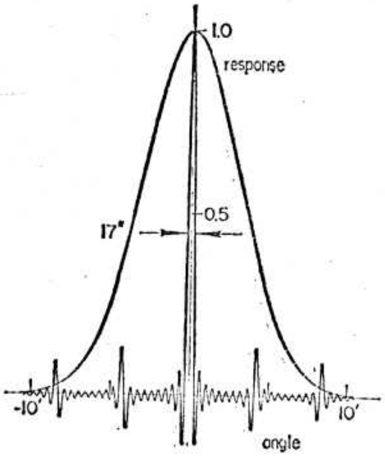

Fig. 2. Radial profile of the principal response pattern (full curve) and of the pattern of a single element (broken).

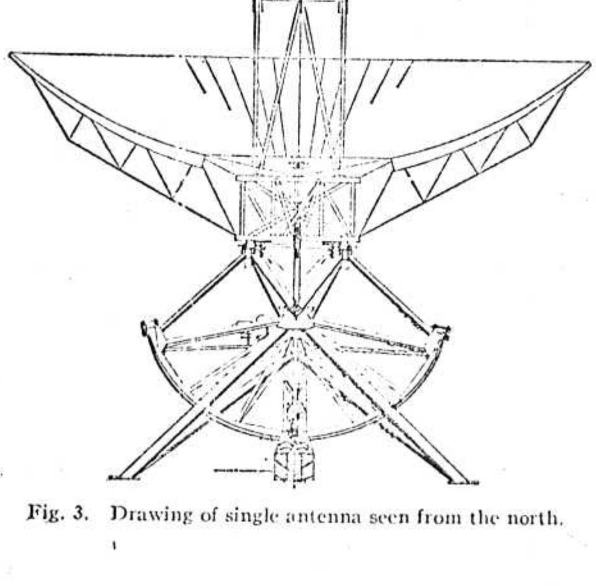

Fig. 3. Drawing of single antenna seen from the north.

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THE LOCAL OSCILLATOR SYSTEM FOR THE FIVE-ELEMENT ARRAY

A. R. Thompson

A. Choice of the Type of System

The receiving system for the Stanford five-element array requires a synchronous local oscillator signal at each antenna. The power level required to drive the mixer is about 1 mw and the frequency is 10.690 GHz. Three possible local oscillator schemes have been considered and are:

1. direct distribution of X-band power from a centrally located oscillator,
2. distribution of a subharmonic of the required X-band frequency to drive a frequency multiplier at each antenna,
3. distribution of a subharmonic signal to which an X-band oscillator at each antenna can be phase locked.

In considering the relative merits of these three schemes several general points should be noted. The distance from the main laboratory to the individual antennas varies between 300 ft. and 500 ft. (approximately 90 meters and 150 meters). Cables transmitting X-band or subharmonic signals should be buried in order to minimize temperature variations and the resulting relative phase changes at the antennas if the cable lengths are not equal. In order to monitor variations in the effective electrical lengths of the cables it is convenient to use the technique developed by Swarup and Yang (Trans. I.R.E., AP 9, 75, 1961) using a modulated reflector at each antenna. To measure the effective cable lengths with sufficient accuracy (10° of phase at the local oscillator frequency corresponds to 0.08 cm in the transmission line), it is necessary to use a wavelength not much longer than 10 cm, and for this reason it would be convenient with schemes 2 or 3 to use a subharmonic frequency lying within the S-band range.

With the first scheme involving direct distribution of X-band power a waveguide type of transmission line would be required to provide a sufficiently low attenuation. With the best coaxial cable at this frequency (1/2" Spiroline), the attenuation is in excess of 10 db per 100 ft., whereas with waveguide the attenuation is approximately 2 db per 100 ft. The standard X-band waveguide is expensive and available only in short lengths and the joints would have to be sealed against moisture before burying. Circular aluminum tube is less expensive but tests show that the rotation of the field pattern in long runs becomes a problem at the transitions. It is also necessary to provide some kind of protection for the aluminum before burying it. Also, at X-band, reflections in waveguide to coaxial transitions, connectors and rotating joints which would be necessary to transmit the power up the antenna to the box at the feed are usually more severe than at lower frequencies.

In the second scheme distribution of the fourth subharmonic at 2.67 MHz would be feasible using 7/8" Spiroline cable for which the attenuation is 2.6 db per 100 ft. at that frequency. Spiroline is available in lengths sufficient to avoid any joints in the buried portions. It is also available with a protective coating suitable for direct burying. Frequency multipliers with S-band input and X-band output typically have efficiencies of about 10% with 200 mw of input power. A 10 watt oscillator at the central location would be required to provide this level at each antenna. However the efficiency of a multiplier usually falls rapidly with decreasing input power so that power variations in the input of the multiplier tend to be magnified in the output. Multipliers using step recovery diodes are to be avoided since the phase difference between the output frequency and the corresponding harmonic of the input frequency can vary with temperature.

The advantages of the third scheme using the phase locked oscillators are that less than 1 mw of S-band power is required at each antenna and that the X-band oscillator provides a signal free from harmonics and at a level which is not dependent upon the level of the S-band signal. Furthermore, the X-band level can be accurately controlled using a current controlled attenuator which if placed before the harmonic mixer of the phase lock loop introduces no associated phase variation.

Because of the ease of transmission of the S-band signal compared with the X-band signal, and the low level required by the phase lock, the third scheme has been chosen for use with the array. In addition approximately 1,000 ft. of 7/8" Spiroline cable and 3 X-band solid state oscillators (Fairchild 1113F) are available from earlier projects for which they are no longer required. The low level of power required by the phase lock scheme has the advantage that if any additional antennas are required to give longer spacings in the future, they can be incorporated into the system with minimum difficulty.

B. Design of the Phase Lock System

The basic phase lock circuit which is required at each antenna is shown in Fig. 1. The fourth harmonic of the S-band oscillator beats with the output of the X-band oscillator in the harmonic mixer and produces a 3 MHz signal which is amplified and then applied to a phase detector which also receives a 3 MHz signal from a reference oscillator. The output of the phase detector controls the frequency of the X-band oscillator to lock the phase of the 3 MHz beat frequency to the phase of the 3 MHz reference. In principle one could design the system so that the S-band and X-band signals interact in a phase detector to produce directly a dc output to control the X-band oscillator. In practice however, the S-band and X-band signals are only a milliwatt or less in power and further amplification would be required which is most conveniently accomplished at an intermediate frequency. This intermediate frequency must lie outside the IF band of the interferometer system so as to avoid causing interference, and thus it must be less than 5 MHz or greater than 70 MHz. The choice of a low frequency eliminates the necessity to use a low-loss buried cable to distribute the IF reference signal, since one degree of phase at 3 MHz corresponds to a path length of 28 cm.

The X-band oscillator frequency is controlled by a second order servo loop of which the characteristics are determined by the resistors R1 and R2 and the capacitor C shown in Fig. 1. To choose the values of these components we follow the treatment by Gardner (Gardner, F.M. 1966, Phase Lock Techniques, John Wiley & Sons, New York, pp. 7-10).

Natural frequency of loop $= \omega_n = \left(\frac{K_o K_d}{\tau_1}\right)^{\frac{1}{2}}$

Damping factor $= \xi = \frac{\tau_2}{2}\left(\frac{K_o K_d}{\tau_1}\right)^{\frac{1}{2}}$

$\tau_1 = R_1 C$

$\tau_2 = R_2 C$

K_o = frequency deviation of the oscillator being controlled (X-band oscillator) per volt of control signal (radians $\sec^{-1}$ volt^{-1}).

K_d = output signal from phase detector per radian of phase change of the IF input signal (volt radian^{-1}).

ω_n is chosen so that the loop does not drop out of lock in the presence of fast frequency changes in the X-band oscillator. We estimate that such frequency changes resulting from mechanical vibration of the oscillator might be a few MHz in a time of a few milliseconds. A loop will drop out of lock for a rate of frequency change of $\delta\omega/\delta t \geq \omega_n^2$ (Phase Lock Techniques, p. 36). We therefore choose a value of $\omega_n = 10^5$. An optimum value for the damping factor ξ is about 0.8 (Phase Lock Techniques, p. 74). K_o is approximately 3×10^7 radians $\sec^{-1}$ volt^{-1} (3 to 10 MHz per volt for the Fairchild MS 1113F oscillator). K_d is approximately 0.5 volt per radian, a value which may be estimated from the peak amplitude of the beat signal at the output of the detector when the loop is not locked. Using these values we obtain $\tau_1 = 1.5 \times 10^{-3}$ sec. and $\tau_2 = 1.6 \times 10^{-5}$ sec. The chosen values for the resistors and capacitor are R_1 = 100K, R_2 = 1K,* and C = 0.02 mf. These approximately satisfy the above design criteria and have been found to give satisfactory operation. The operational amplifier used (Fairchild ADO 27-B) has a gain-band with product of 1.5 MHz and thus its response does not affect the loop characteristics.

*Increase of R_2 reduces phase jitter (display Lissajous figure using 3 MHz IF and reference) but too high a value results in spurious locks, particularly with control voltage near zero end of range. R_2 = 3.3K is near optimum value.

The complete phase lock circuit excluding the oscillators and the harmonic mixer is shown in Fig. 2. This contains a second phase detector to indicate when the system is in lock, and a sweep circuit to search automatically if the lock is lost. The two phase detectors are fed in the same phase from the IF output signal and in phase quadrature from the 3 MHz reference signal which passes through 45° phase lag and phase lead networks. The outputs of the two phase detectors are filtered to remove radio frequency components and applied to the inputs of two operational amplifiers. The loop amplifier has the same feedback components as shown in Fig. 1 with the values derived above. When the loop is locked the output of the loop phase detector is held near zero volts, and the output of the lock-indicator phase detector is a negative dc voltage for a low lock (X-band oscillator frequency 3 MHz lower than the fourth harmonic of the S-band oscillator) and positive for a high lock. The feedback resistor of the lock indicator amplifier provides a gain of approximately 470 which is sufficient to saturate the amplifier and produce an output voltage of approximately +12 volts for a low lock and -12 volts for a high lock. The type of amplifier used, Fairchild ADO-27B has no difficulty recovering from a saturated condition. The low lock is chosen as the one required for operation of the system, and this condition is indicated by closure of the lock relay through transistor T1. In the low lock condition the collector voltage of transistor T2 is typically 0.03 volts, but if the lock is lost it goes up to 14.5 volts. The collector voltage of T2 is applied through a 4.7 MΩ resistor to the summing junction of the loop amplifier, and if the lock is lost, the high voltage produced by T2 causes the output of the loop amplifier to sweep negative in voltage. The emitter of T3 follows this voltage and when it reaches -10 volts the gate terminal of the p.u.t. (programmable unijunction transistor Type D13T1) reaches zero volts and the p.u.t. then shorts the 0.02 μF capacitor in the amplifier feedback loop causing the amplifier output to return to zero. The diode between the emitter of T3 and the p.u.t.

gate slows down the recovery of the p.u.t. and insures that the amplifier capacitor is completely discharged. Thus the output voltage of the loop amplifier in the absence of a lock is a sawtooth waveform sweeping from approximately 0 to -10 volts with a frequency of approximately 20 c/s. If the required control voltage for the X-band oscillator lies within the sweep range the system will automatically go back into lock. Since the frequency of the X-band oscillator increases with increasing negative control voltage the low lock condition will be reached before the high lock as the loop amplifier sweeps. If however the system finds itself in the high lock condition the negative signal from the output of the lock-indicator amplifier acting through transistor T4 causes the p.u.t. to discharge the loop amplifier capacitor and initiate the sweep again. The output of the lock indicator amplifier also produces a negative transient as the system approaches the required low lock and to prevent this triggering the p.u.t. a time constant of 50 ms is inserted at the base of the transistor T4. The emitter voltage of T5 is about 0.4 volts higher than the output voltage of the loop amplifier, and is used as an isolated output for remote monitoring of the operation of the system. The complete circuit shown in Fig. 2 together with a level control circuit is mounted on a printed circuit board of dimensions 4" X 5". The input and output connections to the board are shown in Fig. 3.

The following procedure should be used for adjustment of the phase lock circuit.

1. With no IF or reference input the trimmer of the lock-indicator amplifier is adjusted for zero output voltage from the amplifier.

2. With no IF or reference input and with the 4.7 MΩ resistor disconnected from the summing junction of the loop amplifier, the trimmer of the loop amplifier is adjusted for zero drift rate of the amplifier output.

3. The input of the lock-indicator amplifier is connected through a 1 MΩ resistor to +15 volts to simulate detection of a high lock. The output voltage of the amplifier is then typically -12.5 volts. This should be about 1 volt more negative than the output of the loop amplifier at the negative peak of its voltage sweep so that a high lock will trigger the p.u.t. To achieve this condition the range of the sweep of the loop amplifier can be adjusted by trimming the 150 k or 100 k resistor

connected to the gate of the p.u.t. The sweep range of the output of the loop amplifier should be typically -0.4 to -10 volts.

C. The IF Amplifier for the Phase Lock System

The circuit of the IF amplifier designed for the phase lock system is shown in Fig. 3. The signal to be amplified is at a frequency of 3 MHz. The amplifier consists of two PA7600 (Philco) microcircuits which have a nominal gain of 43 db with input and output impedances of 50 ohms. The frequency response of the amplifier is controlled by single T-section low pass filters at the input and output by a double T-section high pass filter between the two stages. The cut-off frequencies are 2 MHz and 5 MHz, and the theoretical values for the inductors and capacitors for a 50 ohm characteristic impedance (see Reference Data for Radio Engineers, 4th Edition, pp. 166-169) are given by $L_k = 4.0$ uH and $C_k = 1600$ pf for 2 MHz cutoff frequency and $L_k = 1.6$ uH and $C_k = 640$ pf for a cutoff frequency of 5 MHz. The values used are chosen from the available stock components to approximate the theoretical values. The response of the amplifier typically peaks close to 3.0 MHz, and the response at 3.0 MHz is within 0.2 db of the maximum. The response is broad and the -3db points are typically 2.4 MHz and 4.5 MHz. The gain depends on the characteristics of individual microcircuits and for the first three units constructed the values measured at 3 MHz were 72 db, 66 db and 73 db. The bias adjustment of the first microcircuit should be set for maximum gain and the adjustment for the second microcircuit should be set near maximum gain but for minimum distortion of the output waveform. This is best done by using a 3 MHz signal generator and displaying the undetected amplifier output on a broadband oscilloscope. The maximum undistorted output voltage should be at least 0.5 volts peak. The gain of the amplifier depends critically on the supply voltage* which during operation should remain within 0.05 volts of the value used when adjusting the bias trimmers of the microcircuits. The amplifier also contains a detector for monitoring the IF level.

The amplifier is constructed on a copper-clad board 1 5/16 inches by 3 5/8 inches and mounted in a die-cast box (Pomona Electronics No. 2902). The stability of the circuit was greatly improved by grounding the board at one end of the box only, and for this reason the input is coupled through a transformer which consists of 20 turns of number 32 wire wound on a Q1 ferrite core.

*Refers to +6v; individual regulators (805-v6) eliminate this difficulty.

D. The Level Control Circuit

The output of the X-band oscillator passes through a current controlled attenuator (HP 3505, 3550, or 3551), to hold constant the current measured by the level detector. The attenuator is controlled by a second order loop with one ADO-27B operational amplifier. The signal from the level detector is offset by a control voltage from a 10 K fixed resistor and a 20 K potentiometer. This is used to set the power level reaching the mixer of the interferometer receiving system for optimum noise figure and frequency response. If the current controlled attenuator requires a positive bias (HP 3550) the level detector should produce a negative signal and the 10 K resistor from the level control potentiometer should be returned to +15 volts. If the attenuator requires a negative bias (HP 3505 or 3551) the polarity of the detector crystal should be reversed and the 10 K resistor returned +15 volts. The level control circuit excluding the potentiometer is mounted on the same circuit board as the phase lock system and provision is made to connect the 10 K resistor of the level control potentiometer to either +15 volts or -15 volts by changing a single jumper connection.

The trimmer potentiometer of ADO-27B amplifier should be set for zero drift of the amplifier output with the input level detector disconnected and the 20 K level set potentiometer at the zero resistance end of its range.

E. Physical Layout of the Phase Lock and Level Control System

The components which comprise the phase lock system with the exception of the S-band oscillator and the 3 MHz reference level oscillator are shown in Figs. 4 and 5. The components shown in Fig. 4 are mounted in a box of dimensions 11" x 3 3/4" x 7" which is mounted close to the mixer in the box at the feed of each antenna. This contains all of the phase lock system except the power supplies and certain monitoring and control components which comprise the local oscillator control unit (Fig. 5). The control unit is mounted in an enclosure at the base of each antenna. It contains two 100 μa meters, one of which provides a continuous monitor of the output level of the X-band oscillator and the other can be switched to monitor the level of the 3 MHz IF signal, the 3 MHz reference signal, or the frequency control voltage applied to the

* See Figs. 6, 7 and 8.

oscillator. The control unit also contains the potentiometer for adjustment of the local oscillator level, and a lamp to indicate when the system is in lock (lamp on equals in lock). An output contact for a second lock indicator lamp in the main control room is also available.

F. The S-band Reference Signal

The S-band oscillator is located in the main laboratory building and its output is fed through a cable to the equipment building in the center of the array where it is split five ways using four hybrid junctions (Narda 3033), arranged so that three of the outputs each contain one quarter of the input power and the remaining two outputs, one eighth of the input power. The low power outputs go to the two closest antennas. All cables are 7/8" Spiroline and are buried. The attenuation from the laboratory through the power splitter to the base of any antenna is 17 to 19 db. A further attenuation of approximately 4 db occurs in the cables between the ground level and the feedbox of the antenna. Assuming a total loss of 23 db to each antenna where 1 mw of power is required at the harmonic mixer, the power required from the S-band oscillator is at least 0.2 watts. A capability of 0.5 to 1 watt output is desirable to cover loss of power of the oscillator with aging and any additional loss in the transmission system.

The difference in the lengths of the cables to the closest and the most distant antenna is approximately 225 ft. (The cables go directly to the antennas and no attempt is made to equalize the lengths.) This difference is equal to 2,300 wavelengths at 10.69 GHz and puts a requirement on the frequency stability of the oscillator in terms of tolerable relative phase shifts of the antennas. If a maximum phase error of 12° or 1/30 of a fringe can be tolerated the oscillator frequency must be stabilized within one part in 7 × 10^4. A crystal controlled S-band oscillator is therefore required. The requirements of the oscillator can therefore be summarized as follows:

Frequency : 2673.25 MHz
Frequency stability : 1 part in 10^5 or better
Output power : 0.5 to 1 watt.

A solid state S-band source with built in crystal control of the frequency which fulfills the above requirements is available from Microwave

Technology Laboratories, Model NT-90. The S-band oscillator will consist either of this unit or a Sperry 2K42 klystron with a phase lock frequency control.

