7-1970

Determination of the Time Delay in the Arrival of Jovian Signals at Opposite Ends of a Long Baseline Fringe Synthesis Interferometer

Roger Scott
Western Kentucky University

Scott,

Roger L.

1970

DETERMINATION OF THE TIME DELAY IN THE ARRIVAL

OF JOVIAN SIGNALS AT OPPOSITE ENDS OF A LONG

BASELINE FRINGE SYNTHESIS INTERFEROMETER

A Thesis

Presented to

the Faculty of the Department of Physics and Astronomy

Western Kentucky University

Bowling Green, Kentucky

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Roger L. Scott

July 1970

DETERMINATION OF THE TIME DELAY IN THE ARRIVAL

OF JOVIAN SIGNALS AT OPPOSITE ENDS OF A LONG

BASELINE FRINGE SYNTHESIS INTERFEROMETER

APPROVED ___7- 31 -1970_____ :

(Date)

Committee

_____, Chairman

_____

_____

Dean of the Graduate College

ACKNOWLEDGEMENT

TABLE OF CONTENTS

Appendix   Page

v

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

In early 1955 while testing a large radio interferometer of the "Mill Cross" design near Washington, D. C., K. L. Franklin and B. F. Burke discovered that the planet Jupiter was the source of powerful radio waves. Strange signals had been received which at first were thought to be terrestrial interference. However, the signals returned each day at about the same sidereal time. This indicated a celestial source. Amazingly, the positions of the source coincided with the positions of Jupiter. The interference was never received unless Jupiter was in the principle beam of the Mills Cross antenna. (1)

Since 1955, Jupiter has been the object of intense study. Burke and Franklin had been working at a frequency of 22.2 MHz. Other observers have received radiation from Jupiter over much of the short wave radio spectrum and have also detected microwave emission. Undoubtedly some of the microwave emission is of purely thermal origin; however, the microwave spectrum does not fall off as the inverse square of the wavelength as is characteristic of a blackbody radiator. (2) In contrast, the flux density of the Jovian microwave emission remains relatively

constant over a wavelength range of 20 to 1 as shown in

Figure 1. A possible explanation for the enhanced microwave

emission is that it is the composite radiation from two or

more sources. One of these components is believed to be pure-

ly thermal. The other component is probably synchrotron radi-

ation from electrons trapped in Jupiter's magnetic field. The

observations of Radhakrishnan, Roberts, and Morris, [4] of the Cali-

fornia Institure of Technology, demonstrated that much of the

microwave emission is coming from a halo surrounding the planet.

