Some Considerations
for a
Very Long Baseline Interferometer

AIO - NRAO

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I. Introduction

It is proposed to build a very long baseline interferometer (VLBI) to investigate the structure of radio sources having features with dimensions of the order of 10^{-3} to 10^{-2} seconds of arc. In order to achieve this resolution at convenient radio frequencies, baselines of several thousand kilometers are required. In conventional interferometer systems coaxial cable or radio links are used both to carry the local oscillator signal to provide coherent oscillators at the two elements,and to return the i.f. signal to a common correlator. For baselines of thousands of kilometers, however, the cost of coaxial cable is prohibitive, while the use of existing telephone lines does not provide adequate bandwidth. Microwave radio links could be used, but they are very expensive to operate and difficult to procure. Also little is known about their overall phase stability.

The cost and inconvenience of an elaborate communications link is avoided by operating the individual interferometer elements independently. This can be done by using atomic standards both as local oscillators and as a time reference, and by separately recording the intermediate frequency outputs on high speed magnetic tape. The two magnetic tapes are later brought together, and the two i.f. signals are correlated in a digital computer.

Such a scheme is not a new idea, and has been discussed in rather general terms by several radio astronomy groups. Recently a short article appeared in the Soviet journal <u>Radiophysica</u> <u>8</u>, 651, 1965,(1) which briefly discussed the requirements for this type of interferometer. Although the feasibility of such an arrangement has been realized for some time, it was thought until very recently that all radio sources would be resolved by rather modest baselines of a few hundred thousand wavelengths which could be obtained by using more or less conventional techniques. This conclusion was based on the results of several earlier interferometer studies.

The Nancay(2) and CalTech(3) groups, using baselines of a few thousand wavelengths found that about half of all extragalactic radio sources had dimensions greater than one minute of arc. At the same time workers at Jodrell Bank (4) achieved baselines up to 61,100 wavelengths by using radio links between stations 72 miles apart. The long baseline studies indicated that only one or two percent of the extragalactic radio sources were unresolved at this spacing and it was thought that few sources had structure under one second of arc.

Recently, however, four independent lines of research have indicated that there are a number of sources which have components well under 0″.01. Firstly, the English group have extended their baselines first to 180,000 wavelengths and then to 600,000 wavelengths and have found sources which have components which are unresolved with a resolution of .1 seconds of arc.(5,6) A second piece of evidence comes from studies of scintillations of radio sources in the interplanetary medium. From this work, done at Cambridge(7,8), Arecibo(9), Australia, and in the Soviet Union, it is recognized that, in general, only sources having significant features under one second of arc show scintillations, and that other conditions being equal the scintillation amplitude increases with decreasing angular size. While the sources known to be approximately 0.1 seconds of arc or less are all good scintillators, some scintillate much more readily than others indicating dimensions one or possibly even two orders of magnitude smaller. Thirdly, studies of the intensity of extragalactic radio sources as a function of frequency have disclosed sharp low frequency cut-offs in some of their radio frequency spectra. These cannot be due to simple synchrotron radiation and it is thought that the cut-off is due to synchrotron self-absorption. If this is indeed the case the brightness temperature must be exceedingly high and the corresponding source dimensions must be in the range 0".001 to 0".01. Sources with spectra of this type are generally associated with distant quasi-stellar sources or with very active regions in the nuclei of galaxies. Angular dimensions of 0".001 imply linear sizes of only a few parsecs no matter how distant the source. Finally, the finding of rapid time variations in the radio and optical luminosity of some of the quasi stellar sources in the United States and in the Soviet Union again indicate linear dimensions of only a few parsecs. These very small dimensions are important in that they require exceedingly high densities of relativistic particles, resulting in the radiation of about 10^{45} ergs/sec from a very small volume. Direct confirmation of the existence of such small radio sources is important and investigations with resolutions 0".01 will no doubt play a major role in any attempt to understand the origin and evolution of radio galaxies and quasi stellar sources.

Extension of interferometer baselines using radio links cannot be continued much further. Already the Jodrell Bank-Malvern 21-cm interferometer uses two repeater stations over an 80 mile path, thereby producing a baseline of 600,000 wavelengths. It is likely that in the near future the resolution of this instrument will be doubled by going to 10 centimeter wavelength. Increases beyond this do not seem practical using direct radio links and it is likely that the Jodrell Bank group will also attempt to correlate independent receiver, presumably one in the United Kingdom and one in the USSR.