G. Main Components

S-band oscillator

3 MHz oscillator

4 Narda 3033 hybrids (for power splitter)

Oscillator Unit (5 required)

Fairchild MS-1113F X-band oscillator

3 MHz I.F. amplifier

Circuit board 3 Fairchild ADO-27B amplifiers
2 Relcom M6 double balanced mixers (phase detectors)

H.P. 3550 current-controlled attenuator

2 O.S.M. 20156-3 hybrids

O.S.M. 20066-6 6 db coupler

Narda 3003-10 10 db coupler

A.E.L. SNB 110C switch (for modulated reflector)

2 Sage 1071 detectors or OSM 20060 detectors

Oscillator Control Unit (5 required)

2 Con Avionics HT-15-0.45A

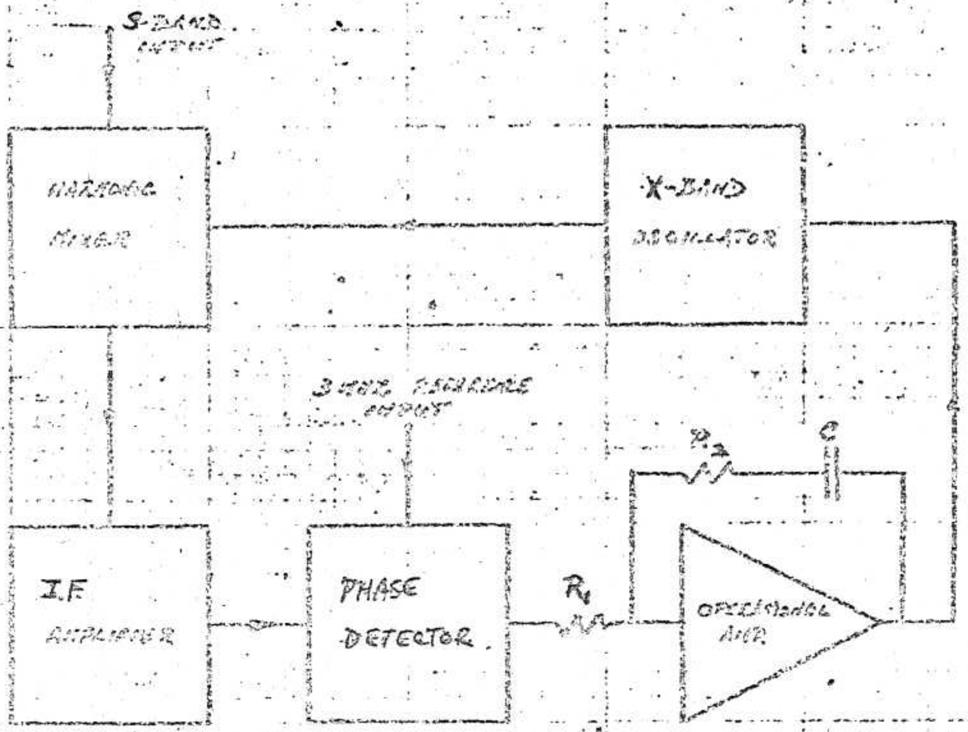
1 Con Avionics HT-28-0-3A

2 Simpson 100 ua meters (2 ½" Wide-Vue Type)

H. Approximate Cable Lengths Required

7/8" Spiroline, lab. to array center	140 ft.
7/8" Spiroline, array center to antennas 2 × 350 ft. + 280 ft. + 200 ft. + 130 ft. =	1310 ft.
7/8" Spiroline, ground box to feed box on antennas 5 × 80 ft.	400 ft.
	1850 ft.
RG8, lab. to each antenna (3 MHz reference to feed box)	2410 ft.
RG58, lab. to each antenna (Modulated reflector drive)	2410 ft.
RG58, ground box to feed box on antennas 5 × 80 ft. (level monitor)	400 ft.
	2810 ft.

16 conductor, ground box to feed box (oscillator units to control units)	400 ft.
2 conductor cable, lab. to each antenna (lock indicator)	2010 ft.



BASIC PHASE-LOCK SYSTEM

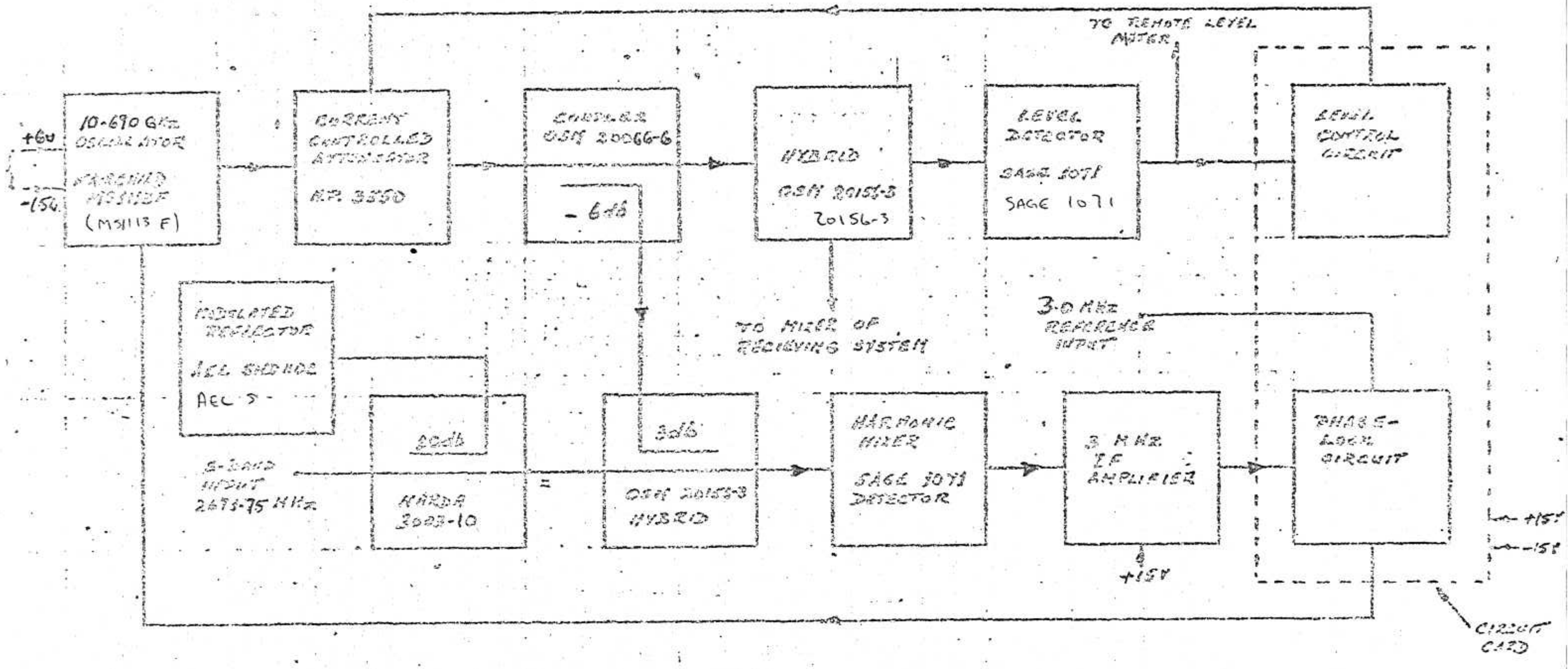
Fig 1

[illegible]

CABLE CONNECTION TO LOCAL OSCILLATOR
CONTROL UNIT

CABLE CONNECTOR - ANTENNA
CIRCUIT CARD

1	A	3MHz REF	9	L	LOCK
2	B	LEVEL	10	M	INDICATOR
3		I.F.	11	N	+15V
4		LEVEL MONITOR	12	O	GROUND
5	H	CONTROL ~~Monitor~~	13	P	-15V
6	K	REMOTE ~~Level~~ LEVEL	14	O	GROUND
7	G	CONTROL	15		+ 22V
8		SPARE	16		-



LOCAL OSCILLATOR UNIT

(LOCATED IN FEED BOX OF ANTENNA)

Fig 4

CLINT NO. 368
December 17, 1963

PHASE MONITORING OF THE LOCAL OSCILLATOR SIGNALS IN THE FIVE-ELEMENT ARRAY

A.R. Thompson

Expected Variations in the Instrumental Phase

In the operation of the five-element X-band array it is expected that for each observation of a source under investigation, one or more observations will also be made of a calibration source to determine the instrumental components of the phase of each of the ten fringe patterns. To obtain a two-dimensional brightness distribution of a source using rotation synthesis requires observation over the full 10 hours of available tracking in hour angle. One cannot predict with certainty the number of calibrator observations that will be necessary to establish the instrumental phase and its variations over a ten-hour observing period. However, it will be shown that the main variations in instrumental phase are likely to arise through thermal effects on the electrical lengths of the cables carrying the local oscillator synchronizing signal. The phase monitoring system allows these variations to be measured at any time during an observation and should enable the phase to be established using only one or two calibrator observations for each observing period.

The signal received at the feed horn of the antenna passes through a directional coupler, a waveguide switch, a tunnel diode amplifier, and several lengths of interconnecting waveguide before entering the mixer. The total electrical length of this signal path is not more than one meter, and the largest day-to-night temperature variation, say 20 °C, will have a negligible effect on the phase length of this path. The effect of the temperature variation of the tunnel diode amplifiers has not yet been fully investigated but these units have a very low power consumption and can be well isolated thermally from outside temperature variations. The receiving system accepts the responses at the mixer input both above and below the local oscillator signal, and it is well known that in this case the phase of the interferometer fringes is independent of phase changes in the i.f. signal path (Read, R.B. 1963, Ap.J., 138, 1). Thus the most important cause of instrumental phase drift is likely to be in the local oscillator signal injected at the mixer.

The local oscillator is a solid state unit (Fairchild MS1113F or MS(X)74F) which runs at a frequency of 10.69 GHz and is phase locked to the fourth harmonic of an S-band signal at 2673.25 MHz minus the 3.0 MHz i.f. reference (see Glint No. 285). Both the S-band and the 3.0 MHz signals are derived from crystal controlled oscillators in the main laboratory building. The S-band signal is transmitted to the delay building through a buried cable and then divided into five components which are each transmitted to the base of an antenna through lengths of 327-380 ft. of 7/8-inch Spiroline buried at a depth of 3 ft. Further lengths of the same cable totalling approximately 100 ft. carry the signal up the antenna structure to the front end box in which the local oscillator is situated. If we allow for an extreme day-to-night temperature variation of 1 °C for the buried cable and 20 °C for the lengths on the antennas, and take the coefficient of electrical length of the cables as equal to the expansion coefficient of aluminum ($2 \times 10^{-5} / {}^{\circ}C$), we find changes in the lengths of the cables of 2.4 mm in the buried portion and 12 mm in the unburied portion. These would give rise to a total phase change of 180° at the X-band oscillator frequency. The corresponding effect on the phase of the 3.0 MHz signal is entirely negligible. If temperature changes occurred slowly and uniformly over the whole array the differential changes in instrumental phase would probably be negligible. In practice, however, the exposure to direct sunlight will vary from one antenna to another, and we must assume that, particularly near times of sunrise and sunset, the temperature variations in the oscillator reference cables on the antennas will give rise to variations in the phase angles of the fringe patterns which are a substantial fraction of the expected local oscillator phase drift of 180°.

The Phase Monitoring System

The method of measuring the variation in the electrical length of the path of the S-band reference signal is based upon the technique developed by Swarup and Yang at Stanford (Swarup, G. and Yang, K.S., 1961, Trans. IRE, AP-9, 75). A fraction of the signal transmitted by the cable is returned by a reflector at the remote end and combined with the outward going signal to form a standing wave pattern. The reflector is modulated so that the required component can be distinguished from other reflections within the system. The change in the positions of the minima of the standing wave pattern indicate corresponding changes in the length of the cable, since the electrical distance between any minimum and the reflection point remains constant. A modulated reflector is located at the input of the local-oscillator synchronizer unit in the front end box of each antenna, and a modulating waveform can be switched to any one of the five reflectors without disturbing the observations in progress.

A block diagram of the phase monitoring components is shown in Fig. 1. The signal from the S-band oscillator passes through a directional coupler, a circulator, and a tuner and is then transmitted through 160 ft. of buried cable to the power divider in the delay building. The power divider consists of four coaxial hybrids. A component of the signal is then transmitted to the local oscillator synchronizer at each antenna, and a small fraction of this is coupled off through a 20 db coupler to a modulated reflector and returns down the cable entering the circulator at port B and emerging at port C. The reflected signal is then combined in a hybrid with a component of the forward going signal from the S-band oscillator, the phase of which can be varied by a calibrated phase shifter. The output of the detector contains a square wave at a frequency equal to the modulation frequency of the reflector, and this is amplified and rectified in a phase detector, and its amplitude is displayed on a center-zero meter. As the phase shifter is varied the meter indicates the equivalent standing wave pattern, alternate maxima being positive and negative. Let us assume that the phase shifter is adjusted so that the output represents a standing-wave minimum. A change δ in the path length of the cable to the antenna will produce a phase change $4\pi\delta/\lambda$ in the phase of the reflected signal (this is equivalent to a path change 2δ since the signal traverses the cable in both directions). The system can be returned to the standing-wave null by an equal phase change in the calibrated phase shifter. The change in the phase of the signal arriving at the synchronizer unit is $2\pi\delta/\lambda$, or half the change of the phase shifter reading. The phase shifter is a Narda Model 3752 coaxial phase shifter with a digital output reading, which is calibrated to an accuracy of 0.25 mm in equivalent path length, which corresponds to 3° of phase in the X-band oscillator signal.

Operation of the phase measuring system as described above requires a preliminary adjustment of the tuner at the input of the cable to the power divider. Since the reverse path attenuation of the circulator is only 20 to 30 db, an unwanted component of the oscillator signal leaks through from port A to port C. This component, the phase of which remains constant, combines with the component from the calibrated phase shifter, effectively producing a phase error in that signal. To minimize this effect the tuner is set to reflect a signal back into port B of the circulator that will cancel the unwanted component at port C. To adjust the tuner the modulation is switched from the reflector to the diode switch at the output of port C of the circulator, and the connection between the calibrated phase shifter and the hybrid is opened. The only signal then reaching the detector is that from port C of the circulator, and the tuner is adjusted to minimize this signal as indicated on the output meter.

Design Details of the System Components

The S-band oscillator is a Contilabs Model 270500X and provides a total output power of 1.0 watts. It consists of a solid state oscillator injection locked to a crystal oscillator at a basic frequency of approximately 133 MHz. An output at 133 MHz is available so that the oscillator stability can be monitored using our Hewlett Packard 5245L frequency counter and 5253B frequency converter. Since we are attempting to measure to an accuracy of 0.25 mm in 150 meters, or 1 part in 6 x 10^5, it is necessary to know the oscillator frequency to a similar degree of accuracy. The accuracy of the HP 5245L frequency counter is about two orders of magnitude better than this requirement.

The total attenuation from the oscillator to the synchronizer input is estimated to be 27 db, of which 14 db results from 540 feet of 7/8-inch Spiroline which is buried, 4 db results from cables on the antennas, and 9 db results from the power splitting (this assumes the worst case where the signal passes through three hybrids). With a 1 watt oscillator 2 mw of power is available at the synchronizer input, which should be 5 to 10 db more than the minimum requirement. The attenuation through the coupler to the modulated reflector involves a further 20 db so that the level of the reflected signal at port B of the circulator is 54 db below the level of the outward going signal. Tests of the system using an S-band signal generator indicate that the sensitivity is sufficient to allow measurements to the required accuracy, although it is not yet possible to make measurements using the 1 watt oscillator since we are awaiting delivery of this unit (December 17, 1969). In an earlier study (A.R. Thompson, Glint No. 251), it was found possible to make phase measurements through a total attenuation of 62 db for the one-way path from the generator to the reflector.

As a result of the use of a 20 db coupler to connect the modulated reflector to the S-band cable, any modulated component that enters the synchronizer should be at least 60 db below the synchronizing signal (assuming 20 db directivity for the coupler). Any phase shift resulting from the appearance of the reflected component at the synchronizer input is therefore negligible. An isolation of 40 db would result in a maximum phase shift of 0.6°, and it should therefore be entirely satisfactory to use 10 db couplers. However, the 20 db couplers were already available from earlier projects.

The modulated reflector consists of a coaxial diode switch (Melabs S-211-112 or AEL SNE110C) in which the power is transmitted in the 'on' condition and reflected in the 'off' condition. The switch can be terminated in a 50 ohm load in which case the power picked up by the side-arm of the coupler is absorbed in the 'on' condition and in the 'off' position the power is reflected back down the side-arm and 1% of it is coupled back down the main line. If, however, instead of a load the switch is terminated in a short placed a quarter wavelength beyond the 'off'-condition reflection point, both conditions of the switch then give rise to a reflection, but with 180° difference in phase. This arrangement doubles the signal at the phase detector, and has therefore been used because of the better sensitivity obtained.

The switching frequency used for the reflector is 1.0 KHz, and a circuit diagram of the switch driver and the phase detector is shown in Fig. 2. This is similar to the circuit described in an earlier report (A.R. Thompson, Glint No. 250) but has an improved square-wave output stage. The multivibrator is driven in a divide-by-two mode from a 2 KHz tuning fork oscillator (Greenray F202) which is not shown in the diagram. The tuned amplifier is a Hewlett Packard 415E SWR meter and has a wide range of variable gain settings which is a great advantage in the initial adjustment of the line tuner.

The tuner consists of two units in series, a double-stub tuner and a slide-screw tuner. The adjustment is made as closely as possible using only the double-stub tuner, the setting of which is then fixed. Final adjustment is made with the slide-screw tuner, and since only small penetration of the tuning screw is required, a high degree of cancellation of the circulator leakage signal is readily achieved.