The origin of the Jovian decameter wavelength bursts is

more difficult to explain. The radiation is very intense over

short periods of time. Pulses have been received at a frequency

of 5 MHz which rival the strongest solar bursts whose flux den-

sity is about 10^{-18} W/M^2/Hz. [3] Since even at its closest approach

(opposition), Jupiter is approximately 4 times as far away as

the sun, some Jovian signals must be about 16 times stronger

than those from the sun. However, as Figure 1 demonstrates,

the flux density of the Jovian decametric radiation falls off

rapidly with increasing wavelength. At a frequency of 18 MHz,

the flux density of the strongest Jovian bursts is about 10^{-19}

W/M^2/Hz. [3] Unlike the enhanced microwave region, the apparent

decametric source size is considerably smaller than the disk

of the planet. Earlier studies suggested the existance of

three active longitude regions on the planet. Recent measure-

ments indicate source sizes as small as .72 seconds of arc. [5]
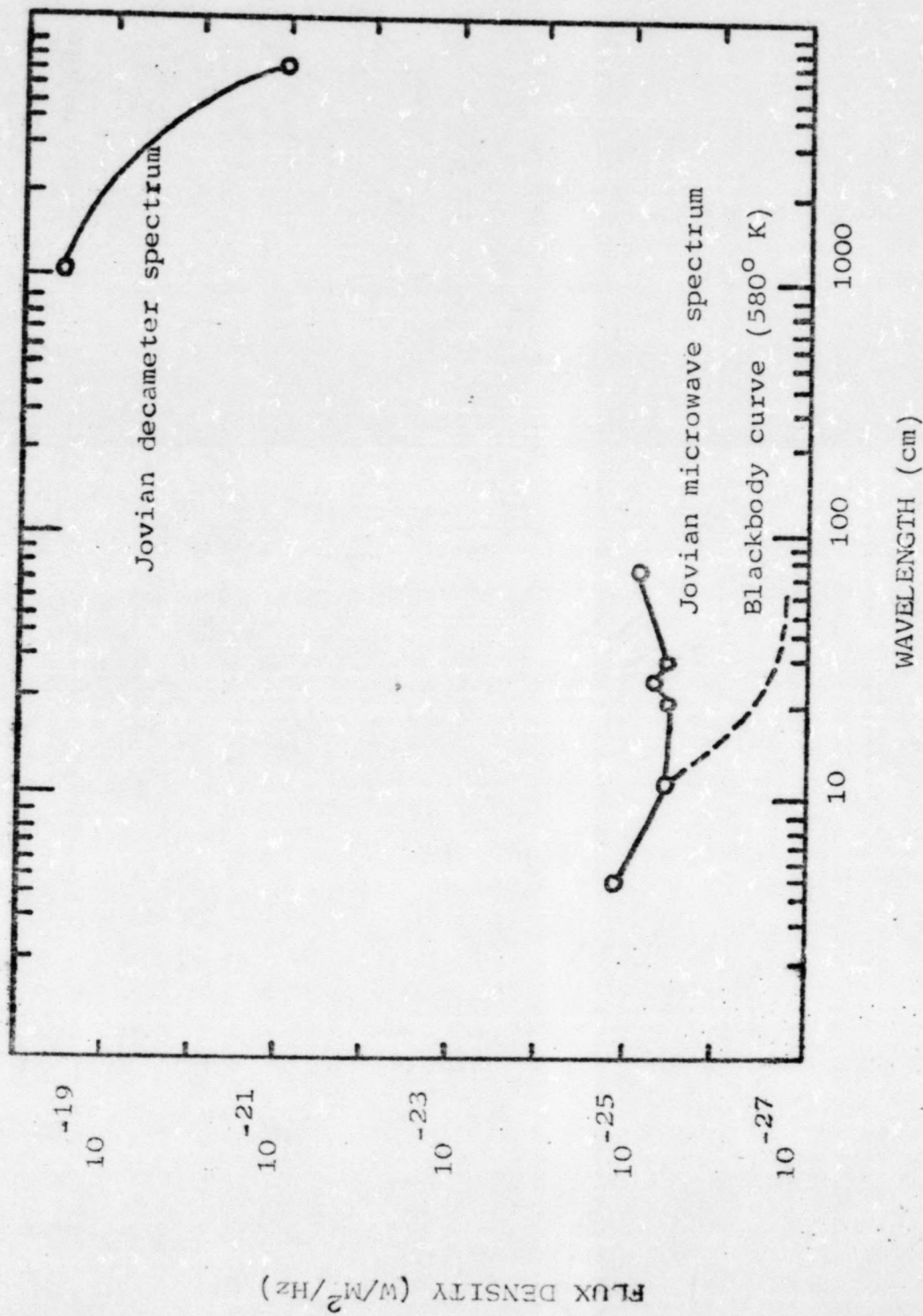
Figure 1 - Jovian microwave and decametric emission as a function of wavelength.

(2, 3)

This corresponds to a linear dimension on Jupiter of 1100 km
which is less than one percent of the equatorial diameter of
approximately 139,500 km.

In 1958, T. D. Carr suggested that cyclotron radiation
from electrons spiraling in a Jovian magnetic field might be
(6)
the mechanism responsible for the long-wave radiation. J. W.
Warwick suggested the bursts might be Cerenkov radiation pro-
duced when electrons jump from Jupiter's radiation belts into
(7)
the atmosphere. However, the resulting emission would most
probably be directed at the Jovian surface. If this theory
is correct, the radiation would have to undergo reflection to
be directed toward earth. Goldreich and Lynden-Bell have ad-
vanced the hypothesis that Io, in cutting through Jupiter's
magnetic field as it revolves in its orbit, constitutes a
(8)
Jovian unipolar inductor. According to this theory, Io is
assumed to revolve in a circular orbit with one face toward
Jupiter allowing the Jovian magnetic field to penetrate the
satellite. Assuming that Io is a fairly good conductor, com-
parable to the earth's upper mantle, the electric field would
vanish inside the tube of magnetic flux that passes through it.
This would freeze the plasma contained in the tube to Io and as
Jupiter rotates, the two feet of the flux tube, where it inter-
sects Jupiter will slip relative to the Jovian surface. This
will induce a voltage in each foot of the flux tube driving a
current down one side of the tube and up the other, the current