The system proposed here, once perfected, could be used with already existing radio telescopes, so that it generally would make use of existing instrumentation. Only the accurately controlled local oscillators and the data recording system would need to be transported to the individual installations. The use with the many existing radio telescopes would provide the variety of baselines necessary to obtain a reasonably detailed structure of radio sources, and would ultimately yield resolutions up to 0.001 seconds of arc. Thus, in the fullest sense this would be a national and hopefully eventually an international operation.

II. Proposed System

The system initially proposed would use the NRAO 140-foot telescope at Greenbank, W.Va., together with the 1,000-foot spherical dish at the Cornell University Arecibo Ionospheric Observatory in Puerto Rico. The distance between these two stations is 2600 km, giving a baseline of 5.3×10^6 wavelengths at an operating frequency of 611 megacycles. This would give a fringe spacing of 0".03 and allow the resolution of sources to about 0".01.

Choice of Operating Frequency

The choice of frequency is a compromise between the longer effective baselines obtainable at higher frequencies and the greater signal strength and simplicity of radiometer systems at the low frequencies. 611 Megacycles has been chosen as an initial operating frequency for the following reasons:

a) It is close to the highest frequency at which the Arecibo dish can presently achieve high efficiency, and the dish is presently instrumented to operate at this frequency.

b) A relatively simple radiometer and feed can be constructed for the 140-ft antenna at this frequency.

c) This baseline gives nearly one order of magnitude increase over the highest resolutions currently available.

d) 611 megacycles is in a protected radio astronomy frequency band.

e) Adequate signal-to-noise ratio is achieved with relatively simple receivers for a reasonable sample of sources.

f) At this frequency the combined effect of ionospheric and atmospheric phase fluctuations is adequately low, although a rather higher frequency would be preferred in this respect.

It is hoped that in perhaps one year the 1000 ft dish may be usable at 20 cm at which time the system could readily be adapted to this frequency. This would give a factor of 2.5 increase in resolution. Twenty centimeters is a logical choice for the second stage of operation, since NRAO, and many other observatories, already have low noise systems operating at this frequency. High frequency operation is desirable as there is growing evidence that at centimeter wavelengths many sources contain fine structure not detectable at longer wavelengths.

Local Oscillator System

The independent local oscillators will be derived from atomic standards. Rubidium and cesium controlled crystal oscillators are available for 10 or 15 thousand dollars. They give a stability of one part in 10^{11} over a one week period. The output of these units are at radio frequencies which can readily be multiplied up to the desired operating frequency.

It should be stressed that there will be no intent to recover any phase information from the interferometer. In order to measure the angular extent of the source, it is sufficient to measure the amplitude of the fringe visibility alone. Thus, only sufficient phase stability is needed to maintain coherence. It appears that the short term stability of the oscillators may be good enough for several minutes of coherent integration.

Time Keeping

If the i.f. bandwidth is 300 kilocycles, it will be necessary to have the times at the two observatories synchronized to better than one microsecond. This can be achieved by using the atomic standards used to derive the LO frequency, since these can provide a time reference which drifts by only about 1 microsecond per day. Once the time difference between the two clocks is established, [illegible], any subsequent small drift may be determined directly from the astronomical measurements. This is discussed further below.

Radiometer Systems

The AIO 611 Mc/s feed illuminates 600 feet of the dish. Thus, the AIO-NRAO combination is equivalent to using 290 ft antennas. This gives a sensitivity of about 1.2 degrees antenna temperature per flux unit. The Arecibo Ionospheric Observatory is currently instrumented at 611 megacycles, with a parametric amplifier. NRAO has no facilities for 611 Mc/s, but a simple feed and crystal mixer receiver could easily be constructed. A parametric amplifier would give about a factor of two increase in the signal to noise at the NRAO and about $\sqrt{2}$ increase in the interferometer sensitivity. It is not clear if this is worth the trouble. With a system temperature of 300 degrees and an i.f. bandwidth of 300 kilocycles, RMS noise fluctuations will be equivalent to about 1.2 flux units in a one second integration period. Thus with integration times of the order of one minute we should be able to detect quite a number of sources even if they are significantly resolved.

Existing radiometer systems will have to be modified for the interferometer. Second conversion to bring the pass band down to, say, 0 to 300 kc is necessary to obtain reasonable sampling rates. Carefully tailored filters will be necessary to ensure that there is no aliasing, and the bands received at the two stations are essentially identical.