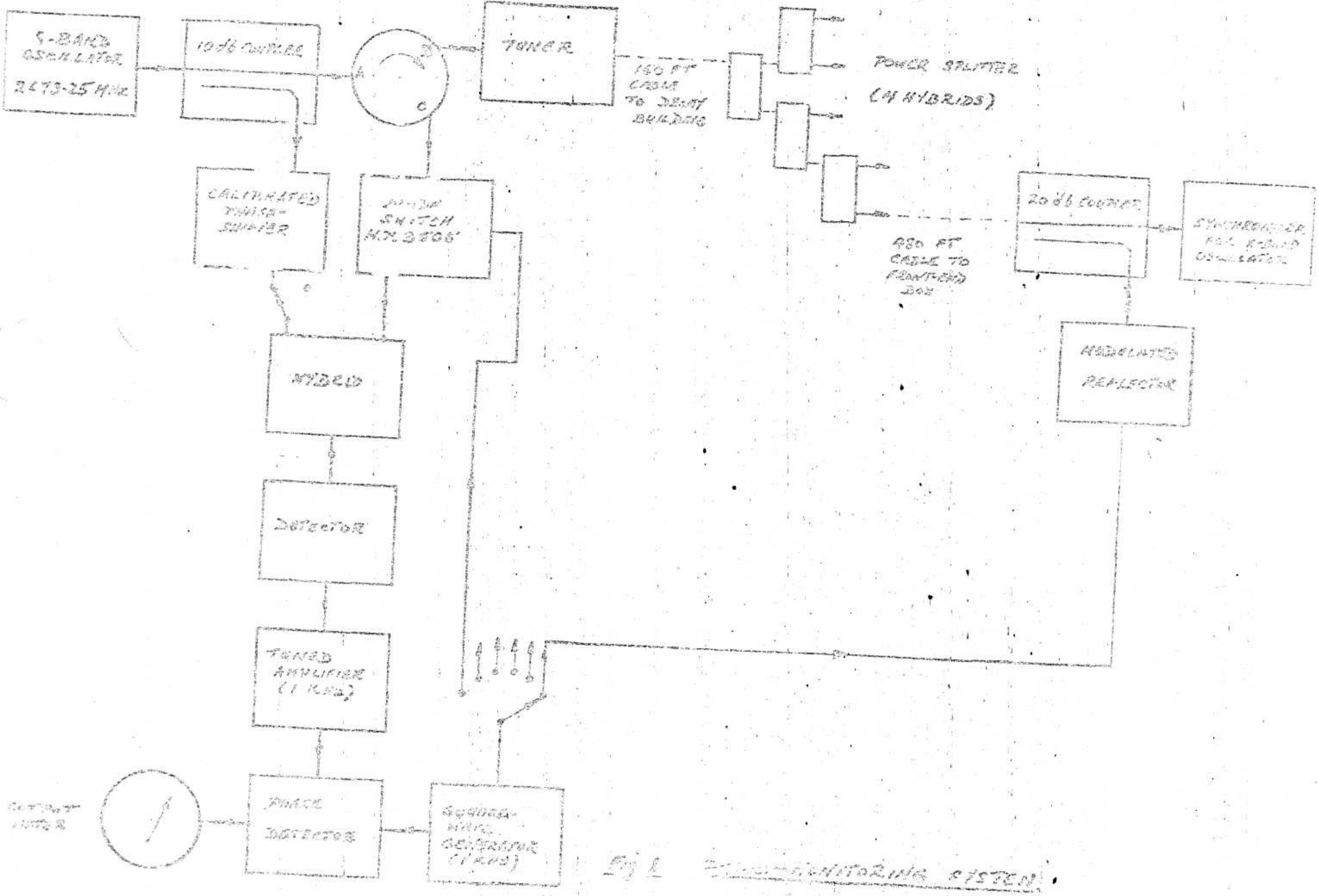
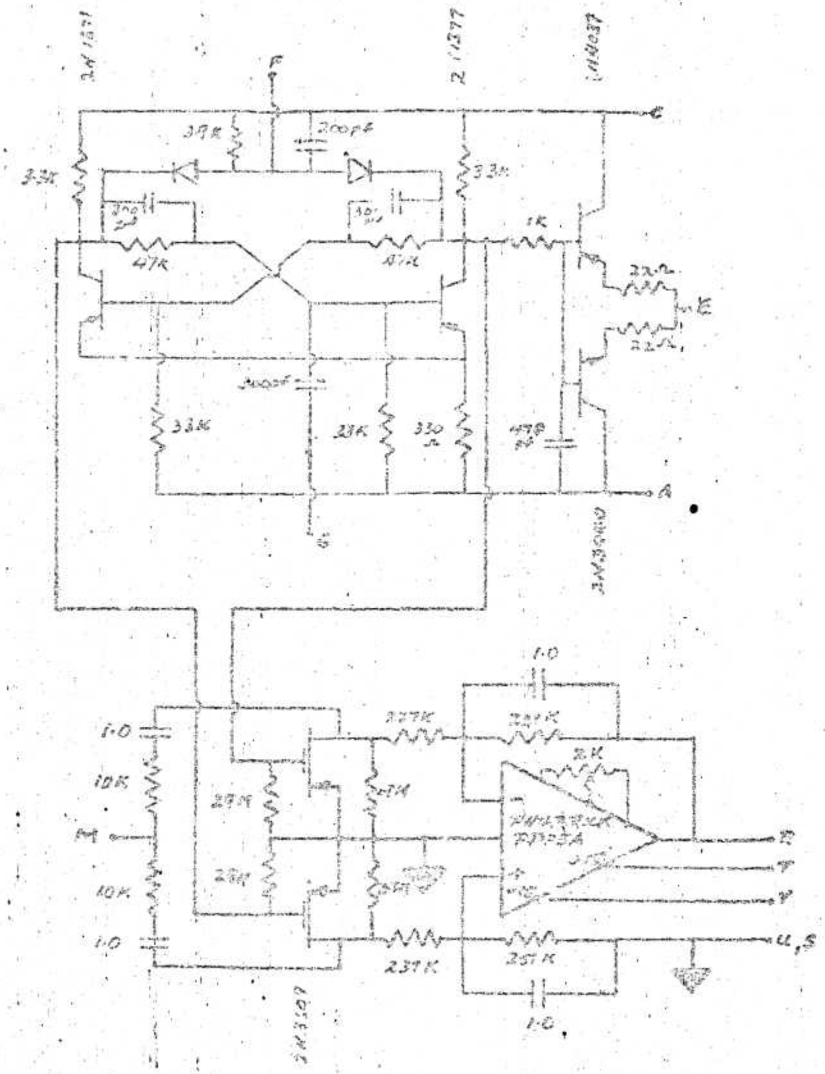


Fig 1 [illegible] MONITORING SYSTEM



A +15V

C -15V

E SQ-WAVE OUT (SWITCH DRIVE)
F REF INPUT DIVIDING
G REF INPUT NON-DIVIDING

M SIGNAL INPUT

R OUTPUT
S OUTPUT GROUND
T +15V
U GROUND
V -15V

Fig 2. PHASE-SENSITIVE DETECTOR.

Modified 8-2-73, SJW
GLINT NO. 410
May 17, 1971

LOAD-GO FORTRAN FOR THE 2114B COMPUTER WITH THE SRAIOS SYSTEM

Larry R. D'Addario

I. Operating Instructions

1. Turn on the computer, the DICOM cassette tape unit, the Hazeltine CRT, and the Line Printer.
2. Place the FORTRAN tape in Deck 1.
3. Press HALT; press PRESET and LOAD simultaneously.
4. When the computer halts, press RUN.
5. Prepare the source tape.
   a. If source tape is already prepared, place it in Deck 2 and go to step 6.
   b. Place a blank tape in Deck 2.
   c. When >> appears on the screen, type WRITE 2 and then press the SHIFT and XMIT keys simultaneously.
   d. Type the source program, with each line followed by SHIFT-XMIT. The first line must be the compiler control statement, which is of the form

      FTN,B,L,A

      where B specifies that a binary object tape is to be produced,
      L specifies that a source listing is to be produced,
      and A specifies that an assembly listing is to be produced. Specifications L and A are optional but B is required for LOAD-GO FORTRAN. Normally, option A is not selected since the assembly listing is very long.
   e. After the last source statement (which must be END$) is entered, press the CONTROL key and type D simultaneously. Strike SHIFT-XMIT. An end-of-file mark is then written on Deck 2.
   f. After >>, type REWIND 2.
      NOTE: The source program must be on File 1 of the tape in Deck 2. The object program will be written on File 2 of the same tape.
6. Place a scratch tape in Deck 3.

7. After >>, type RU FORT,,G. The program will now be compiled, loaded, and executed without further operator intervention, except as noted below.

NOTES:

a. If a listing was requested (option L or A), it will appear on the Hazeltine screen. If SSW 10 is on, the listing will also be printed on the Line Printer.

b. Compiler error codes will appear with the listing.

c. After compilation, the program is loaded with all the required library subroutines. The loader produces a listing of the locations in core where the programs are loaded; if this listing is not desired, turn SSW 15 on anytime before loading begins.

d. If SSW 14 is turned on before loading begins, the loader produces an absolute binary tape on Deck 3 for later execution; the loader then types *END and the program is NOT executed. The user must then write an end-of-file mark on Deck 3 before it is rewound; to do this, manually rewind Deck 1, execute steps 3 and 4, type WEOF 3. The user's program will then be executed if he types

```
>> REWI 3
>> LOAD 3
```

e. If the computer halts at any time before the compiling-loading process is complete, an error has occurred. The user should try to determine the cause of the error by consulting the H-P manuals and the notes posted near the computer. In some cases, the error will not occur again if the compilation is tried again from step 7 after manually rewinding all tapes.

f. To produce the object program only, the command RU FORT,,G,N can be used. The object program will be written on file 2 of the tape in deck 2 as before; however, the program will not be loaded. Control returns to the SRAIOS Executive.

GLINT NO. 1[illegible]0
May 18, 19[illegible]

THE COMPUTER SYSTEM OF THE STANFORD X-BAND ARRAY*

R.S. Colvin & A.R. Thompson

This report describes the system which comprises the computer of the Stanford array and the various units that are interfaced with it. We are concerned mainly with details of the hardware, and driver subprograms for the various units will be described in other glints.

I. General Description of the System

The computer is a Hewlett-Packard Model 2114 B with a memory size of 8 K. Four units are interfaced with the computer to provide for the general input and output requirements associated with programming, etc. These are a teletype (Model ASR-33), a Micom Magnetic Tape Cassette Unit (Model [illegible]), a Hazeltine Cathode Ray Tube Terminal (Model 2000) which includes a keyboard input, and an acoustic coupler ([illegible]) which allows connection to the campus Computation Center. The computer is also interfaced with five other units which are specifically concerned with the operation of the array. These are a sidereal clock, the delay line driver, the analog multiplexer, the counter (Beckman Accumulator Model [illegible]), and a Dymec Digital Scanner (Model [illegible]). The block diagram of the whole system is shown in Fig. 1.

External units are interfaced to the computer by connection to printed circuit cards which are inserted in slots in the computer. Eight such slots are provided, numbered 10 through 17 (octal numbers) in order of decreasing interrupt priority. The cassette unit is interfaced through a special card which was supplied when this unit was purchased, and the CRT Terminal is interfaced through a Hewlett-Packard teletype card. The other units are connected through general-purpose Hewlett-Packard interface cards of which several types are available designed for specific input or output problems. Two types are used here, the Sixteen-Bit Duplex Register which simultaneously provides sixteen lines of input and sixteen of output, and the General Purpose Data Source Interface which provides thirty-two lines of input. Details of interface cards can be found in the Hewlett-Packard manual "A Pocket Guide to Interfacing H-P Computers".

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* The addendum provided at the end of this glint describes equipment purchased after this glint was written. NOT PREPARED YET

The highest interrupt priority is given to the input from the Beckman accumulator which is part of the analog-to-digital converter through which the output from the multipliers of the array is read. A 100 cps signal from the clock is fed to the accumulator unit where it is divided by two and provides a time base for interrupts of the computer at intervals of 20 ms for input of the data. The computer also controls the analog multiplexer and thereby selects the multiplier from which the output is required. The accumulator and multiplexer are interfaced through a general purpose duplex register card which is also used to set the IF delay lines. An assembly language subroutine (IOSB1) for performing the required input and output operations to this card has been written by L. D'Addario.

The Dicom cassette unit is connected through the slot with the second highest interrupt priority. The cassette unit contains three decks for standard audio-type tape cassettes. Reading and writing can be performed on all three decks, although in normal operation Deck 1 is used for reading the system tape and for loading object programs, Deck 2 is used for reading or writing source programs, and Deck 3 for writing intermediate program tapes or data collected during the operation of the array. In addition, the teletype unit can be operated through the cassette unit in which case it may be referred to as Deck 0.

The digital sidereal clock is connected to a data source card in slot 12 of the computer. An assembly language program (Clock) has been written by J. Grebenkemper to read the output of the clock.

The Hazeltine CRT unit is connected to the modified teletype card. The teletype and the acoustic coupler can also be connected to the same card through a switch panel. The Hazeltine unit originally operated with data rates of 110, 150, 300, 600, or 1200 bits per second, selected by a switch at the back of the unit. It has now been modified so that in the original 600 sec^{-1} position the data rate is 4800 bits per second. A modification was required on the teletype card to halt the transmission of data when the CRT terminal is not ready to accept it, and this is indicated by the line marked DTR in Fig. 1. When operating with the 4800 sec^{-1} bit rate the teletype cannot be used or communication made with the campus Computation Center through the acoustic coupler since these require a bit rate of 110 sec^{-1}. For the lower bit rate the switch on the CRT terminal must be set to the 110 sec^{-1} position and the rate switch on the switch panel to the teletype position. The rate for the teletype and the acoustic coupler is then controlled by the internal clock in the teletype card. In addition, a direct line from the CRT terminal to the teletype enables the latter to print out any page of data displayed on the CRT. The mode switch on the switch panel is set to the NORMAL position in all cases where the acoustic coupler is not in use. In the WYLBUR position the system can be connected through the coupler to the IBM 360 Computer in the campus Computation Center. Data can be transmitted to the 360 and the usual facilities of the computation center WYLBUR system are available through the teletype and CRT terminal.

The digital scanner is connected through the lowest priority interrupt slot, and allows data input from three sources to be scanned and read into the computer. These sources are an 8-digit thumb wheel switch for manual data transmission (Dymec Model 2514B), the right ascension encoder in the hour angle readout rack, and one input which is presently spare.

A list of reference manuals for the various units is given in Section 2 and technical details of the interconnection of the various units to the interface cards and any modifications that have been made to standard components are given in Section 3.

2. List of Manuals on Computer System Units

H-P Systems Manual, 2114B Computer System, Serial No. [illegible],
(in three binders)
A Pocket Guide to Interfacing Hewlett-Packard Computers
Dicom 344 Cassette Magnetic Tape Manual, Operation and Interface,
Maintenance Manual, and Software Reference Manual
Hazeltine Model 2000 Desk Top Display, Operating Instructions
IB-1366A, Maintenance Manual IB-1367
Teletype Corporation Bulletin 310B, Vol. 1, Technical Manual,
33 Teletypewriter
H-P Operating and Service Manual Model HP2752A Teleprinter
Instruction Manual Beckman Accumulator Model 6014DJ

3. Details of Interface Connections

a. The Beckman Accumulator, the Multiplexer and the Delay Line Control Unit

The interface card is a Sixteen-Bit Duplex Register Type, EP12554A-001, with negative input and negative output logic. This is described in the [illegible] Systems Manual Binder 1 (with revised version of logic diagram 12554-60024). Interconnection details are shown in Fig. 2.

The interface card is connected to two Buchanon strips mounted on a panel at the rear of the computer rack. Pin numbers of the edge card connector are duplicated in two terminal strips which correspond to the two sides of the card. From these terminal strips cables run to the Beckman 6014 Accumulator (J1), the connector on the bin of the analog multiplexer and the delay line control chassis.

The input to the computer from the Beckman Accumulator consists of 3 full digits of BCD which are the least significant digits plus the three least significant bits from the fourth BCD digit, a total of 15 bits. The largest number which can be input from the accumulator is 7999. The sixteenth input bit is used for sign information; zero volts indicatesa positive number and -15 volts a negative one. Numbers transferred into the [illegible] input register are in the complimentary state and must be complimented by the servicing software to be equivalent BCD numbers in computer logic.

The signal to set the flag for interrupt operation is also entered into the computer. This is derived from a divide-by-two scaler in the accumulator which is normally driven from a 100 Hz signal from the digital sidereal clock. Thus the flag set signal is at a 50 Hz rate. Since this [illegible] card is in slot 103 with the highest interrupt priority, a program interrupt to memory location 103 occurs every 20 ms whenever the interrupt system is turned on.

The output from the computer is as follows:

Bits	0 - 3	BCD Multiplexer channel select code
Bits	4 - 12	Delay line control binary number
Bits	13 - 14	(Not used)
Bit	15	Gate control of accumulator "0" = start count; "1" = stop count
Control Bit		Reset control of accumulator (STC 103 command performs this)

b. The Dicom Cassette Unit

The interface card for the cassette unit was supplied by the Xebec Corp. from whom the cassette unit and the required software were obtained. The interface card is fullydescribed in the operation and interface manual for the Dicom 404.

c. The Sidereal Clock

The sidereal clock is interfaced to the 2114B using a 32-bit data source card (HP12604B) described in the 2114B Systems Manual Binder 1.

The eight digits of time information, hours (0-23), minutes (0-59), and seconds (0.00 to 59.99) are coded in 1,2,2′,4 code, positive true logic. A record command pulse derived from the $0^{s}.01$ one-shot output signal is provided as well as ground and logic level reference voltages. These signals are connected directly to the edge connector of the interface card according to the table in Fig. 3.

Normal operation of the system requires a program to input the information available at the 32 lines coming into the card into two adjacent words of memory with subsequent conversion to the desired format. (We use a radian measure of time for internal computer operations.) When this program issues a STC 15B command, the interface card will be set to wait for the next record command from the clock. When this occurs at the next $0^{s}.01$ digit advance, the 32 bits of time information can be transferred after approximately a 1 ms delay for settling time on the lines.

d. The Buffered Teleprinter Interface Card

The HP teleprinter interface card (No. 12531B) has been modified in three ways. First, drivers have been added so that the teleprinter current loop output and input circuits will operate at the same time as the RS232B dataphone output and input. (See Figs. 4 and 5.) Secondly, an input point for a data terminal ready (DTR) has been provided to inhibit output from the interface card unless the data terminal ready line (DTR) is true (see Fig. 6). This is used with the CRT terminal which has been modified to provide such an output signal.

Thirdly, the internal clock signal has been made available at the interface connection to allow remote switching between internal and external clocks. A diagram showing the interconnections between the card and the various units is shown in Fig. 7.

The Teleprinter (TTY) is an ASR 33 (TBE) which has been modified to be equivalent to the Hewlett-Packard Teleprinter Model HP2752A. In addition a switch has been added which transfers the TTY from the TTY interface card current loop connection to the Dicom 344 TTY driver circuit. The switch is labeled COMPUTER for HP interface card operation and CASSETTE RECORDER for Dicom "Deck 0" operation. The Cassette Recorder position is also used for off-line functions with the Dicom 344.

An additional driver transistor circuit has been added to allow TTY operation from the CRT "Print" output. The transfer switch must be in the COMPUTER position and the CRT rate set to 110 for printing in this mode. The print drive and the computer drive to the TTY are connected in a "logical or" mode.

An interconnection and switch panel is used to allow operation of the various units attached to the TTY card in the required configurations. Either a TTY, CRT or EXT rate for the TTY card clock can be selected. In the TTY position the internal TTY clock is switched back into the external input on the card. In the CRT position a rate derived in the CRT is provided for the TTY card. EXT allows an external pulse generator to provide the clock rate. Since the TTY card contains a divide by four circuit for the clock rate, the signals at the above switch are all at four times the desired rate (i.e. 440 Hz for TTY and 19.2 kHz when the Hazeltine 2000 baud rate switch is at the 4800 baud position).

A second switch makes the appropriate connections between the coupler, the CRT terminal and the TTY card for NORMAL or WYLBUR operation. This basically reverses the TTY card data-phone input-output connections between the two positions. For NORMAL operation, the data-phone output goes to the CRT input while in WYLBUR operation the data-phone output is tied to the coupler in parallel with the CRT output.

The normal operating conditions for our system are as follows:

1. Line printer turned on and selected. Teletype power off.
2. CRT baud rate switch at 4800 (input/output to the CRT are at 4800 baud). Half-duplex operation of the CRT.
3. Rate switch at CRT.
4. WYLBUR/NORMAL switch in NORMAL (both switches).

In this configuration the CRT keyboard is the communication input to the system. The CRT screen provides output listing etc. with a software provision which allows duplicate writing of a line on the CRT and the TTY in tandem.

The Hazeltine 2000 CRT terminal has had a modification of its baud rate clock card so that in the old 600 baud position, the half-duplex clock produces a 4800 baud rate for the CRT while the full-duplex clock produces 19.2 kHz for the TTY card.

A second modification has used the signal which drives the Receiver mode indicator lamp to provide a data terminal ready (DTR) signal in the normal RS 232B fashion on line 20.

c. The Digital Scanner

The Dymec Digital Scanner (2514A) is connected to a 32-bit data source card (HP12604B). The scanner has been slightly modified to scan through three 32-line digital information sources on command in a 1,2,3 sequence and return to home position to await the next scanner call. (A total of 6 sources could be serviced with the purchase of additional relay cards for the scanner.) With the present arrangement reading of the complete sequence of all available sources occurs at each call of the program. If only one source is desired, it should be connected into the data source No. 1 connector and only the corresponding push-button on the scanner be depressed. Software provisions to handle this will be required. Interconnections are shown in Fig. 8.

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The scanner modifications are as follows:

1. A switched choice of print command source has been added. A SPDT slide switch on the rear panel allows either the internal print command or the external data source print command to be selected. For instance the Manual Data Source of eight thumbwheel switches would be operated with a selection of the internal print command while the RA encoder would normally use a command generated at the encoder readout chassis. External commands enter the scanner thru J78, J76, and J74, pin r if positive, or z if negative.
2. Pin e of J72 which is connected to the (+) encode output of the interface card is connected to pin r of J70 to provide an external start command for the scanner and also to pin z of J70 for external step command. The normal (+) home signal coming from the scanner to pin e of J72 has been moved to an unused pin location.