being completed by Io and the Jovian ionosphere. The

decametric bursts are explained as cyclotron radiation pro-

duced by instabilities in the above system.

There does seem to be a relationship between the

probability of receiving Jovian emission and solar activity.

Jovian noise storms have been observed to occur several days
(9)
after a period of intense solar decameter activity. Solar de-

cameter radiation is thought to be associated with activity

which leads to the ejection of charged particles. This sug-

gests the possibility that the mechanism producing the Jovian

decameter bursts might be triggered by particles emitted by

the sun. The long term effect is quite different. Figure 2

shows the relationship between sunspot number and the proba-

bility of receiving Jovian emissions. There now appears to
(3, 10)
be a negative correlation between solar and Jovian activity.

A possible explanation is that when solar activity is high,

interplanetary space is filled with plasma which prevents
(10)
solar electrons and protons from reaching Jupiter. However,

Jupiter's sidereal period is almost identical with the sun-

spot cycle. It has been suggested that the regular varia-

tions in the Jovian emission might be related to the planet's

position in its orbit relative to earth and not to solar

activity.

There is also a relation between the relative positions

of Io, earth, and Jupiter, and the probability of receiving
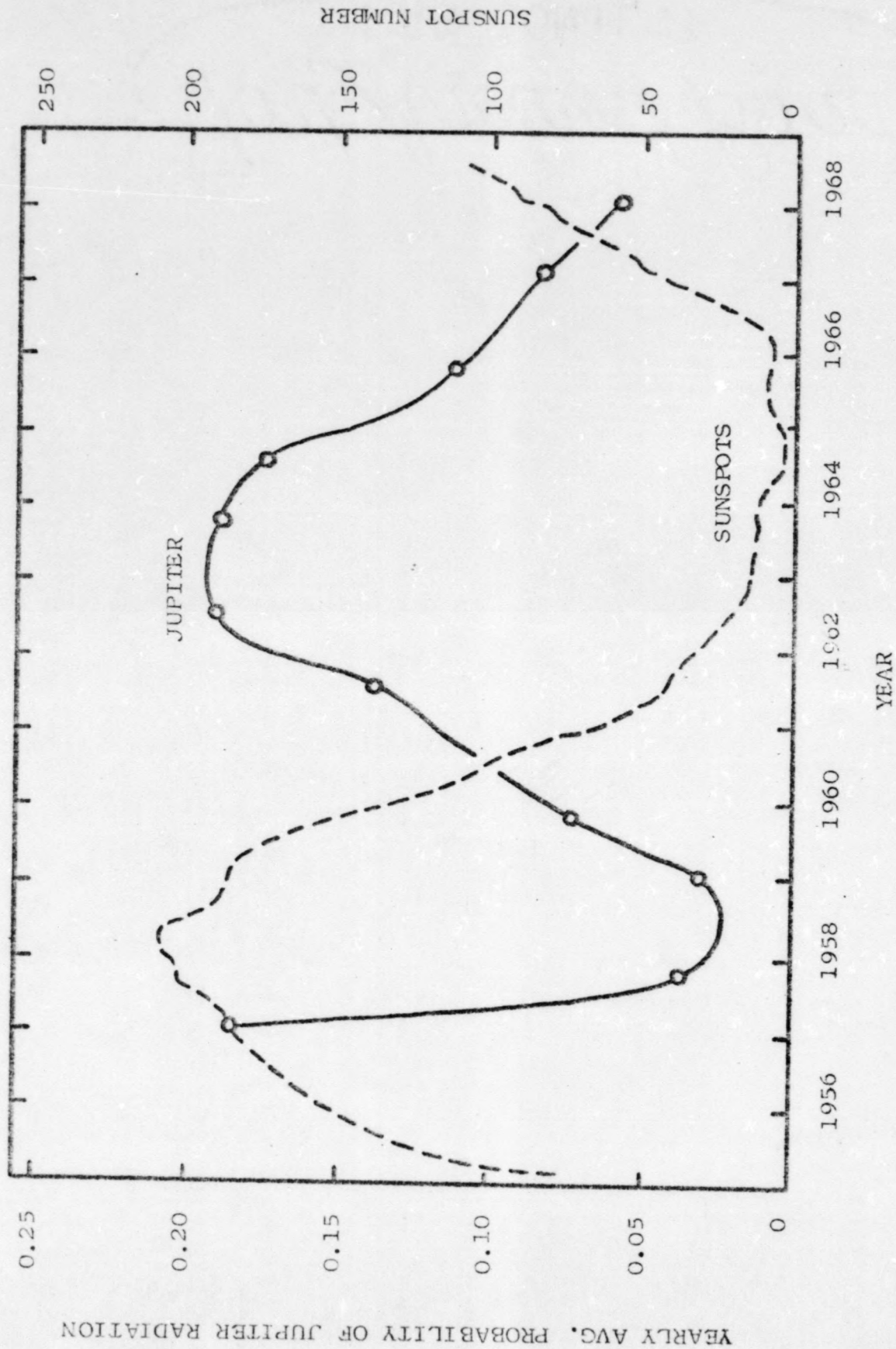
Figure 2 - The inverse relationship between sunspots and the average probability of receiving Jovian radio emission (3, 10).