Calibration

No attempt will be made to directly calibrate the fringe visibility. Instead the relative intensities of the fringe amplitude of sources suspected to be unresolved will be compared with their known flux densities at zero spacing. Those showing the same relative intensities at the two spacings may be assumed to be unresolved. Some check is provided by checking sources to see if the fringe amplitude remains constant with hour angle. However, due to the limited motion of the Arecibo dish, this is not a very sensitive test.

In the unlikely event that there are no unresolved sources at this spacing, a rough absolute calibration may be achieved by the measurement of the ratios of the source antenna temperatures to the receiver temperatures and multiplying this factor times the absolute correlation coefficient to obtain the flux corresponding to the observed fringes. This technique is probably much less accurate than the method of ratios, but may be resorted to in case of need.

Preliminary Tests

The two local oscillators must be tested to find their mutual coherence time. This is most simply done in Ithaca, using the polarimeter at the Danby Radio Observatory.

The data reduction system must also be thoroughly tested before long baseline operation is attempted. If two complete data processing systems are available at NRAO, it would be useful to test the complete operation using the existing NRAO interferometer. However, since AIO already has such equipment, it may be expedient to organize only one such set of data processing equipment. Operation of the system may then be simulated by generating two magnetic tapes with identical random numbers and independent noises.

III. Atmospheric and Propagation Effects

Rays to the ends of the interferometer will propagate through independent columns of the atmosphere. Differential behavior in the two columns may cause a loss in coherence. The major effects are propagation time, refraction, and Faraday rotation.

A differential propagation time, $\Delta\tau$, will destroy the coherence between the two rays if it is greater than the reciprocal bandwidth. If $\Delta\tau$ is constant the coherence can be restored *ex post facto* by adjusting the zero of time in the computing process. An unknown (but constant) $\Delta\tau$ could be found by having the computer search for maximum coherence. However, if $\Delta\tau$ varies in a time comparable to the observing time, the coherence cannot be restored in any easy manner.

Differential refraction will give a differential propagation time, and the considerations are the same as above.

Differential Faraday rotation will bring some of the incoherent perpendicular component into one of the antennas. If $\Delta\phi$ is the differential rotation, the coherence is reduced by $\cos \Delta\phi$. The coherence cannot be restored in the computing process. The effect can be eliminated, however, by using circularly polarized antennas, or by adjusting the position angles of the linear antennas to take account of $\Delta\phi$, if it is known in advance.

Interplanetary scintillations will only introduce noise into a phase-coherent interferometer. They would, however, directly reduce the measurable coherence in an intensity interferometer, although their effect could be eliminated by appropriate filters.

The general conclusions are:

1) Night-time observations, with a 100 kc band, will be unaffected by the atmosphere, at 611 Mc/s.

2) Daytime observations will be difficult, because of Faraday Rotation.

3) Observations at sunrise and sunset will probably be impossible.

4) A 1 Mc/s band may occasionally show some loss of coherence in the day, but rarely or never at night.

a. Propagation time, troposphere

In a distance z the departure of the propagation time from that given by the velocity of light is $\tau = z(n-1)/c$ where n is the index of refraction. Taking $(n-1) = 3 \times 10^{-4}$ and $z = 10$ km gives $\tau = 10^{-8}$ sec. Random variations in τ will become serious only when the bandwidth is in excess of 10 Mc/s, which value is much greater than any contemplated for the VLBI. A heavy rainfall, which might correspond to a filled one-millimeter layer of liquid water, gives $\tau \sim 3 \times 10^{-9}$ sec, which is negligible. Heavy rainfall, however, is usually accompanied by heavy lightning (at Arecibo) and the extra noise that would give makes it advisable not to observe at such times.

b. Propagation time, ionosphere

The appropriate formula for excess propagation time in the ionosphere is $\tau = 27 \times 10^{-4} (zN) f^{-2}$, where (zN) is the number of electrons in a one square-cm column, and f is the observing frequency in cps. For $f = 6.11 \times 10^{8}$ and $(zN) = 5 \times 10^{13}$ (a typical number for the daytime ionosphere, looking vertically(10)), $\tau \sim 4 \times 10^{-7}$ sec. If oblique propagation is allowed for, τ might be nearly one microsecond in the day, and one-tenth microsecond at night. The electron content is very variable, so differential propagation times of this order must be expected.