The operating sequence is as follows:

1. The computer program sets the control flip flop on the interface card and a (+) encode command is issued. Hold-off is removed from scanner.
2. The (+) encode command is interpreted as an "external start" command at the scanner to initiate a scan, remove hold-offs from data sources, and advance to data source No. 1.
3. The print command from data source No. 1 (external or internal) arrives.
4. The scanner issues a record command to the computer which sends a hold signal to the scanner. Bits 0-15 are enabled for a load into memory and the flag flip flop is set.
5. Two load commands in succession automatically load bits 0-15 and then bits 16-31.
6. A clear flag command removes the hold-off signal to the scanner.

7. The scanner advances to the next data source and waits for a print command.
8. Steps 1 thru 7 are repeated for each data source. The (+) encode provides "external step" commands.
9. When the scanner leaves data source No. 3 it returns to a home position awaiting another (+) encode which would be an "external start" command.

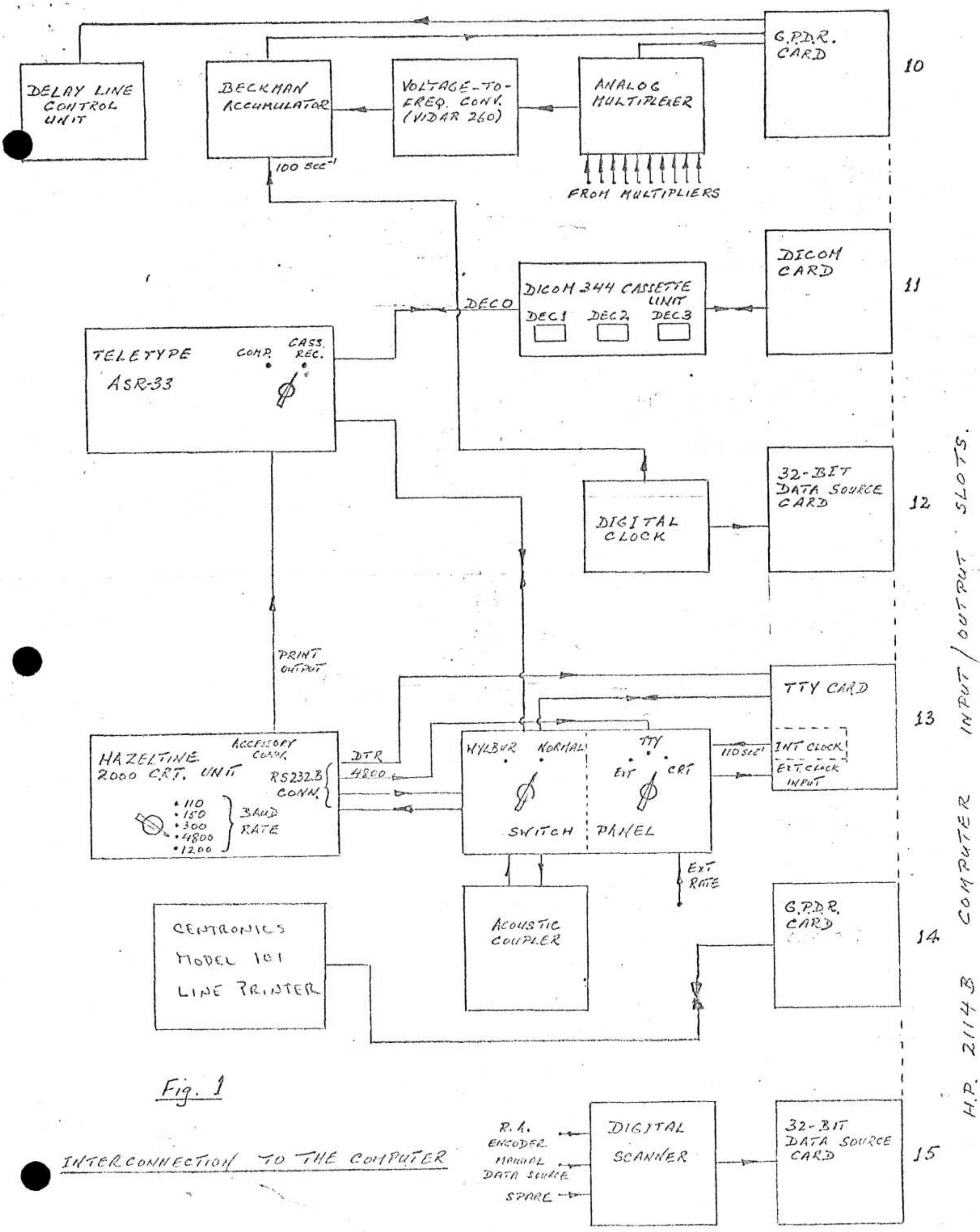

Fig. 1

INTERCONNECTION TO THE COMPUTER

Mod. SJW 9/20/73

A.R.T. 6/1/71

CLINT NO. 431
August 13, 1971

THE SRAI OPERATING SYSTEM

C.J. Grebenkemper

The SRAI Operating System (SRAIOS) was written to allow more efficient usage of the available core of the HP-2114B computer. It replaces the following DICOM supplied software:

DICOM NO.	NAME
344-01012B	HPC System Loader
344-01015B	HPC TTY SIO Driver
344-01017B	HPC 344 SIO/DIO Driver

In addition DICOM No. 344-01019B, HPC CMTOS-II Executive, was modified to allow proper linkage with the SRAIOS drivers.

SRAIOS was written as an overlay for the DICOM-supplied CMTOS system. To generate a SRAIOS system tape the CMTOS system must be resident in core. The absolute output of SRAIOS is then bootloaded into core, and execution is begun at 14000B. A SRAIOS tape may then be generated using the SYSTEM command. Since, in SRAIOS, the DIO entry point is 17000B instead of 16000B, all of the DICOM overlays for the HP processors must be changed. Processors linked correctly for SRAIOS are available on the SRAIOS Binary Object Tape, tape no. 41. Use of this tape is identical to the CMTOS Binary Object Tape, as described in the CMTOS manual.

The Fortran compiler on the SRAIOS Binary Object Tape is the latest version of the HP Fortran Compiler (No. 205[illegible]). Operation is identical to the old version of HP Fortran with the exception that a symbol table may be obtained by specifying a "T" in the Fortran control statement. The Fortran overlay has been changed such that the listing output now produces a line number for each line, and blocks the listing into 11 pages. Also by specifying a G in the first parameter position of the RUN command, the Fortran will operate as a Load-and-Go Fortran. For this type of operation, the Fortran source must be on the first file of the tape in Deck 2 and a scratch tape must be in Deck 3. The relocatable binary object will be written in the second file of the tape in Deck 3.

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If Switch 14 of the Switch Register is on, an absolute binary tape will be written on Deck 3.

Listings of the SRAIOS and Fortran overlays are available in the DICOM CMTOS II LISTINGS notebook in the Butler Building.

SRAIOS system operation is the same as described in the CMTOS manual with the following exceptions:

1. If switch 10 of the Switch Register is on, each line written on the Hazeltine is also written on the teletype (the line printer when it is installed).

2. If switch 12 of the Switch Register is on, output on the Hazeltine pauses after each 26 lines of consecutive output. The output resumes when a single character is transmitted from the Hazeltine keyboard.

3. The COPY command mode default is now Binary, not ASC II. Both binary and ASC II tapes may be copied under the binary option.

4. The VERIFY command mode default is now Binary, not ASC II.

5. Entry points for the SRAIOS system:

14000B	CMTOS-II Executive
14004B	CMTOS-II Executive (no rewind Deck 1)
37000B	DIO
37105B	Keyboard Input
37171B	System Input
37273B	System Output
37301B	Listing Output

6. Load Map for SRAIOS and Executive

12000B - 13153B	Executive Storage
13154B - 15734B	CMTOS-II Executive
36700B - 37510B	SRAIOS Drivers
37534B - 37677B	System Loader
37700B - 37777B	Bootloader

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7. Load Map for SRAIOS and Processor (using DIO)

0 - 36477B	Available for Processor
36500B - 36677B	Available for Processor overlay
36700B - 37510B	SRAIOS Drivers
37534B - 37677B	System Loader
37700B - 37777B	Bootloader

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SRAIOS COMMAND SUMMARY

C.J. Grebenkemper

COMMANDS

```
REwind I                              (Default:  I = 1)
SKip I,N                              (Defaults:  I = 1, N = 1)
WEof I                                (Default:  I = 3)
COpy I,J,N,M                          (Defaults:  I = 2, J = 3, N = 1, M = B)
VErify I,J,N,M                        (Defaults:  I = 2, J = 3, N = 1, M = B)
DUmp I                                (Default:  I = 3)
LIst I                                (Default:  I = 2)
WRite I                               (Default:  I = 2)
SAve I, (from) B, (thru) E            (Default:  I = 3)
BAtch I                               (Default:  I = 2)
LOad I, SA, P1, ..., P7
RUn, Name, SA, P1, ..., P7
GO
DIrectory
SYstem
```

```
I .......                   deck number for operation
J .......                   deck to be copied or verified to
N .......                   number of files
M .......                   mode of operation, B or A
SA ......                   optional starting address of program
P1, ..., P7                 parameters for program
```

PROCESSOR COMMANDS

```
BTAP
     RU BTAP,,P1            P1 = R for relocatable paper tape; otherwise
                                  assumed to be absolute

PTAP
     RU PTAP

HP EDITOR
     RU EDIT,,P1            P1 = T for edit file on Deck 2

HP ASSEMBLER
     RU ASMB,,P1,P2,P3      P1 = K for assembly control statement on keyboard

                            P2 = file on which source resides (default = 1)

                            P3 = T for listing on Deck 3 after object output

CROSS REFERENCE
     RU CROS,,P1,P2         P1 = file on which source resides (default = 1)

                            P2 = T for listing on Deck 3

HP FORTRAN
     RU FORT,,P1            P1 = G for Load-and-Go Fortran

ALGOL
     RU ALGO

RELOCATABLE LOADER
     RU RLOAD
```

Modified 8-3-73, SJW
GLINT NO. 459
February 3, 1972

DRIVING INSTRUCTIONS

R.S. Colvin

The five-element array involves large structures driven by powerful motors spread out over a considerable area. Normal operation includes the interaction of several people with the whole system. Consequently, a procedure for safe operation must be followed. One person must assume the responsibility for operation at any time.

The control room is the focal point for all operations. Any use or service on the array needs to begin in the control room with the proper procedures which will be given below. The standard quiescent conditions are:

1. All antennas stowed.
2. Contactor box controls set to Control Room and Use.
3. Power on at all antennas (power switches are located on the north side of the contactor boxes).
4. Automatic stow lock air supply ready (air supply should never be turned off except for maintenance).
5. Contactor boxes, ground boxes and delay shelter locked.
6. Log book on operating console.
7. Power toggle switches on declination and right ascension control panels switched ON, pilot light on.

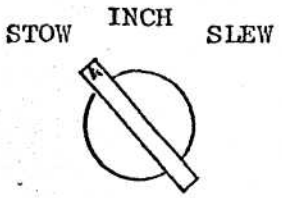
Refer to the appropriate figure for locations and arrangements of controls mentioned below.

Operational Procedures:

I. Normal use

A. Carry out procedures on Control Room Driving Check List [Fig. 5]

B. Antenna driving instructions



[5 ea S_4
Dec. Readout Panel]

1. To Exit Stow: Manually unstow each antenna. (All STOW lights should be lit to start and all MERIDIAN lights should be on.) Place all S_4's in STOW position. Depress S drive button until antenna passes thru N boundary as indicated by the yellow N boundary light coming on momentarily. (When first depressed there is a slight delay while the automatic stow latch retracts before driving starts.) The STOW light goes out, the declination readout will indicate motion of the antenna and the declination drive motor current meter will be indicating. Repeat for other antennas.

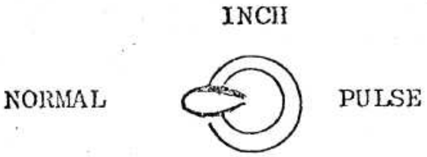
2. To Drive to a Desired Declination when Unstowed:

   a. Determine desired readout setting

   b. Set PRESET DECLINATION thumbwheel switch to N > 9000. (If this feature is not needed.)

   c. Switch S_4 in SLEW position.

   d. Depress S or N pushbutton as desired. (To go to smaller readout settings drive S.) Antenna will drive in direction chosen. Depress STOP button as desired setting is approached. Switch S_4 to INCH, S_{10} to NORMAL and depress S and N buttons as needed to set desired readout value.



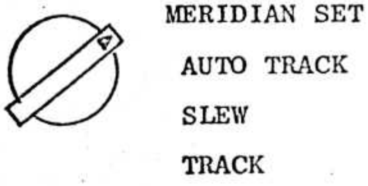
[S_{10}
Dec. Readout Panel]

e. In some cases the pulsed inch mode is useful to set declination. To use this feature in the INCH mode, set S_{10} to PULSE. When the N and S buttons are depressed regular short pulses are applied to the corresponding contactor and hence the motor is inched in a somewhat controlled fashion.

f. To use the preset declination feature (the readout counters and the electrical impulse counters should correspond), set the desired number in the PRESET DECLINATION thumbwheel switch and slew in the desired direction. The drive motion will stop individually as the antenna readouts (and impulse counters) coincide with the preset number. This operation takes place with S_4 in the SLEW mode and it is necessary to leave the SLEW position at least momentarily to release the coincidence stop circuit.

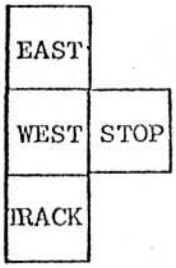
3. To Enter Stow: All antennas must be on the meridian and S_4 on the RA control panel in MERIDIAN SET position. Meridian lights should be on. Drive antennas north in SLEW mode until they stop at N boundary. Switch S_4 to STOW and manually drive N until motor stops and STOW light comes on. Antenna is now stowed. The N limit light will also be on.

4. Driving in Hour Angle: Four modes of operation exist for hour angle motion. These are selected by switch S_6 on the RA control panel. (The antennas must be unstowed.) Except in the case of corrections all antennas operate together.



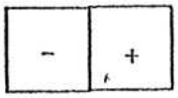
[S 6
RA Control Panel]

a. Slewing east or west is done with the switch S_6 in the SLEW position. The push button labeled EAST or WEST is used to start the desired direction of motion. The STOP push button stops hour angle motion in all modes.



[Lighted Push Buttons
RA Control Panel]

b. Tracking at the sidereal rate is done with the mode switch S_6 in the TRACK position. Depressing the button marked TRACK starts the tracking of all antennas. The STOP switch stops tracking.



[5 ea.
Lighted Push Buttons
RA Readout Panel]

c. Correction: Individual antennas may be adjusted in the hour angle coordinate by using the corresponding buttons labeled "+" and "-" on the RA readout panel while the antennas are tracking. Depressing the "+" button stops the track motor, while depressing the "-" button stops the track motor and starts the correct motor. (The correct motor is an induction motor whose speed is approximately twice that of the track motor.)

d. Driving to the Meridian: For convenience the antennas can be set to the meridian in an automatic fashion. Select the Meridian Set position of S_6 and start slewing towards the meridian with either the EAST or WEST buttons. As each antenna reaches the meridian it will stop automatically and its MERIDIAN light will come on. When all antennas are on the meridian the dummy meridian light also lights. A stowing operation would normally use this mode.

e. Auto-track Operation: The final mode selectable by S_6 is AUTO-TRACK. This mode allows one to start the antennas slewing to a chosen right ascension using the EAST or WEST buttons and have the antennas stop at the desired right ascension which has been entered into the thumbwheel switch on the Decitrak readout panel just above the RA readout panel. After a short delay the track motors start and all antennas begin tracking the desired right ascension position. After this mode has been used the auto-stop circuit must be released by pushing the OFF push button alongside the thumbwheel switch before slewing can take place during a subsequent use of this mode.

C. Procedures if Boundary Switches are Actuated:

LIMIT RESET

[Dec. Control Panel]

The boundary switches prevent antenna motion beyond a predesignated boundary. These function to stop all antennas whenever any antenna activates a boundary switch.* Recovery from this condition requires driving in a direction away from the boundary and subsequently resetting the limit circuitry by pushing P_7 the LIMIT RESET button on the declination control panel. (Motion away from the boundary is always possible but after moving away it is necessary to use the LIMIT RESET button before motion back towards that boundary can occur.)

*Remember we have five boundary zones, i.e., North, East, Southeast, Southwest, and West. The North boundary acts independently on each antenna. The other four operate with the all stop feature. The Southeast and Southwest boundaries can be approached by either declination or hour angle motion and leaving the boundary can be accomplished by both motions. Near the southern horizon the boundary is effectively one South boundary, and hour angle motion will be unimportant compared to declination motion.

II. Special Procedures

A. Danger-zone operation

There is a small zone of operation possible beyond the boundaries. Operation within this zone is reserved for special uses and requires unusual caution. Special considerations govern the use of this feature.

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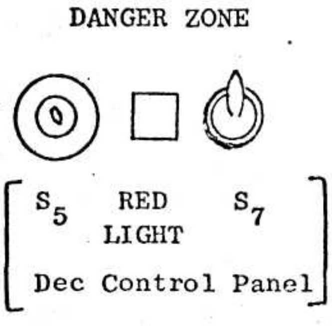


1. Danger-zone entry switches: On both the declination (S_5) and right ascension (S_2) control panels is a key operated switch. Actuation of this switch bypasses the boundary switches of the appropriate drive system and allows the antenna to be driven past the boundaries into the danger-zone and up to the limits. However, it is necessary to hold down the spring loaded switch S_7 on the dec. control panel to drive in declination and a similar switch S_3 on the RA control panel for hour angle motion. In danger zone to drive in HA requires <u>both</u> key switches to be on; to drive in dec., only the dec. key switch need be on. In any case, only one of the S_7 switches need be on at one time.

B. Emergency Stop:

A large red button on the RA readout panel labeled EMERGENCY STOP actuates a remote contactor in the delay shelter to remove all power from the antennas in emergency situations. To return power to the array it is necessary to go to the delay shelter and press the ON button on the contactor itself. Since this is an emergency procedure it is necessary to follow a very cautious course before turning on the power. If you did not turn it off you must obtain clearance from all involved people before turning it on.

C. Emergency Stow:

This feature is not present and all controls intended for its use are not to be used. Leave S_9 (EMERG, NORM) in NORM position.

D. Mechanical Interference Protection between PRIMO, SECUNDO and TERTIO.

Since the three closely spaced antennas can physically touch in some positions a sensing circuit has been installed to stop all antenna motion if the antennas approach a condition where this could occur. If either PRIMO or TERTIO is on the opposite side of the meridian from SECUNDO the circuit stops the drives. To recover from this condition it is necessary to locally drive SECUNDO back to the meridian using the special push button (INT) provided at the SECUNDO contactor box.

CAUTION: You must select the proper direction to drive.

E. Driving Selected Antennas.

An option of selecting antennas to be driven in hour angle is provided by HA drive select switches on the HA DRIVE SELECT panel. A toggle switch for each antenna can be thrown to remove that antenna from the number to be driven. (Notice the switches have a center off position which is not used and is labeled NULL.) The pilot light above each switch indicates the disconnect switch at that antenna is on and that power is available at the antenna.

III. Local Driving

A. Go to control room and clear the local driving requirement with the operator and/or switch the Hour Angle Select switch for the involved antennas off.

B. Follow the Local Driving Checklist posted in the contactor box.

C. Normal Local Use:

The local control consists of controls for declination and a set for hour angle motion. In particular a separate stop button is used for each function. Be sure you are using the switch or switches associated with the motion you intend to use.

1. To Exit Stow: Select INCH position of declination Slew/Inch switch. Press S button until antenna clears N boundary.

2. To Drive in Declination: Switch to SLEW if desired and drive into position at which point use the STOP button to stop the declination motor. Small motions can be accomplished in the INCH mode using short punches of the drive button for the desired direction.