emissions. Figure 3 is a polar diagram of the decameter sources drawn by radio astronomers at the University of Florida. According to the diagram, the probability of receiving emissions should increase when one of the sources is pointed toward earth. This is not the case. Often, no signals are received, even when a source is "pointed" directly at the observer. In 1964, the Australian statistician E. K. Bigg showed that the position of Io in its orbit was directly related to the probability of receiving emissions. (11) When Io is 90° from the point directly behind Jupiter as seen from earth (superior conjunction), source B is activated, and when the satellite is 240° from superior conjunction, sources A and C tend to radiate. Source A also emits radiation that is apparently unrelated to Io's position. Io's position seems to influence the emission of sources B and C to a much greater degree than that of source A.

In order to determine the size of the decametric sources, the technique of long baseline radio interferometry is being employed. The University of Florida at Gainesville is a pioneer in this field. In 1964, T. D. Carr introduced the procedure of recording the signals received at each end of an interferometer on magnetic tape and comparing the recorded signals at a later time. (12) This eliminated the necessity for transmission lines over the length of the baseline, allowing greater separation to attain higher resolution.

FLORIDA, 18 MHz

Source A

Source B

180°

90° — Jupiter — 270°

0°
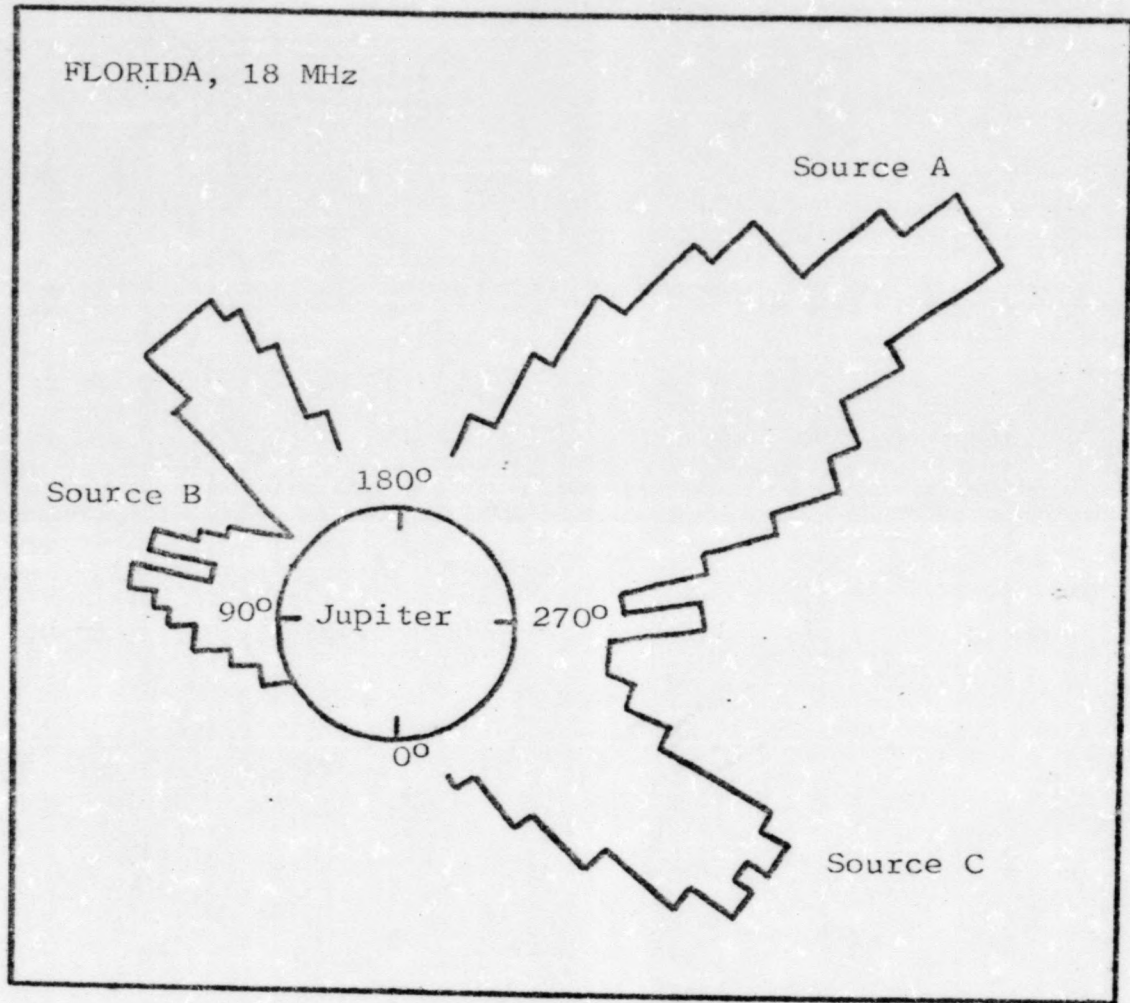
Source C

Figure 3 - A polar diagram of Jupiter's short
wave radio sources. The radial coordinate is