Rapid changes in the ionosphere are known to occur at sunrise and sunset, and during times of disturbances. It appears that the coherence in a 100 kc band would not be affected. A 1 Mc/s band would not be affected in the middle of the night, but should be used at other times only when the ionosphere is stable over both locations.

c. Refraction

The above estimates for excess propagation time assume that there is no refraction. In fact, there will be a substantial differential refraction, since the two stations are 23° apart on the earth's surface. When AIO looks at zenith angle $\zeta = 20^{\circ}$ to the southeast, NRAO will be at $\zeta = 43^{\circ}$. The maximum differential refraction due to the troposphere will be about $0\overset{\prime}{.}5$. The ionospheric refraction, at $\zeta = 43^{\circ}$, will be on the order of seconds of arc normally, but it also will be variable, and might be $10''$ or more at a time of rapid change, such as sunrise, when there are strong horizontal gradients.

The effect of refraction is to make the path longer, and change the propagation time. The tropospheric refraction takes place near the bottom of the atmosphere, and has a negligible effect. A refraction of $10''$ at 500 km would add about 0.4 microseconds to the propagation time.

Refraction normally changes very little in an observing period, so its effects, even if large, could generally be removed *ex post facto*, by appropriate processing. The unusually large refractions will also occur on a short time scale. They will hardly ever affect the coherence in a 100 kc band, but might occasionally do so in a 1 Mc/s band, at the highest zenith angles.

d. Faraday Rotation

The appropriate formula for Faraday rotation is $\phi = 2.4 \times 10^4 B_z (zN) f^{-2}$ with B_z in gauss and the other quantities as above. Since B_z changes slowly with azimuth and elevation (for the limited range available at AIO), differential Faraday rotation is proportional to differential propagation time. Assume $B_z = 0.4$, $(zN) = 5 \cdot 10^{13}$, and $f = 6.11 \times 10^8$; this gives $\phi \approx 1.3$ radians as a typical daytime value at the zenith; and ϕ might get to 1.8 radians at the highest zenith angles. There would be a variable fraction also, which would approach unity at sunrise, sunset, and at times of disturbances.

The linearly polarized antenna at AIO is fixed on the carriage house, so that its position angle changes continuously as the az-el drive moves. The NRAO antenna (equatorially mounted) will have to be programmed to be parallel with the AIO feed. It would be possible to compute a "normal differential Faraday rotation" and program the NRAO antenna to remove it. This would be a maximum of about 35°. If this correction were itself correct to 50%, the residual daytime errors would be no more than about 15°. This is an acceptable value, since the coherence is reduced only by the cosine of the error angle.

It is doubtful that sunrise and sunset effects could be computed closely enough that such a correction scheme could be used. Very large errors might also be introduced during disturbances.

In the middle of the night the electron content is reduced from the daytime value by a factor of 5 to 10. The differential

Faraday rotation would be less than 10°, and could be ignored.

Faraday rotation decoherence effects can be eliminated by using circularly polarized antennas. This, however, would be extremely difficult at AIO and it appears that a linear antenna must be used there. If a linear antenna is used at AIO and a circular antenna at NRAO, the coherence will be reudced by $1/\sqrt{2}$. The observing and processing times would have to be increased by 2.

Faraday rotation appears to severely limit daytime observations, unless one or two circularly polarized antennas are used, or unless the first-order effect is removed by programming the position angle of one of the antennas.

e. Interplanetary scintillation

All sources which will be studied by the interferometer will also display interplanetary scintillations when the source is close enough to the sun. For example, CTA-21 has relative rms fluctuations of 10% at an elongation of 35°, at 611 MHz. It is thought that these scintillations will be independent at the two stations. Their effect will be to add noise to the measurement, and so observations close to the sun should be avoided.

The scintillations are indicative of irregularities in the outer corona. Since the first Fresnel zones at 1 A.U. are only 270 km in diameter, the rays are essentially independent. The coronal irregularities are thought to be of scale less than the interferometer baseline (2600 km) so that there is the possibility of a differential propagation time in the corona. As long as the scintillations are weak, however, this effect will be negligible. For, if the differential propagation time through independent irregularities were as much as one rf period, the scintillations would be strong, not weak.