3. To Enter Stow: The antenna must be "on the meridian"* and the Meridian Set/Use switch S_8 in the MERIDIAN SET

---

*An antenna is considered to be "on the meridian" when its meridian switch has its arm in the corresponding hole on the hour angle wheel. This may differ slightly from having the antenna's beam pointed to the true meridian, which in turn may differ slightly from having the antenna's hour angle readout indicating $h = 0$.

position. Drive to the N boundary where motion stops. Now depress the LOCAL STOW button and the N dec. drive pushbutton and motion will continue into the automatic stow lock. When the stowed position is reached the drive stops and the LOCAL STOW button lights. At this point, return the Meridian Set/Use swtich to the USE position.

4. To Enter Service Position: Antenna must be on the meridian and S_8 in the USE position. Drive S to the boundary position. This position allows the service tower to be moved into place. Switch S_8 to MERIDIAN SET which allows further motion south. With the help of a second person drive S into the desired location. Great care is needed since no protection is present to prevent driving into the service tower, etc.

5. To Leave Service Position: Drive N in two stages to remove the service tower and return the antenna to normal use.

6. To Drive in Hour Angle: Antenna must be unstowed. Then select slew or track/correct functions with S_2. EAST, WEST and STOP pushbuttons are used for slew. TRACK, CORRECT and STOP pushbuttons are available for these two motions.

7. To Drive to Meridian: Place S_8 in MERIDIAN SET position and S_2 in the SLEW position. Start the antenna driving toward the meridian and motion will stop when the meridian is reached. Visual checking of the meridian switch can confirm the location of the antenna on the meridian.

D. Boundary Switch Considerations

No indicating lights are present locally for boundary switch actuations. The "all stop" function is operative during local driving so that if more than one antenna is involved it will be stopped as well. This fact makes it important to coordinate with other operators. A LIMIT RESET button P_8 is provided locally to reset the system after a boundary has been reached and cleared. Note that if an antenna is in local (ANTENNA) mode, in MERIDIAN SET mode, and on the meridian, then its SE and SW boundaries are disabled; this includes disabling of the all-stop feature for these boundaries on that antenna.

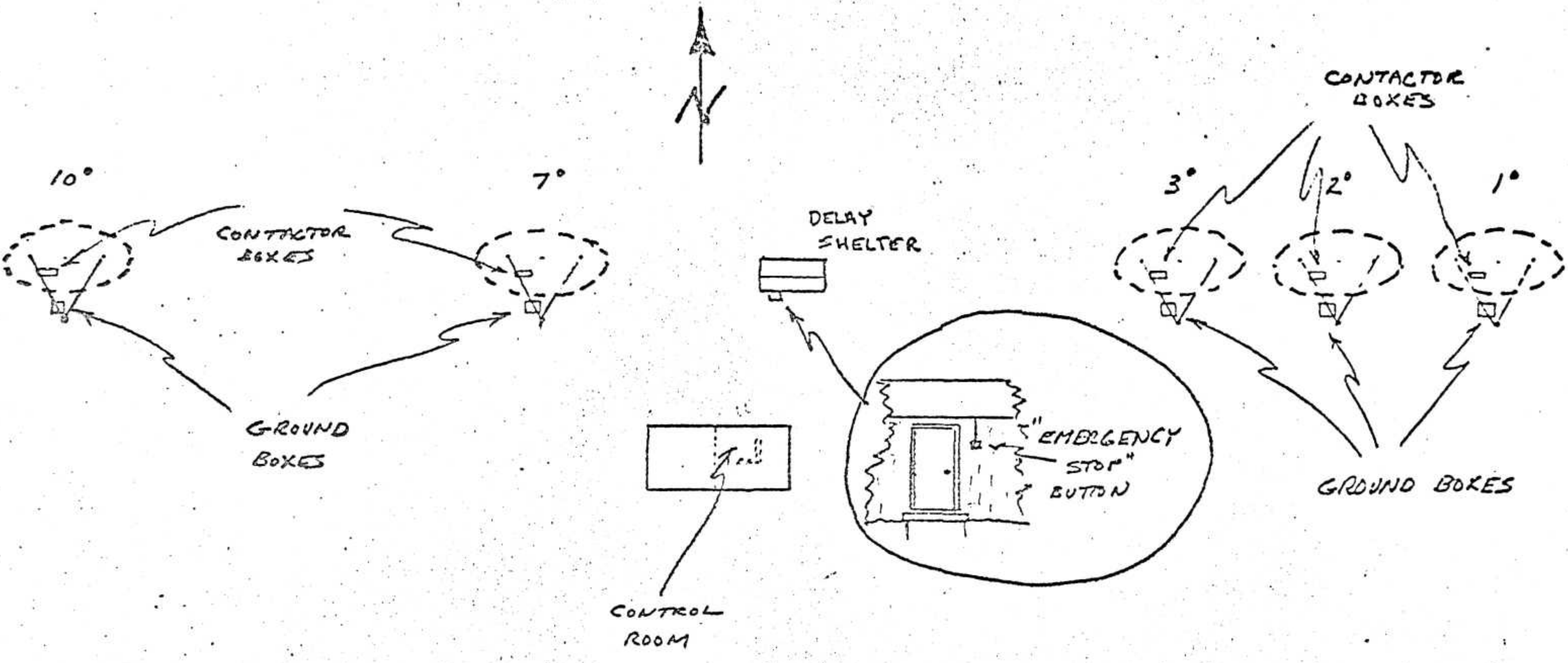
IV. Service

The operator is to be informed of any service activity taking place on the array and the required entries made in the log book.

Relevant Documents:

Glints: No. 325 - Declination Readout
No. 326 - Hour Angle and Right Ascension Readout
No. 309 - The Mercury Switches
No. 383 - Array Limit Switches

Drawings: RA-628 - Common Line Reset Connection Diagram
RA- - Mechanical Interference Diagram
RD-627 - Array Limit Switch Schematic
RB-686 - RA Drive, Antenna
RB-687 - Declination Drive
RB-688 - RA Drive Control



LOCATION OF VARIOUS ARRAY ITEMS

FIG. 1

Modified 8-6-73, SJW

CHECKLIST FOR LOCAL DRIVING

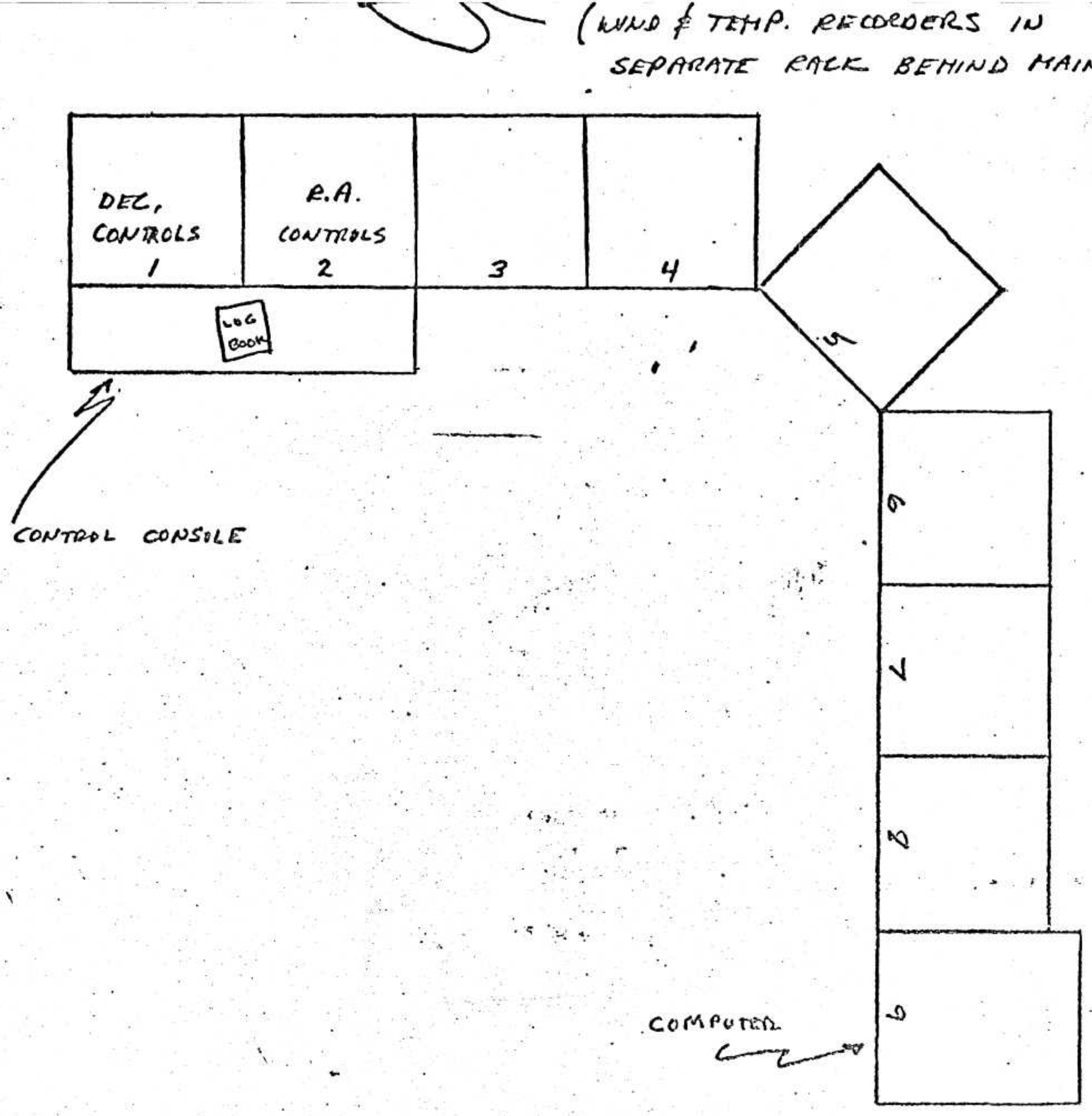
BEFORE DRIVING:

1. PREDICTED WIND SPEED < 30 MPH PEAK (Forecast can be obtained from the Weather Bureau. The telephone number can be found by the observing console.)
2. FOCUS ROAD CHAINS IN PLACE
3. NO OBSTACLES WITHIN CHAINED-OFF AREA
4. (a) ALL OTHER ANTENNAS STOWED, OR
   (b) PERMISSION OBTAINED FROM PERSON USING OTHER ANTENNAS
5. BOTH CONTROL-SELECT SWITCHES SET TO "ANTENNA"

WHEN FINISHED:

1. ANTENNA STOWED
2. CONTROL-SELECT SWITCHES SET TO "CONTROL ROOM"
3. MERIDIAN-SET SWITCH SET TO "USE"
4. CONTACTOR BOX COVER LOCKED
5. NO TOWERS, VEHICLES, OR TOOLS LEFT ON OR NEAR ANTENNA
6. LOG ENTRY MADE IF APPROPRIATE

Fig. 2



(WIND & TEMP. RECORDERS IN SEPARATE RACK BEHIND MAIN RACKS.)

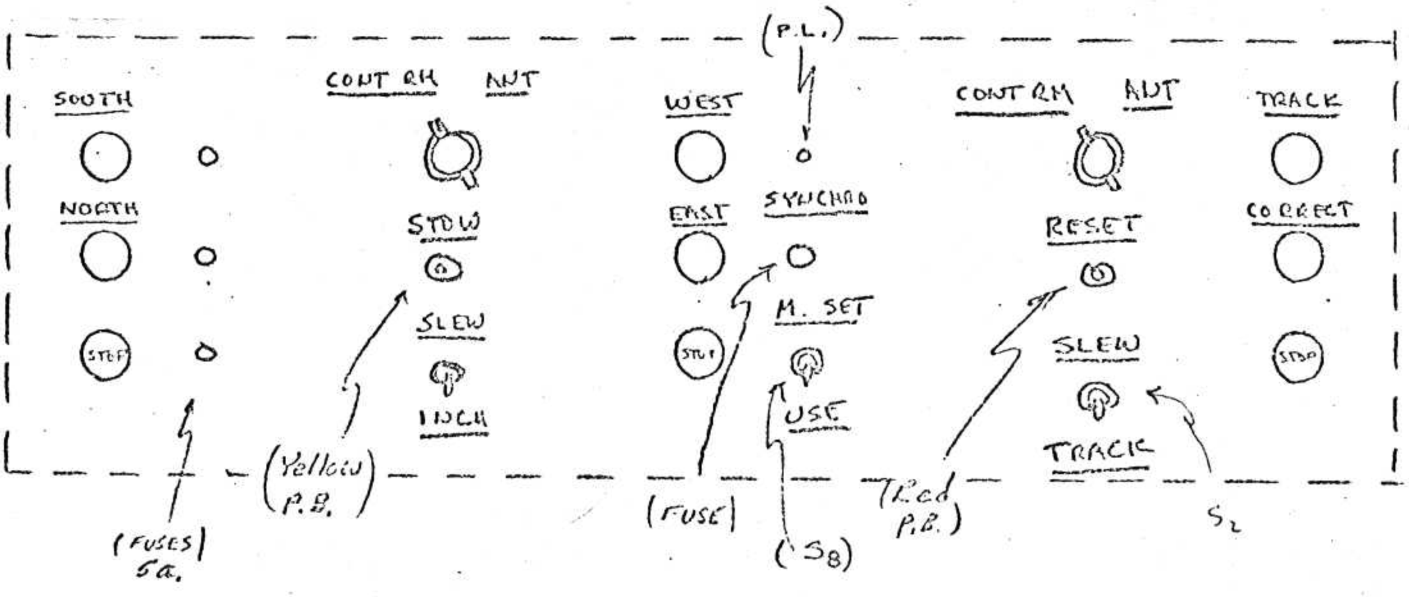


Fig. 3. Typical LOCAL CONTROL PANEL.

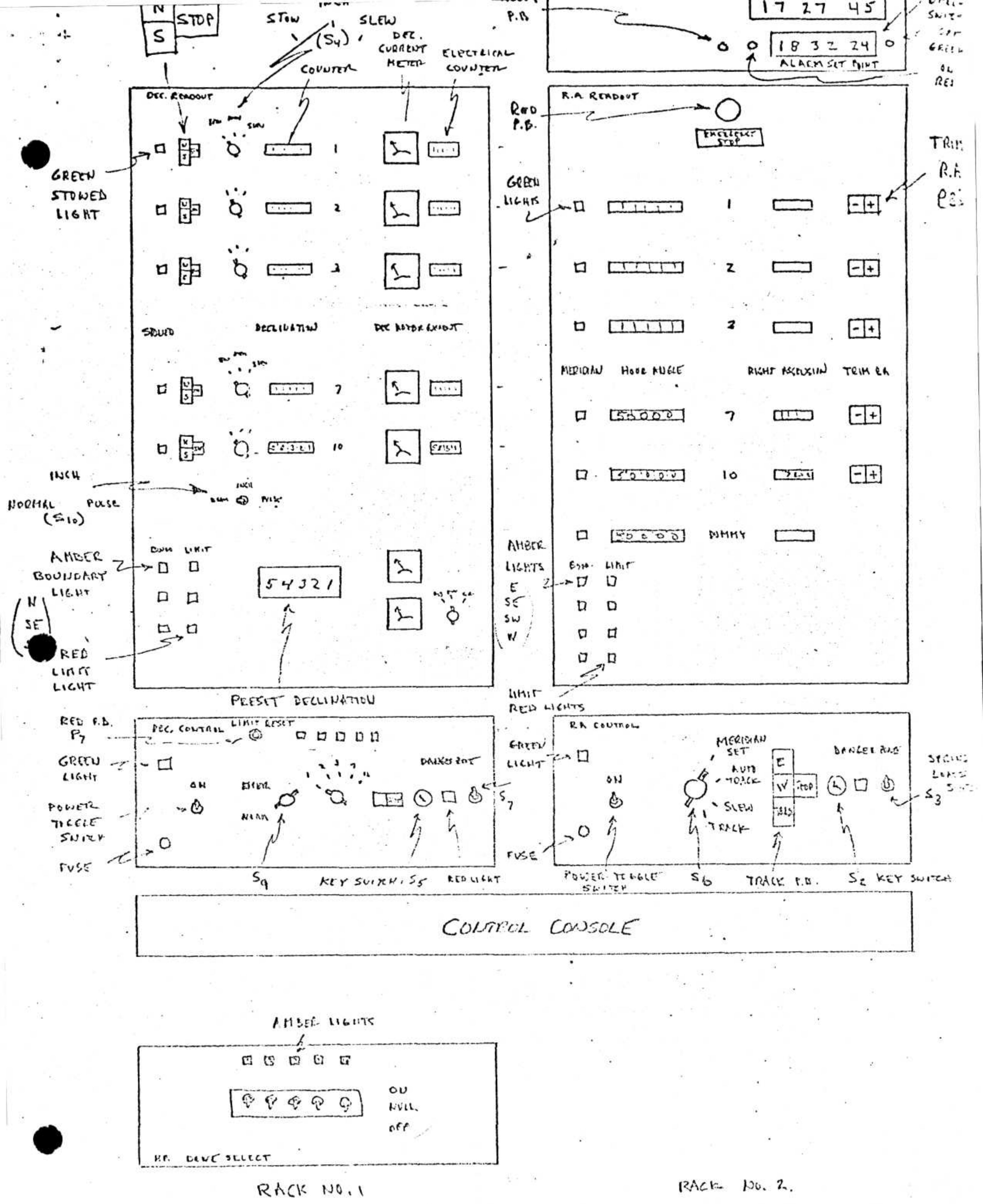


FIG. 4. CONTROL AND READOUT PANELS

Modified 8-6-73, SJW

CONTROL ROOM DRIVING CHECKLIST

BEFORE DRIVING:

1. WALK AROUND CHECK
    - -- FOCUS-ROAD CHAINS IN PLACE
    - -- NO OBSTACLES WITHIN CHAINED-OFF AREAS
    - -- ANTENNAS FULLY STOWED (If any antennas are not stowed, notify person using those antennas of your intentions. Insure that those antennas are set to LOCAL control.)
2. ALL PERSONNEL ON SITE INFORMED OF YOUR INTENDED USE
3. PREDICTED WIND SPEED <30 MPH PEAK (Forecast can be obtained from the Weather Bureau. The telephone number can be found by the observing console.)
4. INTERCOM ON (CHANNEL 6)
5. AT NIGHT, ANTENNA LIGHTS ON
6. LOG SIGN-ON COMPLETED AND LOG CHECKED FOR:
    - -- NOTES FROM PREVIOUS OPERATORS
    - -- VERIFICATION OF WEEKLY MAINTENANCE
7. H.A. DRIVE SELECT SWITCHES ON FOR EACH ANTENNA TO BE USED

WHEN FINISHED:

1. ALL ANTENNAS FULLY STOWED
2. H.A. FUNCTION SWITCH SET ON SLEW
3. H.A. DRIVE SELECT SWITCHES ALL OFF
4. ANTENNA LIGHTS OFF
5. LOG ENTRY COMPLETE

Fig. 5

GLINT NO. 481
February 10, 1972

PROCEDURE FOR SETTING AND CHECKING THE SIDEREAL CLOCK

L.R. D'Addario

1. Load the SHAIOS "UTILITIES" system tape or the "INTERFEROMETER" system tape.

2. Type RUN STIME; operation of the program should be self-explanatory, except that if Switch 10 is on, output will appear on the line printer; otherwise it appears on the CRT screen only.

3. Display the WWV audio signal on the scope, triggered externally from the signal labeled "1 sec solar". Normally, the scope should be set up so that this can be accomplished merely by throwing one or two switches. The WWV "clicks" each appear as 6 cycles of 1 KHz tone; two clicks appear each second, about 10 msec apart: the first is from Ft. Collins (WWV) and the second from Hawaii (WWVH).