IV. Data Output

The i.f. output of the individual radiometers may be recorded in one of three different forms: as a direct analogue tape recording, as the output of an A/D converter operating at twice the bandwidth, or as the output of a clipper recorded as digital bits (essentially the output of a one bit A/D converter).

In all of these methods the basic difficulty is synchronization. In order that not too large an area of tape be searched to find the necessary delay setting, the absolute synchronization of the clocks must be known to an accuracy of a few tens of times the reciprocal of the i.f. bandwidth. In order that this necessarily time consuming search need not be repeated for every observation, the clocks, once synchronized for the day, should remain synchronized to an accuracy of one or two times the reciprocal i.f. bandpass for the few hours that may pass between the observation of unresolved sources.

Let us consider the analogue method of recording the i.f. signals. Then, when the signals are brought to a central point for correlation, there are two ways to proceed: the signals may be processed in a machine constructed especially for this purpose, or they may be immediately converted by an A/D converter and then processed digitally. In the latter case, the considerations are much the same as in the case of direct digital recording, and will be considered together with that case. In either case the output of the master clock would be recorded on the tape along with the i.f. information to supply the synchronization.

Let us consider the requirements of a device to perform the first correlation of the tapes from an interferometer operating at 600 Mc/s between Green Bank and Arecibo. Firstly, the synchronization must be accurate to a fraction of the reciprocal bandwidth. If no variable delay buffer (a difficult feat, especially for analogue signals) is provided, then one tape drive must be slaved to the other. It is unlikely that this slaving can be achieved to better than a degree or so of capstan revolution, about 20 microseconds at 150 ips. This imposes an upper limit of about 30 kc/s bandwidth, so that it may not be possible to utilize the full bandwidth inherent in the recorder.

Even given an electronic "signal stretcher," this correlating device must have several other features that are difficult to obtain. Firstly, the delays must be variable between the two tapes at intervals (depending on the bandwidth) of a few seconds in order to keep the correlator in the "white light" fringe of the interferometer. Secondly, it must have an output every millisecond in order to avoid smearing the fringes, or else have built in a device which phase detects the fringes. These functions are sufficiently complicated that it would seem most profitable to have this correlator controlled by and linked to a small stored program digital computer. This special correlator would appear to be a sufficiently complicated device that it would be cheaper and easier, at least in this first attempt, to do the correlating in a large general purpose digital computer.

Doing the correlation in a digital computer consumes a great deal of computing time. (Perhaps much more computer time than telescope time.) With this thought in mind, the experiment should be designed to require a minimum of computation, which is to say that the maximum amount of information be placed in each number that the computer must process. It is known that about half of the information in a noise-like signal is contained in the first bit, so that a one-bit correlator recovers all the correlation with a degradation in signal to noise ratio of $\pi/2$ at the advantage of handling a much smaller number of bits than any other procedure.

If the one-bit conversion is done before recording, it also solves some of the difficulties in the recording. The master clock may drive a shift register so that each bit comes from a precisely defined interval, and if the tape unit is controlled from a slower output of the master clock, it may be started at a given clock time. Further, if a standard digital recorder is used as the tape recorder, the tapes may be fed directly into the general purpose digital computer for processing with no further ado. This appears to require a minimum of equipment in terms of A/D conversion in the tape controller.

Bandwidth and Sampling Considerations

The number of bits of data required to detect a given source is independent of the bandwidth used and is $\gamma\left(\frac{T_a}{T_r}\right)^2$ where T_a and T_r are the antenna temperature of the source and the receiver temperature, respectively, and γ is a numerical coefficient of order 10 depending on the certainty required in the detection and the degree of correlation between adjacent bits. Since the computer processing and the physical length of the tapes are the controlling factors in the processing rather than the telescope time required, The bandwidths are determined by considerations other than the required signal to noise ratio. Firstly, there is a maximum bandwidth set by the maximum speed of commercially available recorders. The fastest tape drives now on the market operate at a rate of 1.2×10^5 6-bit words per second, or 7.2×10^5 bits per second. On the other hand, we would like the maximum integration time to be shorter than the time in which any system parameter may change appreciably. The local oscillator coherence time may be on the order of minutes. The time during which the phase path through the ionosphere may change significantly is also of the same order. Since a 2,400 foot reel of tape, holding 1.2×10^8 bits, would last about 3 minutes at the rate of 7.2×10^5 bits per second, this seems to be the optimum bit recording rate.

Let us, then, assume that the recording rate will be 7.2×10^5 bits per second. The corresponding maximum bandwidth is 360 kc. This is about as high as would be desirable, in terms of coherence loss due to ionospheric effects. Another consideration is that the varying delay should be able to be handled by shifting the two records relative to each other by an integral number of bits, else a time-consuming interpolation will have to be done. In the worst possible case the delays are off by half a sampling period, $\Delta t/2$, and there will be a frequency-dependent phase error. If the bandpass is square, from 0 to B cps, then the loss in coherence is

$$(2\pi B)^{-1} \quad \cos\ (\omega\Delta t/2)d\omega = \frac{\sin\ \pi B\Delta t}{\pi B\Delta t} \ .$$

If this factor is to be held to a minimum of 0.8, then $B \quad 0.36/\Delta t = 260$ kc. Since the alignment error will be random, the average loss in coherence over many delays will be smaller than 0.8. This appears to be a tolerable situation, so that, for most sources, we assume B 260 kc.

The logic feeding the tape recorder would have to perform one more function, the generation of inter-record gaps. It would be desirable to break the records into blocks of about 100,000 bits to facilitate machine processing. In order to playback these blocks the digital computer requires a minimum tape gap of 3/4" (= 5 miliseconds), so that these gaps must be inserted in the records. This function could be performed by the computer, but can be done more easily with only a small modification to the commercial tape unit, to allow suppression of the parity bit to write blank tape.

V. Data Processing

AIO has a CDC 3200 computer. By the time this system is put together NRAO will probably have an IBM 360/50 computer. Both of these appear to be equivalent in terms of the processing times for the VLBI records. There are three basic operations to be performed by the computer: the shifting to set the delays to the white light fringe, the bit-by-bit correlation, and the rectification and integration of the fringe pattern. The fringe rectification may be done before or after the correlation, by complementing the output of one i.f. for half a cycle of the fringe before correlation, or by multiplication by a sine wave after the i.f.'s have been correlated and accumulated for about a millisecond. It is probably slightly more efficient to do the rectification after the correlation, but this can be looked into in more detail when the actual programming is to be done.

In any event, it appears likely that the computation of the amounts of the shifts and the shifting operations will take the order of 1 microsecond per bit. The actual multiplication is simply an "exclusive or" and takes very little time to perform. The accumulation is probably most efficiently done by a table lookup to find the sums of 12 or 16 (depending on the machine) bits, and then adding to accumulate these sums. This can also be done in about 1 microsecond per bit. The rectification of the fringes and miscellaneous housekeeping will probably add another microsecond per bit, so that the total processing time is about 3 microseconds per bit per pass. This must be repeated for at least two different delay settings to check the synchronization of the clocks, so at the end the total computer processing time may amount to an average of 10 microseconds per bit, or about 7 times the telescope time.

The synchronization of the clocks may be done by observing a strong unresolved or partially resolved source. It seems likely that unresolved sources with an antenna temperature of $\frac{1}{30} T_r$ are to be expected. Such sources can be detected with about 10^5 bits. With only 10^5 bits, a complete correlation can be done in only a few tenths of a second, so that by monitoring such sources the clock synchronization can be continuously updated.

Moreover, because of the small amount of computing time per pass for such sources, the initial synchronization can be established by making a number of passes each with a different delay. In this manner a timing error of 5 milliseconds, as may be found from observations of WWVL or Loran C, can be tolerated.

References.

1. Matveenko, L.I., Kardasher, N.W. and Sholomitskii, G.B., Radiophysika 8, 651 (1965).
2. Joshi, M., Ann. d'Ast. 25, 377 (1962).
3. Maltby, P. and Moffet, A.T., Ap. J. Supp. 7, 141 (1962).
4. Allen, L.R., Anderson, B., Conway, R.G., Palmer, H.P., Reddish, V.C., and Rowson, B., M.N. 124, 477 (1962).
5. Anderson, B., Donaldson, W., Palmer, H.P. and Rowson, B., Nature 205, 375 (1965).

6. Anderson *et al*, in press.

7. Lawrence, R.S., Posakony, D.J., Garriott, O.K., and Hall, S.C., J.G.R. *68*, 1889 (1963).

8. Hewish, A., Scott, P.F., and Wills, D., Nature *203*. ;2;4 (1964).

9. Hewish, A., and Okoye, S.E., Nature *207*, 59 (1965).

10. Cohen, M.H., Nature *208*,