4. Obtain the current UT correction. This number is encoded in the WWV transmissions to the nearest 0.1 sec as follows:

Following the beginning of the minute, some of the seconds clicks may be doubled. If N of the first 8 clicks are doubled, the correction is +0.N second; if N of the 9th through 16th clicks are doubled, the correction is -0.N second. The corrections are given to higher precision in weekly predictions published by the Naval Observatory; we should be receiving these regularly. (EXTRAPOLATED UTC-UT1)

5. Add +7 milliseconds to the UT correction and set the dials of the TIME INTERVAL GENERATOR to the result.

6. By pressing the red "PULSE ADVANCE" buttons on the Time Interval Generator, adjust the WWV click so that it occurs within 2 msec of the beginning of the scope sweep.

7(a). To <u>check</u> the clock: Listen to WWV; at the beginning of each minute, a 0.8 sec burst of 1 KHz tone is transmitted. <u>During</u> this tone, throw the "DISPLAY CONTROL" switch on the clock to "EXT SEC". The time displayed should then be <u>1 sec greater</u> than the time computed by the program for the current PST.

(b) To <u>set</u> the clock: Set the clock thumbwheel switches to the computed sidereal time at the beginning of the next solar minute, <u>plus 1 sec</u>. Remove the cover from the clock setting controls. About 10 sec before the minute (during the voice announcement on WWV), throw the rotary switch to "STOP" (full CW) and press the "SET" button. Check that the display equals the thumbwheel switch setting. During the WWV minute tone, turn the rotary switch one step CCW ("START"). Replace the cover. Sometime in the next several minutes, check the setting according to (a) above.

NOTE: When the display is in its "hold" state, sometimes one or two digits will read incorrectly, even though the clock is keeping the correct time internally. If checking shows a gross error, it is probably due to this and the check should be repeated.

IMPORTANT: Enter your results in the clock log, which is kept in the center desk drawer in the control room.

GLINT NO. 475
May 23, 1972

NELI: AN ON-LINE PROGRAM FOR THE STANFORD FIVE-ELEMENT ARRAY

L.R. D'Addario

This Glint describes program NELI2, as of the revision dated 3/17/72. Some statements made here may not apply to later revisions of the program. It is my intention to update this Glint only if program revisions are substantial, or if they are likely to cause confusion. The program has been operating for some time now, and it is believed to be free of significant bugs; but if problems should be discovered, I'll attempt to document and correct them. Finally, the reader should be aware that an entirely new on-line program may some day be written, rendering this Glint obsolete.

CONTENTS

Clint No. 475-2
May 23, 1972

I. GENERAL DESCRIPTION

This Clint describes an actual, operating program for the HP 2114B computer (Earlier Clints[1,2] described proposed programs which were not actually implemented). The present program is designed to operate as an interferometer any two or more elements of the Stanford five-element array; hence the name N-Element Interferometer (NELI). It performs the following functions:

1. NELI interacts with the operator via the Hazeltine terminal's screen and keyboard, providing informative prompts for the input of source coordinates, integration time, delay offset, calibration information, baseline vectors, and pointing data. The last two of these may be read in from a cassette tape. In addition, NELI accepts commands from the operator, enabling him to control the data-taking and I/O activities of the program.

2. The computations and data sampling needed to produce estimates of the complex visibility in each channel are performed. In particular, the active multipliers are sampled, and the series of samples from each is applied to a filter which is matched to the fringes of the corresponding antenna pair. The result is the best (MMSE) linear estimate of the complex visibility in each channel.

3. During the sampling, the delay lines are maintained at the optimum setting.

4. The antenna position readout settings for proper pointing are displayed on the CRT screen for the operator. These are computed for the current sidereal time at the end of each data sampling period (integration), and at other times upon command from the operator. The computation is based on pointing error vs antenna position information which is read in from a tape near the beginning of program execution.

5. Permanent records of the observations are produced on either or both of two devices: line printer and cassette tape. The visibility estimates from each integration are recorded, as well as source coordinates, baseline vectors, operator comments, local oscillator line length measurements, and receiver gain measurements. (Line length and gain measurements must be made manually and entered through the keyboard.)

A major consideration in the design of this program was that it be flexible. Several features and special commands were included in order to allow operation in non-standard modes. For example, any subset of the 10 channels may be sampled, and they may be sampled in any order; any baseline vector may be assigned to any channel. Thus, for testing or other special purposes, it is possible to connect antennas 1 and 10 to channel 1. In addition, the integration time is freely selectable by the operator, with some cautions (see Section II, para. 4 below). Also, an offset can be added to the delay line settings.

The organization of subroutines was also designed for high flexibility. Wherever possible, subroutines were written so that they would be easily usable with other main programs which might be written by some observers for special purposes. Assembly-language programming was restricted to functions for which it was quite necessary; the main program and most of the subroutines are written in HP FORTRAN.

II. OPERATING INSTRUCTIONS

A copy of the program in absolute form resides on a SRAIOS system tape labeled "INTERFEROMETER". In what follows, it is assumed that the reader is familiar with the operation of the computer system[8] and with the SRAIOS executive (a modified version of the DICOM-supplied CMTOS executive; see references 5 and 6).

Operator interaction with NELI is almost entirely through the Hazeltine keyboard and display. The top portion of the screen is reserved for display of the latest pointing information and visibility data; computer prompts to the operator and his responses and commands appear immediately below the reserved area. CAUTION: USE OF THE HAZELTINE EDITING KEYS SHOULD BE AVOIDED, SINCE THIS MAY INTERFERE WITH THE RESERVED-AREA FEATURES OF THE PROGRAM. Throughout this Clint, prompts by the program will be indicated by underscoring; non-underscored characters in the examples are entered by the operator.

All numerical data entered from the keyboard is read in free-field format (fields separated by commas or blanks, decimal points optional; see ref. 3, pp. 7-16 FORTRAN).

1. Loading and initialization. After loading SRAIOS from the INTERFEROMETER tape, place a write-enabled tape in Deck 3 (if an output data file is to be written), and position it at the beginning of the desired file. Then type:

```
>> RUN NELI
```

When the program has been loaded the operator will be prompted for the following information:

a. Today's date

b. Header. This may be any 40 or fewer characters; it will be written on the output tape (if any), along with the date, in the first record; it will also be printed at the top of the first page of printed output (if any).

c. Last serial number. All integrations are automatically numbered by consecutive integers. The operator may wish to begin at a particular serial number, especially if the current observations are part of a series. If so, he should enter the last serial number previously used; otherwise he should enter zero.

d. Output flags. The operator's responses indicate whether or not the line printer is to be used, and whether or not an output tape is to be written. Any response other than YES is taken as "no".

Example:

```
DATE (MM,DD,YY) ?  4,15,72
HEADER                                        :
CALIBRATION OBSERVATIONS BY LRD
LAST SERIAL NO.?  0
PRINTER?  YES
OUTPUT TAPE?  YES
```

2. Pointing and Baseline Data. Pointing and baseline data are entered next. Each of these may be a tape file on Deck 2; the baselines may also be entered from the keyboard. Pointing data, if available, must be written on the tape in a special binary format (given under "Programming Details") and must be terminated by a file mark. When NELI asks

```
POINTING DATA TAPE?
```

a response of YES will cause the next file on Deck 2 to be read. (CAUTION: NO CHECK IS MADE TO SEE THAT THE CORRECT TAPE HAS BEEN LOADED.) Any other response causes NELI to assume that all pointing errors are zero; the tape is not read, and the pointing display will later contain the nominal readout settings. Next, the numbers of the antennas being used are entered, e.g.,

```
ANTENNA NOS. (1 TO 5) ?  2,3,4
```

indicates that SECUNDO, TERTIO, and SEPTIMO are in USE.* (This information is used only to control the display of readout settings; it is independent of the channels being sampled.)

NELI then asks for the baseline data:

---

[*] In this and many other programs, it will be convenient to number the antennas 1 thru 5. I shall refer to these as the "antenna numbers", and to the corresponding numbers 1,2,3,7,10 as "antenna position numbers". Note also that the channels are most conveniently numbered 0 thru 9 in the software.

BASELINE PARAMETER ENTRY. TAPE?

A YES response indicates that the data is in the next file on Deck 2. Any other response causes a prompt for keyboard entry of the baselines. The operator then types one line for each channel to be sampled, giving the channel number (0-9), Sx, Sy, and Sz (= Bx, By, Bz of Glint 418, p. 3). The last line must be terminated by a zero (don't forget this!). If the tape is used, the information is in ASCII form with this same format.[**] The baseline data is written on the output tape and/or the line printer when it is entered.

The channel numbers and baselines may be entered in any order; the order in which they are entered is the order in which the channels will be sampled. In addition, the baseline of the *first* channel entered affects the integration time: an integral number of fringes on this channel is always accumulated. Therefore, the first channel should normally be the one with the shortest baseline (further discussion of this is given below under "Integration Time"). Finally, the baseline of the *last* channel entered is used to compute the delay line settings; since all of the baselines are very nearly collinear, it should normally make little difference which channel is entered last.

NELI next prompts the operator for the delay offset, in units of the switched-delay increment; normally, this is set to zero:

DELAY CENTER OFFSET? 0

3. *Source data.* The name of the first source to be observed and its right ascension and declination of date are entered next. Up to 10 characters may be used for the source name. (The source being observed may be changed at any later time by giving an appropriate command to NELI.) Whenever new source information is entered, it is written on the output tape and/or the line printer.

Example:

SOURCE NAME? 3C461

R.A. (HH,MM,SS) ? 23,22,6.57

DECLINATION (DD,MM,SS) ? 58,39,31.3

4. *Integration time.* NELI next prompts the operator for the approximate time, in minutes, for which multiplier output samples will be accumulated for each estimate of the complex visibilities. We refer to each such interval as an "integration" and to a series of successive integrations as a "run". The

---

[**] Currently, a tape is maintained in the tape library with the latest pointing and baseline data on Files 1 and 2, respectively. Approximate baseline vectors, based on surveying, are given in Glint 429. Preliminary observations indicate these baselines are in error by approximately 1λ on channel 9, and proportionately less for the closer spacings.

length of the integration period may be changed at any later time by an appropriate command to NELI. Example:

<u>INTEGRATION TIME (MIN)?</u> 2.5

In choosing an integration time, the operator should take into account the following:

(a). The actual integration time will always be slightly longer than the value entered: the program integrates for whatever additional time is needed in order to make the change in path difference on the first channel equal to an integral number of wavelengths (integral number of fringes). Normally, this will result in an integral path difference change on all channels. This is necessary in order to minimize errors in the complex visibility estimates.[9] The maximum additional integration time is given approximately by

$$\Delta t_{max} = 13751/S \cos\delta \cos h \text{ seconds}$$

where S is the baseline length for the first channel, in wavelengths. Thus, for antennas 1 and 2 or 2 and 3,

$$\Delta t_{max} = 16.9 \text{ sec at } \delta = 0,\ h = 0$$
$$= 131 \text{ sec at } \delta = 60^{\circ},\ h = 5 \text{ hrs.}$$

(b) Very long integrations, especially on strong signals, may result in floating point underflow in adding data samples to the accumulators. If all 10 channels are being sampled, this should not occur unless the integration time exceeds 50 minutes. But if only one channel is being sampled, it is possible for underflow to occur in integrations as short as 5 minutes.

(c) Very short integrations may prevent 10 hours of data from fitting on a 300-foot cassette tape (the longest available). Ten hours of 5-minute integrations is known to fit.

WARNING: THE OPERATOR WILL RECEIVE NO INDICATION IF THE END OF THE TAPE IS REACHED.

(d) Pointing errors can be computed only between integrations. Thus, if frequent updating of the pointing is required, a short integration time is favored.

5. <u>Commands</u>. NELI will next prompt the operator for a command. From this point on, operation of the program proceeds according to commands given by the operator. A list of the valid commands and their effects is given in Table I. Only the first two characters of each command are meaningful to NELI.

During integrations, no other operations can be performed and no commands can be given. However, it is possible to force immediate termination of the current integration by turning on Switch 0. In this case, the actual termination time will appear in the output; but large errors may be present in the visibility estimates, especially if the integration time was very short.

6. Outputs. NELI makes use of three output devices: DICOM Deck 3, the line printer, and the Hazeltine CRT display (the latter is duplicated on the TV monitor above the R.A. readout panel).

(a) CRT display. The uppermost 8 lines of the screen are reserved for the display of output data; the remainder of the screen is used for interaction with the operator. The left-hand side of the reserved area displays the declination and right ascension readout settings for each of the antennas in use, for the source position currently in effect, and for the most recent computation of the pointing errors. The right-hand side of the reserved area displays the results of the most recent integration: amplitude and phase estimates for each channel sampled, and the average ("d.c.") output of the corresponding multiplier.

(b) Line printer. Amplitudes, phases, and d.c. values are printed for each channel sampled. Zeros are printed for each channel not sampled. Also printed for each integration are the serial number and the beginning and ending hour angle.

Self-explanatory line printer output also occurs whenever source coordinates, baseline vectors, comments, L.O. line measurements, or gain measurements are entered, provided that the PRINT option is in effect.

(c) Tape. All data is written on the tape in binary form. It is divided into "logical records", where one logical record is written for each output operation. Each logical record is coded according to the type of data it contains. NELI supports seven types of records, as listed in Table II. The first word of each logical record is the type code -- simply an integer from 1 to 7. The second word of each logical record is the number of words it contains (including the first two). In principle, a logical record can be of any length; however, physical records on the tape have a maximum length of 60 words. Thus, a logical record may consist of more than one physical record. This is of concern to any programs which later read the tape. (A subroutine called RDATA is available for reading NELI data tapes. If it is used, the programmer need not be concerned about the tape format. RDATA will be described in a separate GLint.) The full content of each type of record written by NELI is given in Table II.

(d) Normalization. For all output media, visibilities and d.c. values are given in units of counts on the Beckman accumulator. The d.c. values are equal to the average number of counts for all samples taken on the corresponding channel. Visibility amplitudes are equal to half the peak amplitude in counts of the MMSE sinusoid fitting the samples taken on the corresponding channel. Complex visibilities are displayed in polar form on the printer and CRT, and written in rectangular form on the tape; the normalization is the same in both cases. Phases are given in cycles (fringes), so that they are always in the range 0.0 to 1.00. For a given channel, the resultant complex visibility estimate is independent of the number of channels being sampled or the integration time, except for the effects of noise.

CAUTION: If the number of counts in the accumulator reaches 2000 in a sample period, then the VIDAR voltage-to-frequency converter is saturated. Thus, d.c. values in the vicinity of ±2000 are an indication of difficulty; in fact, one should always have

$$|dc_i| + |A_i| < 2000 .$$

Large d.c. values may indicate strong interference, particularly if it is a strong function of the delay line setting. It may also indicate imbalance in the multiplier.

TABLE I - COMMANDS

BEGIN	Restart the program from the beginning. All information previously entered is lost.
COMMENT	Allows typing in one line of comments, up to 70 characters; the text is written on the tape and/or line printer.
SOURCE	Allows entering data for a new source. Appropriate prompts are given. Source record written on tape and/or printer.
BASELINE	Allows changing the channels and baseline parameters. Baseline record written on tape and/or printer.
ITIME	Allows changing the integration time.
POINT	Causes computation of the readout settings for the current sidereal time, and updating of the reserved area of the screen.
GO	Causes one integration to be accumulated, beginning immediately. Data record written on tape and/or printer. At the end, readout settings are re-computed and the screen is updated.
RUN	Causes consecutive integrations to be accumulated, beginning immediately. At end of each, data record is written on tape and/or printer; screen is updated with new printing; and, if Switch 1 is OFF, another integration is initiated. Switch 1 ON causes return to Command Mode.
LO	Allows entry of local oscillator reference line length measurements. Appropriate prompts given. L.O. record written on tape and/or printer.
GAIN	Allows entry of receiver gain measurements; similar to LO.

DELAY	Allows changing the delay offset.
NPRINT	Suppresses all line printer output.
PRINT	Resumes line printer output, if printer output is currently suppressed.
WEOF	Writes end-of-file mark on output tape (Deck 3); if no output tape is being written, this command is ignored.
SPECIAL	Causes execution of a user-supplied subroutine named SPECL. In the standard version of NELI, SPECL is a dummy program. This command allows preparation of special versions of NELI with additional capabilities.
/E	Terminates the program, and executes the System Loader. EOF is not written on the output tape.

TABLE II - OUTPUT TAPE FORMATS

RECORD TYPE	CODE	NO. WORDS	CONTENTS
Header	1	24	ITEXT, DATE
Baselines	2	7*NC+2	(IC(I),SX(I),SY(I),SZ(I),I=1,NC)
Source	3	11	NAME,DEC,RA
Data	4	7*NC+7	NSER,T1,T2, (IC(I),FREAL(I),FIMAG(I),DC(I), I=1,NC)
L.O. lines	5	14	TIME,X1,X2,X3,X4,X5
Gains	6	14	TIME,G1,G2,G3,G4,G5
Comment	7	37	LINE

Notes

a. Note that floating point numbers take up two words, and integers take up one; ITEXT,NAME, and LINE contain 2 characters per word.

b. "Contents" are given in the form of a FORTRAN output list.

Variables used here, with their dimensions if they are arrays, are:

NC... number of channels being sampled

ITEXT(20) ... header text, 40 characters

DATE ... floating-point date code: YY.DDD (e.g., 72.082)

IC(10) ... channel numbers, in order of sampling

SX(10),SY(10),SZ(10) ... baseline vectors

NAME(5) ... source name

DEC ... declination, radians

RA ... right ascension, radians

NSER ... serial number

T1,T2 ... starting and ending sidereal times, radians

FREAL(10),FIMAG(10) ... complex visibility estimates

DC(10) ... average multiplier outputs

TIME ... sidereal time, radians

X1,X2, etc. ... l.o. line measurements (= -1.0 if no data was entered)

G1,G2, etc. ... receiver gain measurements (as above)

LINE(35) ... comment text, 70 characters

III. PROGRAMMING DETAILS

It is assumed in this section that the reader is an experienced FORTRAN programmer, and that the operation of the program can for the most part be understood from the flow charts (Figs. 2 thru 4); the list of subprograms (Table IV, which includes all FORTRAN-callable non-library programs and some of the library programs used); and the listings of the source code (Section IV), the latter being fairly well commented. The discussion in this section, then, is limited to a few special points which demand more detailed discussion.

1. *Logical flags.* Several flags are used to control branching in the main program. They are KPRIN, KTAPE, KRUN, and KSWCH. Each may be thought of as a logical variable with .TRUE.= -1, .FALSE.= 0. The first two indicate which output devices are in use. KRUN is TRUE if the program is in "run" mode. KSWCH is set TRUE when certain sections of the program are entered (e.g., the display update, lines 551-554) unless they are entered via the command interpreter. This allows in-line execution of the program segment, and also execution in response to a command, after which control returns to the command interpreter.

2. *Linearized phase prediction.* Estimation of the complex visibility in each channel requires knowledge of the interferometer phase $\phi = 2\pi P$, where P is the path difference in wavelengths, at which each sample is taken. P is computed for the currently entered source position, which is assumed to be at the center of the field of view. The phase ϕ is then equal to the phase of the complex visibility for a point source at that position. In general, we have

$$P_i = \vec{s} \cdot \vec{S}_i \qquad (1)$$

where $\vec{s}$ is a unit vector in the source direction and $\vec{S}_i$ is the baseline vector for the i-th channel. However, the computation of $\vec{s}(h)$ requires sin h and cos h to high precision; use of the Hewlett-Packard SIN and COS functions (which are slow) precludes making this computation for each sample. Accordingly, a linearization of $P_i(h)$ is performed:

$$P_i(h_o + k\Lambda) \approx P_{io} + k\,\Delta P_i \qquad k = 1, \ldots, k_{max} \qquad (2)$$

where Λ = 20 msec (sampling interval), h_o is the hour angle of the first sample, and k is the sample number. The linearization results in an error in P_i which will have zero mean and minimum variance over $k = 1, \ldots, k_{max}$ if[*]

---

[*] The remarks in Glint 418, p. 6 do not apply; that discussion assumes $P_{io} = P_i(h_o)$, which is not the best choice.

$$P_{io} = \frac{1}{3}P_i(h_o) + \frac{2}{3}[P_i(h_o + k_{max}\,\Delta/2) - \frac{k_{max}}{2}\,\Delta P_i]$$

$$\Delta P_i = \frac{P_i(h_o + k_{max}\Delta) - P_i(h_o)}{k_{max}}$$

The calculation is illustrated in Fig. 1. It is carried out in lines 206-229 of NELI 2.

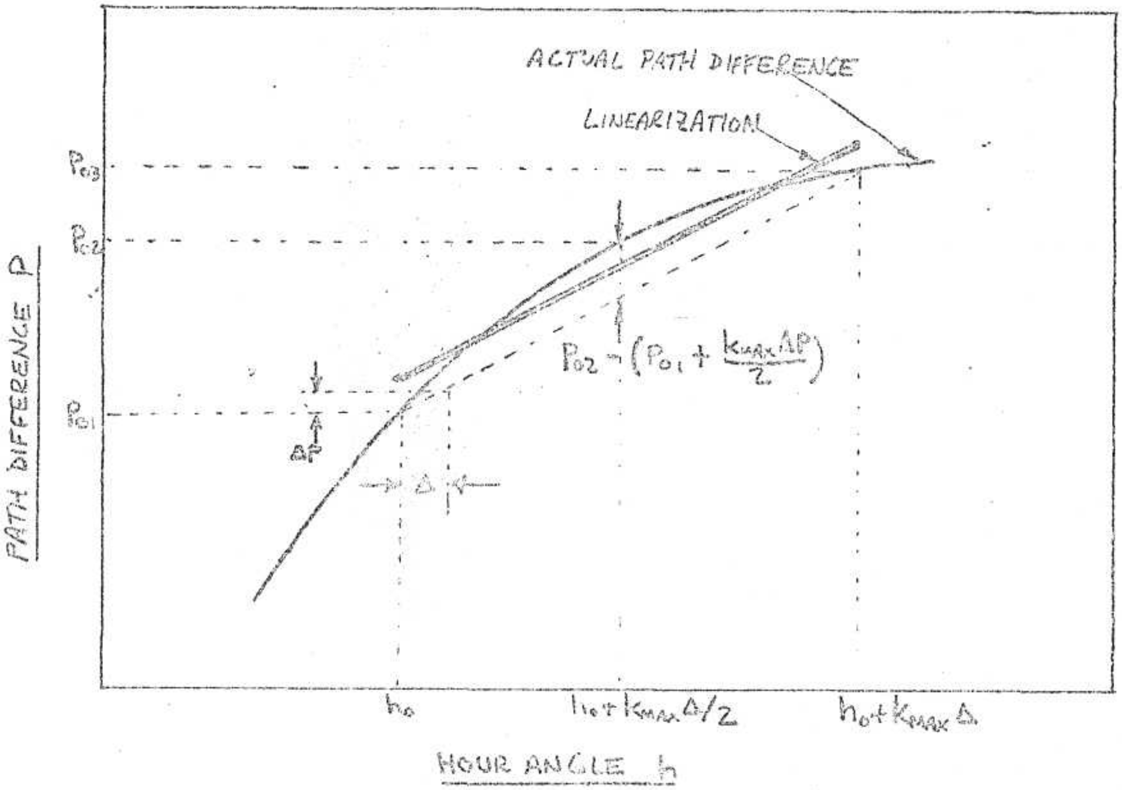


Fig. 1. Linearization of Phase Prediction

In order to keep the r.m.s. error small while allowing maximum freedom in the choice of integration time, each integration is broken up into sub-integrations of approximately 1 minute each, and sampling is briefly suspended after each sub-integration to allow the linearization constants P_{io} and ΔP_i to be re-computed. Thus, $k_{max} = 3000$. The logic for the sub-integrations is contained in lines 197-204.

Finally, a correction is made to P_{io} for the time required to perform the linearization calculations. Subroutine COUNT is called (line 208), allowing interrupts to occur on I/O channel 10 every 20 msec; these are counted to determine the time used by the calculation, and the appropriate correction is applied (lines 228-229). Interrupts are terminated by FINIS (line 227).

3. Integral number of fringes. As shown elsewhere,[9] estimation of a sinusoid in the presence of noise is most efficient if an integral number of cycles is observed. Accordingly, each of the sub-integrations is made to last for an integral number of fringes on the first channel (assumed to have the shortest baseline and hence the slowest fringes). Each sub-integration is somewhat longer than 1 minute; enough additional samples are taken so that the change in path difference on the first channel is an integral number of wavelengths. This is accomplished in line 232.

4. Sampling and visibility estimation. The complex visibility in each channel for each integration is estimated from

$$\mathrm{Re}\ \underline{V} = \frac{1}{N_s} \sum_{j=1}^{N_s} d_j \cos \phi_j$$

$$\mathrm{Im}\ \underline{V} = \frac{1}{N_s} \sum_{j=1}^{N_s} d_j \sin \phi_j$$

where N_s is the number of samples taken on the channel in question, d_j is the accumulator reading for the j-th sample on that channel, and ϕ_j is the computed phase of that channel at the time of the j-th sample. This is the minimum mean square error estimate.

The sampling and data accumulation is controlled by subroutine LOOP. The sine and cosine computations are performed by a table-lookup and interpolation routine written in assembly language and called through subroutine VISIB. The accuracy of the sines and cosines is 5 to 6 decimal places. The table-lookup scheme is used in order to obtain sufficient speed; the accuracy is more than sufficient.

5. Pointing computations. Subroutine POINT returns the pointing errors for a given hour angle, declination, and antenna by evaluating a simple function of hour angle and declination. The pointing errors are converted to readout settings and displayed on the CRT by subroutine DSPLY. Presently,* the function evaluated by POINT contains 9 parameters for each coordinate of each antenna; however, space is allocated for up to 10 parameters each, for a total of 100 floating point numbers. The 9 parameters are coefficients by which terms of the form $f_1(\delta)f_2(h)$ are linearly combined, where $f_1, f_2 \in \left\{\sin, \cos, 1.0\right\}$. The parameters are read in from Deck 2 in binary form.

---

* Plans call for determination of a more optimum functional form, with as few parameters as possible. When this is changed, POINT should be re-written.

TABLE IV - FORTRAN CALLABLE SUBPROGRAMS

Entry Point	*	Description
CHANL	A	Causes the multiplexer to select a given channel.
CHECK	A	Checks that the sampling loop is fast enough; if not, halt occurs with (H) = 102070 B.
COUNT	A	Counts interrupts on I/O channel 10 B for timing purposes.
DELAY	A	Sets the delay lines.
DLCTR	A	Offsets delay lines by a given number of delay units by changing a constant in DELAY.
DSPLY	F	Updates reserved area of CRT; calls POINT.
FINIS	A	Terminates interrupts on I/O channel 10 B.
LOOP	F	Accumulates a specified number of data samples from the active channels, along with their products with sin ϕ and cos ϕ, while maintaining correct delay line setting.
POINT	F	1. Loads pointing data from binary tape in Deck 2. 2. Computes pointing errors for given h, δ, and antenna.
SPECL	F	Dummy routine to allow addition of special functions.
START	A	Initiates sampling on I/O channel 10 B.
VISIB	A	Given path difference P and data sample d, returns d cos 2πP and d sin 2πP.
Library Programs:		
HMS(DMS)	F	Hours (deg.), min., sec. from radians.
RADH(RADD)	F	Radians from hours (deg.), minutes, and seconds.
CLOCK	A	Reads sidereal clock; see Glint 411
FCMND	A	Interprets a 2-character command by finding its location in a list of valid commands.
ILINE	A	Inserts a blank line on CRT screen; see Glint 454.
BINRD	A	Initiates a binary tape read operation; Glint 442.
IEOF	A	Checks whether EOF mark was read on last binary tape read operation; Glint 442.

---

*Language in which subprogram is written:
F = HP FORTRAN
A = HP ASSEMBLER

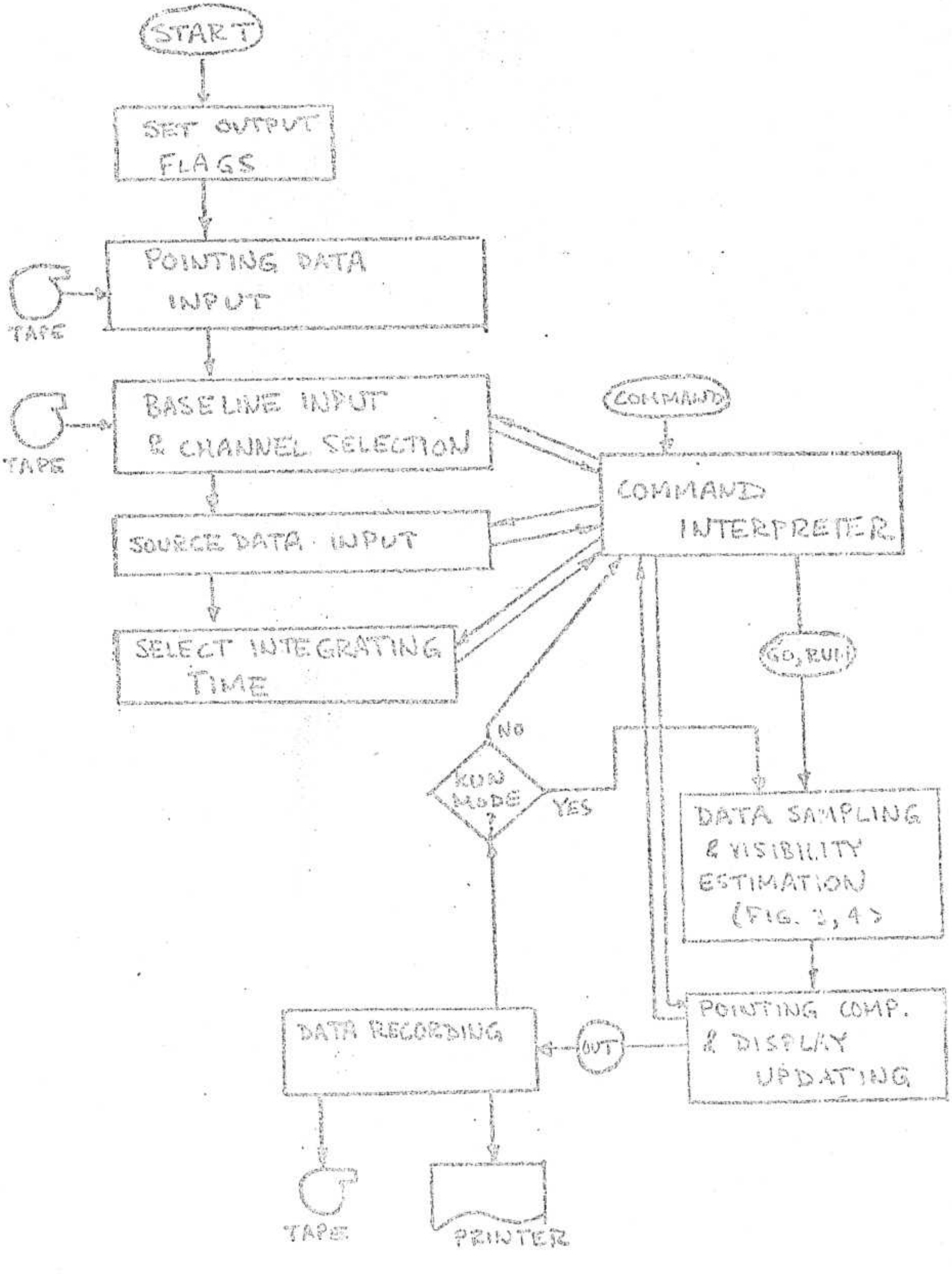


Figure 2 — Overall Flow Chart

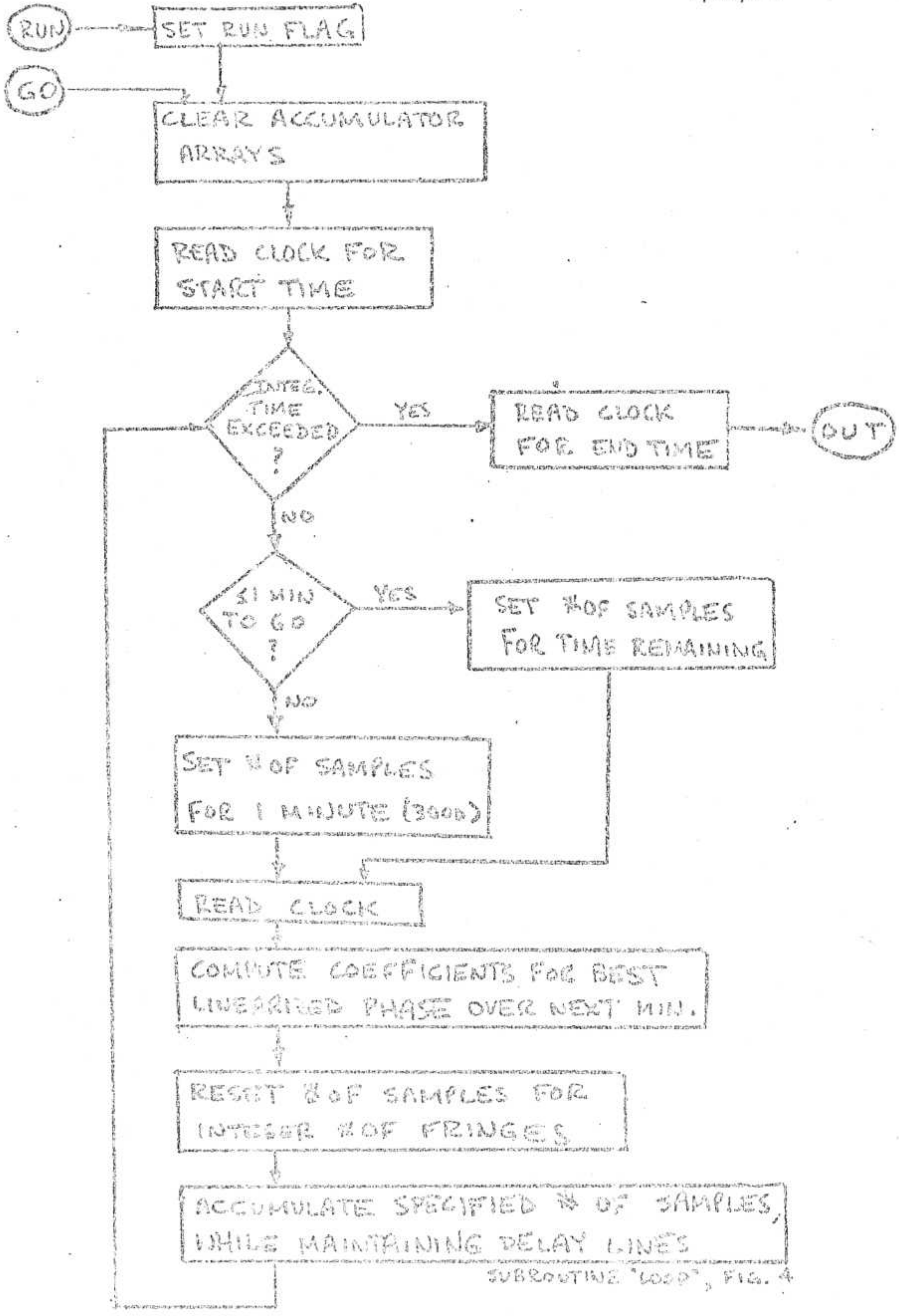


FIGURE 3 — INTEGRATION LOOP FLOW CHART

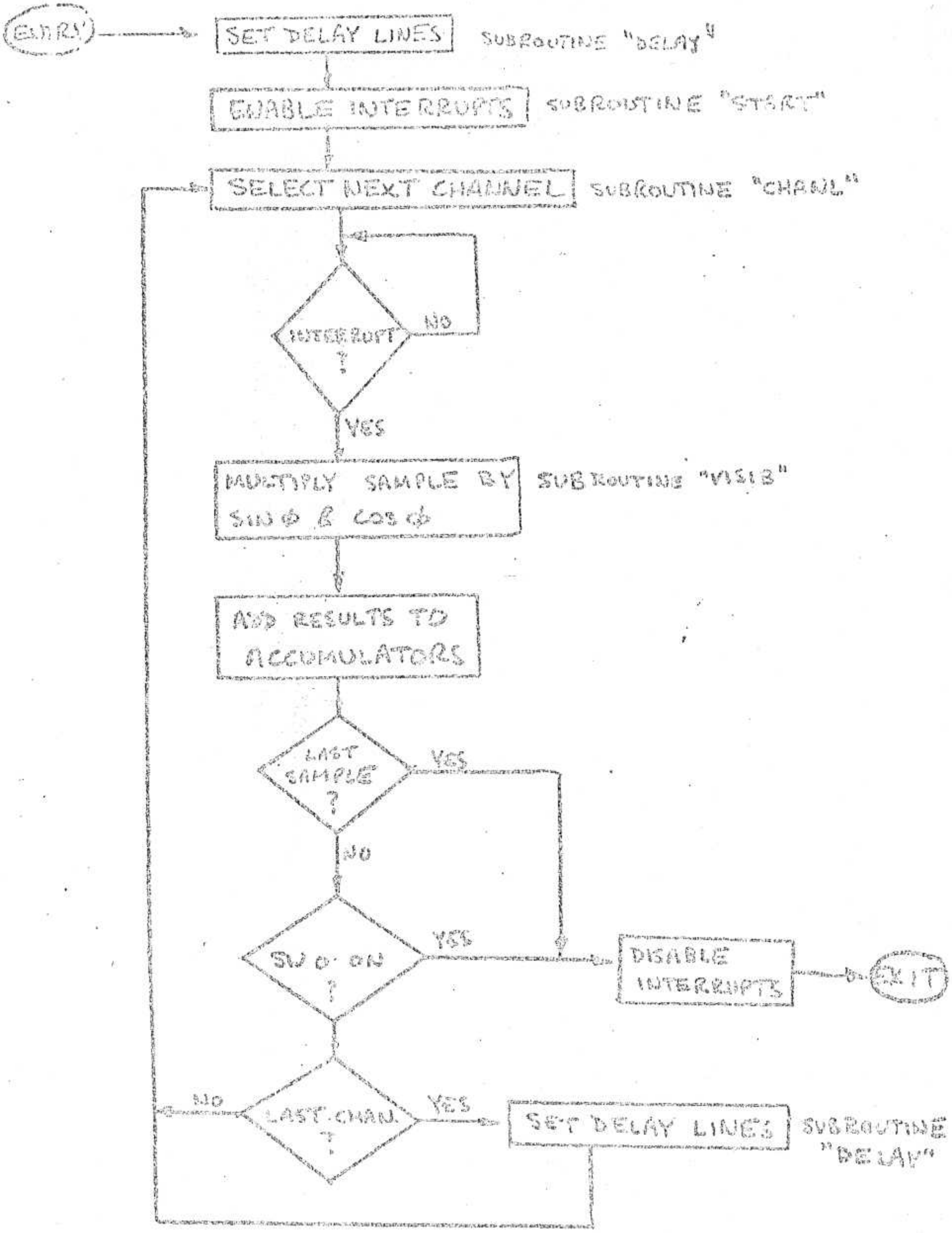


FIGURE 4 – SUBROUTINE "LOOP" FLOW CHART

CLINT NO. 524
May 25, 1973

SOURCE PRECESSION

S.J. Wernecke

A program, PREC, for reducing a 1950.0 source position to apparent position of date has been added to the INTERFEROMETER systems tape. PREC is capable of processing any subset of a source catalog on tape. Alternatively, source names and 1950.0 positions can be entered through the Hazeltine keyboard. PREC can also be used to create user source catalogs. A catalog containing the standard calibrators can be found on the PARAMETERS tape.

The previous precession program, written for the IBM 360, used double precision to calculate the general precessional constants and to solve the rigorous precession formulae. PREC uses single precision to evaluate a second order expansion of the rigorous precession formulae. Precessional constants are stored in the program rather than calculated and are suitable for reduction to the period July 1, 1972 through June 30, 1980. Details of program calculations can be found in the Appendix, along with comments on accuracy.

PROGRAM OPERATION

The mode of program operation is established in the opening dialogue. The program then prompts for information relevant to that mode. Most prompts are self-explanatory; exceptions are explained below.

Regardless of the mode chosen, the user will eventually be prompted for SOURCE NAME?. If the user intends to precess sources from a catalog, valid responses are /A, /E or a source name. /A means precess all sources in the catalog. If precession of only a few sources is desired, the names should now be entered (chaining names on a single line is not allowed). /E is the terminator of such a list. The program will search the catalog and precess any source whose name is on the input list. No error is caused by input of a name not in the catalog or by multiple entries of the same source name in the catalog (all such entries will be precessed).

If a source catalog is not being used the user should respond to prompts by entering source names and (1950.0) position, again using /E as a list terminator. If a source tape is being created, /E will cause an end of file mark to be written. In response to COMMENT, the user is allowed 40 characters.

When PREC encounters an end of file while reading a source catalog or when a /E is received in either of the other two modes, the user will be prompted for branching instructions. He can choose to stop execution or to re-initialize the program for precession to the same day or to a new day. If the "same day" option is chosen, day numbers and equation of equinoxes will not need to be re-entered.

If a read error occurs while searching the source catalog, a PAUSE will be executed. The user is allowed to skip the bad record or to re-initialize the program to the same day or to a new day.

Miscellaneous comments: in response to DATE (M,D,Y)? the year should be entered without 19 as a prefix. Equation of Equinoxes can be found on pp. 12-19 of the Ephemeris. Independent day numbers are found on pp. 309-325 and are entered f through i in order with spaces (or commas) separating hours, minutes and seconds for G and H. Be careful to get signs correct! For days Jan. 1 through July 2 day numbers in the Ephemeris are referenced to the beginning of tropical year; for July 1 through December 31 they are referenced to the end of tropical year. For July 1 and 2, values referenced to the end of tropical year must be used (this caution has been noted in the Ephemeris at the Field Site). Negative declinations should be entered as -DD -MM -SS as with the on-line program. Numeric data is read under free format but source name (and comments) are read under ASCII format. Consequently, when using a source catalog, source names must be entered exactly as they appear in the catalog.

SOURCE CATALOG

A source catalog is an ASCII file so it can be modified with the HP editor if required. It could also be created with a WRITE command in SRAIOS although formats will have to be observed. PREC reads the catalog under the following format:

```
    READ (LU, 201) NAME, RH RM,RS,DD,DM,DS,ITEXT
201 FORMAT (5A2,I3,I3,F6.3,I4,I4,F6.2,X,20A2)
```

A listing of the calibrator source catalog is included in the documentation at the end of this Glint. It is expected that multiple entries will be eliminated as the best position of each source is confirmed.

APPENDIX

Reduction of a 1950.0 position to apparent position of date is a two-step procedure in which the 1950.0 position is first precessed to the mean position at the nearest beginning of tropical year. Then, day numbers are used to reduce the mean position to the apparent position of date. It is shown in Woolard and Clemence, Spherical Astronomy, Academic Press, 1966, Ch. 12, that for times preceeding the epoch 1950.0 the rigorous formulae for reduction to mean position are

$$\tan[(\alpha - \alpha_o) - \zeta_o - z] = \frac{q \sin(\alpha_o + \zeta_o)}{1 - q \cos(\alpha_o + \zeta_o)}$$

$$\tan \frac{1}{2}(\delta - \delta_o) = \frac{\tan(\frac{1}{2}\theta)\cos[(\alpha_o + \zeta_o) + \frac{1}{2}(\alpha - \alpha_o - \zeta_o - z)]}{\cos \frac{1}{2}(\alpha - \alpha_o - \zeta_o - z)}$$

$$q = \sin \theta [\tan \delta_o + \cos(\alpha_o + \zeta_o) \tan \frac{1}{2} \theta]$$

For reduction to times after the epoch the substitutions required are $\zeta_o \to -z$, $z \to -\zeta_o$, $\theta \to -\theta$. With these substitutions, a second order expansion yields:

$$\alpha' = \alpha_o - \zeta_o - z - \theta \sin(\alpha_o - z) \tan \delta_o + \frac{1}{4}\theta^2 \sin 2(\alpha_o - z)$$
$$+ \frac{1}{2} \theta^2 \sin 2(\alpha_o - z) \tan^2 \delta_o \qquad (1)$$

and

$$\delta' = \delta_o - \theta \cos(\alpha_o - z) - \frac{1}{2}\theta^2 \sin^2(\alpha_o - z) \tan \delta_o \qquad (2)$$

In these approximate expressions, (α_o, δ_o) is the 1950.0 position; ζ_o, z and θ are general precessional constants for the tropical year in question; (α', δ') is the mean position at the beginning of the tropical year. These are the equations implemented in PREC. The precessional constants to 1980.0 were obtained from the Explanatory Supplement to the Ephemeris and are stored in the program.

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5/25/73

For reduction of these mean positions to the apparent position of date we use

$$\alpha = \alpha' + f + g \sin(G + \alpha') \tan \delta' + h \sin(H + \alpha') \sec \delta' \qquad (3)$$

$$\delta = \delta' + g \cos(G + \alpha') + h \cos(H + \alpha') \sin \delta' + i \cos \delta' \qquad (4)$$

where f, g, G, h, H and i are independent day numbers. f, g and G give reduction for precession and nutation. h, H and i give reduction for aberration. Independent day numbers are used in place of Besselian day numbers as formulas with the latter involve additional yearly constants which could not be found past 1974.0 in any convenient tables. It is possible to use second order day numbers to further refine the calculations, but this is complicated as the constants involve the source position as well as the date. By reducing the 1950.0 position to the nearest beginning of year (instead of beginning of current year) these corrections are kept small.

The accuracy of equations (1) and (2) is of interest since some terms include tan δ. $\theta < 40^s \approx .003$ radian for the remainder of this decade. In equation (1) and $\delta_o = 80^o$, the second order term is less than $(.003)^2(.25 + .5 \tan^2 \delta_o) \approx (.003)^2(18) = 1.6 \times 10^{-4} \approx 2^s$. The third order term will be down by another factor of .003 and if the coefficient of this term contains $\tan^3(\delta)$ it will have a magnitude around 0.03^s. In equation (2) for the same declination, the magnitude of the second order term is less than $.5(.003)^2\ 6 = 2.7 \times 10^{-5} \approx 5''$. The third order term (allowing a $\tan^2 \delta$ in the coefficient) will then be no greater than $5(.003)(6) \approx .1''$. Thus we expect that an expansion of the rigorous expressions to second order will be satisfactory for our purposes, if there are no serious round off errors introduced in computation.

To check these conclusions, the standard calibrator list was processed to 6/1/73 using PREC and the 360 program. In the vast majority of cases, the results agreed exactly to hundredths of a second in right ascension and to tenths of an arc second in declination. Worst errors were $\pm 0.01^s$ in right ascension and $\pm 0.1''$ in declination. This includes 3C 309.1 at a declination of $\approx 72^o$ and right ascension of $\approx 15^h$.

The author intends to compare the results at a higher declination; however, for the regions of the sky we are currently observing there are no difficulties foreseen.

GLINT NO. 525
May 31, 1973

NELI3 USER'S GUIDE

L. D'Addario

INTRODUCTION

NELI3 is a new version of the on-line interferometer program for the Stanford Five Element Radiotelescope. It supersedes NELI2, which was described in detail in Glint 475. The new version is a completely new program, but in many respects it appears to the user to be similar to NELI2. Therefore, in this Glint I shall assume the reader is familiar with NELI2 and give only a brief description of the differences. I shall not attempt to explain the programming details at all; source program listings, with extensive comments, are kept on file in the Butler Building for anyone interested.

The principal improvements are:

1. Data sampling can proceed simultaneously with other operations; it takes place in the "background" under the control of the interrupt system, while other I/O and computations take place in the "foreground". This allows implementation of the next 3 improvements.

2. In "RUN" mode, no observing time is lost for I/O between integrations. Output from one integration is overlapped with data sampling for the next.

3. Commands and operator-supplied data (including comments, line length measurements, etc.) may be entered simultaneously with data sampling.

4. Computation and display of the readout settings for correct pointing can take place simultaneously with data taking. This allows the pointing display to be updated every few seconds.

5. The internal phase function includes six terms instead of just the three "baseline" terms; see Glint 489.

6. Corrections for L.O. lines and receiver gains may be computed on-line; and, if a calibration source has been observed, each integration may be calibrated on-line.

7. The tape handling has been improved. The output file is automatically selected; each record contains a checksum; and more error checks are made.

Glint No. 525-2
5/31/73

ACKNOWLEDGMENT

Putting the data sampling into the background required coding all of the computations needed to process each sample in assembly language. The necessarily long and complicated routine was written by John Grebenkemper, who therefore should be credited with making possible the major advances incorporated in NEL13. He also helped immeasurably with the debugging of the entire I/O system needed to allow a multitude of simultaneous operations without hangups.

DESCRIPTION OF PROGRAM FEATURES

1. Initialization Phase (Part I). When the program is loaded, the operator is required to enter certain information in response to prompts. These should be self-explanatory. The prompt "Non-standard Channels" allows the operator to inform the program if any multiplier is connected to other than the standard antennas. If only the standard channels will be used, just strike SHIFT/XMIT in response to this prompt.

The phase and pointing parameters will be read from an operator-specified file in Deck 2. If the file cannot be read, an error message is given. The codes have the following meanings:

-3 checksum error
-2 end-of-tape
-1 tape read error
0 end-of-file encountered when not expected

The operator will be asked whether he wishes an output tape to be produced. If he answers "YES", he must then place a labeled tape in Deck 3. Special labeled tapes will be kept on hand for this purpose (see labeled tapes, below). The program will automatically position the tape at the beginning of the next available file and will write two records (header and parameters) on the new file. If the tape label cannot be read correctly, a message is given and the prompt repeated; the operator may insert another tape, or request that no tape be written, or try again to read the label.

When the initialization phase is complete, header information is printed on the line printer. The printer must be on and selected at this point, although printing may later be suppressed by a command.

Finally, the main phase (Part II) of NELI3 is loaded from Deck 1. This is necessary because the initialization routines and the observing routines cannot all fit in core at once.

2. Commands. When the main phase is loaded, the prompt ">>" at line 11 on the CRT indicates that NELI is ready to accept a command. The valid commands are listed in Table I. Only the first two characters are examined by the program to determine which command has been given; however, many of the commands require one or more numerical parameters, which must follow the command on the same line. The parameters are in Hewlett-Packard free-field format (see H-P Fortran Manual, p. 7-16). All of the parameters are set to default values when the program is loaded, so that none of these commands need be given unless non-default values are desired; the defaults are given in Table II. However, whenever a command is given, its entire parameter list (if any) must be included.

3. On-line corrections and calibration. At the end of each integration, the visibility data is automatically corrected for measured local oscillator reference line lengths and receiver gains, using the measurements last entered by the operator (or the defaults if none has been entered). The corrections reduce the data to the standard gain of 100.0 units and the standard line length of 00.0. The required computation is carried out simultaneously with data sampling for the next integration (if any) so that no observing time is lost. To obtain the results of this computation, the operator must set the tape level and/or printer level (see Table I) to 1 or 2; the corrected data will then be written on the tape and/or line printer, respectively, following the uncorrected data (see also Table IV, Output Tape Format).

The corrected data may then be calibrated by the on-line program; it will compute for each channel the complex ratio of the corrected visibility from the latest integration to the average corrected visibility obtained from a series of observations of a calibration source. To accomplish this, the calibration source must be observed first, using the "CALIBRATE" command; this causes the corrected visibilities to be added to a "calibration buffer" in core, in addition to being written on the tape and/or printer. Thereafter following each integration taken under the "GO" or "RUN" command, the complex ratio of the corrected visibilities to those in the calibration buffer will be computed (the result is also multiplied by the number of calibrator integrations, so that in effect the average of the calibrator integrations is used). To obtain the results of this computation, the operator must set the tape level and/or printer level to 2 (see Table I and Table IV).

4. Labeled tapes. In order to minimize tape use, to provide protection of output data from operator errors, and to allow the original output tapes to be retained as archives of all observations, a system of magnetically labeled tapes has been devised. A labeled tape is simply one in which the first file, called the label, has a special format. The label contains 2 records:

Record 1, word 1: Number of data files on the tape
word 2: Tape serial number
word 3: Checksum = (word 1) + (word 2)
Record 2 : 23 words of junk; may contain parity errors.

The files following the label are called data files. When the output tape is loaded, MELI reads the label to see how many data files are already there; it then re-writes record 1 of the label with the number of data files incremented by 1, re-reads the label to be sure it is correct, and finally skips to the beginning of the new data file about to be created. A new labeled tape may be created from a blank tape by the utility program LABEL; the number of data files is then set to zero.

5. Error conditions and messages. All of the messages and error conditions which can occur, or at least all those I can think of, have been explained in Table III.

6. Phase and pointing parameters. The 6-term phase function of Glint 489 and the 14-term pointing function (8 hour angle, 6 declination) of Glint 507 have been implemented as of 1 June 1973. The coefficients of these functions are read in from the "parameters" tape in Deck 2 during the initialization phase. They are written on the output tape as the second record of the file. Space has been provided for 125 floating-point parameters, with 100 being used in the present version.

The parameter tape format, along with the functions to which each coefficient corresponds, is given in Table V.

TABLE I - NELL COMMANDS

Command[3]	Parameters[4]	Explanation
SOURCE[1]	h,m,s d,m,s	Coordinates of date for source to be observed next.
ITIME[1]	m	Reset integrating time to m minutes.
BEGIN[1]	h,m,s	Wait until this LST before executing the next GO,RUN, or CALIBRATE command.
END[1]	h,m,s	Exit from RUN or CAL mode at end of integration in progress at this LST.
TAPE=[1]	n	Reset tape level: 0 = no cor or cal records 1 = cor records 2 = cor & cal records
PRINT=[1]	n	Reset printer level: -1 = no print 0,1,2 = same as tape levels
DELAY=[1]	n	Reset delay offset, no. of delay units
GO		Take one integration
RUN		Take multiple integrations
CALIBRATE		RUN and add data to calibration buffer
ZCAL		Zero the calibration buffer (it is initially zero)
STOP		Exit RUN or CAL mode at end of current integration
ABORT		Terminate data taking immediately; do not record anything
LO[1]	v_1, v_2, v_3, v_4, v_5	Enter LO line length data
GAIN[1]	v_1, v_2, v_3, v_4, v_5	Enter receiver gain data.
COMMENT	text	Enter a comment; 70 characters including the command 'COMMENT', are recorded
POINT		Update the pointing display
CHECK[2]		Display the system status word and record a status record on tape (if tape is in use).
PLOT[2]		Plot integrated brightness on CRT using latest calibrated data
/E		Write EOF on output tape (if any); execute STOP

Notes:
1. If these commands are not given, default values are assumed; see Table II.
2. Not implemented as of 5/30/73.
3. Only the first two characters of each command are significant.
4. Under parameters, h,d,m,s refer to hours, degrees, minutes, and seconds, respectively; n and v_i are numerical values; and 'text' is any character string. All parameters are Hewlett-Packard free-field (see HP Fortran Manual).

TABLE II - DEFAULT PARAMETERS

SOURCE	$12^h\ 00^m\ 00^s$ $0^\circ\ 00'\ 00''$ [NAME=TESTSOURCE]
ITIME	5.0 minutes
BEGIN	0:00:00 LST
END	23:59:59 LST
TAPE	level = 0 (unless "no tape" specified in Initialization Phase)
PRINT	level = 0
LO	0.0 0.0 0.0 0.0 0.0 [LST = 12:00:00]
GAIN	100.0 100.0 100.0 100.0 100.0 [LST = 12:00:00]
DELAY	offset = 0 delay units

TABLE III -- MESSAGES POSSIBLE UNDER NELI

All of these appear on the CRT unless otherwise noted. Those preceded by a + sign here are accompanied by a sounding of the line printer alarm.

Message	Explanation
>>	Ready to accept a command.
+ MORE TAPE!	End-of-tape reached on output file. Load another labeled tape; press SWO when ready. The record being written when the EOT was encountered will be re-written at the beginning of the next available file on the new tape. If the tape label is unreadable, the message is repeated; try again with another tape. Switch 0 is NOT cleared.
+ TAPE ERR	Write error on output tape. Pressing SWO causes another attempt to write the record. Do not load another labeled tape. If the problem recurs, halt the computer, unload the tape and try to determine the cause. If the tape is suspected, re-load NELI using a different tape. Note that the original tape is missing a file mark. Report the problem to the technical staff.
+ PANIC:TIMEOUT	Insufficient time to process a data sample. Probable hardware I/O error. Integration in progress automatically aborted, return to command mode. No data recorded.
+ PANIC:OVERFLO	Data accumulator overflow. Probable excessive integration time. Same action as TIMEOUT.
I'M ALREADY TAKING DATA!	Attempt to issue GO, RUN, CAL, or /E command while integrating.
+ STATUS XXXXXX	Where XXXXXX is the system status word in octal. An alarm condition has been detected while integrating; e.g., a L.O. is out of lock. Data taking is continuing. [Not implemented as of 5/30/73.]
WHAT??	Unrecognized command.
*EQR	(Line printer; computer halted) I/O device error. A-register contains unit number, B-register contains status word. Record memory address at time of halt, then (A) and (B). Re-load address and press RUN to resume execution. Do not press PRESET.
*FMT	(Line printer; computer halted). Format error; (A)= error code. Probable illegal form in parameters field of a command; e.g., two decimal points in a row. See HP Fortran Manual for free-field input rules. If you know that this was the cause of the error, press RUN to resume execution. Otherwise, there may possibly be a program error. Record (A),(B). To be safe, re-load the SRAIOS executive manually, write an EOF on the output tape (if any), and RUN NELI again.

Table III - cont'd

Message	Explanation
LST?	Enter local sidereal time: h,m,[s].
NAME?	Enter source name, up to 10 characters.
TAPE ERROR ON DECK 2; CODE=n	(Initialization phase only) The parameters file could not be read correctly. See p. 2 for further explanation.
BAD TAPE LABEL ON DECK 3	(Initialization phase only) The output tape label was unreadable, either before or after it was re-written. Try again with another tape, or respond "NO" to the next "OUTPUT TAPE?" prompt.

TABLE IV - OUTPUT TAPE FORMAT

Word 1: Type code K

Word 2: Length N in words, excluding checksum

Word 3 thru Word N: dependent on record type

Word N+1: Checksum, sum of all other words (mod 2^{16}).

Rec. Type	K	N	Contents (Fortran Conventions)
Header	1	52	ITEXT(30),DATE,STIME,PST,IWX,IOP,NTAPE,NFILE,KCHAN(10)
Parameters	2	252	PHASE(6,5),POINT(19,5)
Source	3	11	NAME(5),DEC,RA
Data	4	91	FDATA(2,10),DC(10),RMS(10),NSER,T1,NSAMP,MODE,DEC,RA
L.O.	5	14	DATA(5),STIME
Gain	6	14	DATA(5),STIME
Comment	7	37	ITEXT(35)
Status	8	12	ISTAT(10)
Corrected	9	42	FDATA(2,10)
Calibrated	10	85	CDATA(2,10),NINTC,JUNK(2),FDATA(2,10)