the probability of receiving Jovian emission [10].
(Longitude system III)

Prior to 1968, the interferometer used by the Florida group was the 218 km baseline between the University of Florida Radio Observatory in Old Town and the Florida Presbyterian College Observatory in St. Petersburg.

In August of 1967, the University of Florida undertook a joint project with Western Kentucky University in Bowling Green to construct another interferometer to be used primarily in the investigation of the size of the decameter sources. The south element of the interferometer was located 50 miles from the University of Florida near Old Town, Florida, and the north element was placed about 10 miles from Bowling Green near Alvaton, Kentucky. This gave an effective baseline of 880 km $(52,800 \lambda)$. The Kentucky observatory was completed late in 1967 and was in operation for the 1968 apparition of Jupiter. Data was recorded in the frequency band between 17.9976 and 17.9997 MHz during both the 1968 and 1969 observing seasons. The Western Kentucky University Radio Observatory was seriously damaged in a flash flood on June 23, 1969, and is presently being rebuilt at a new location. During the 1971 apparition, efforts will be made to detect Jupiter pulses at opposite ends of a 7040 km baseline interferometer extending from Maipu, Chile, to Bowling Green, Kentucky. The determination of the size of the emitting regions at Jupiter should make it possible to decide which theory best describes the complex mechanism producing the intense decameter radiation.

CHAPTER II

DETERMINATION OF THE TIME DELAY AT OPPOSITE
ENDS OF A FRINGE SYNTHESIS INTERFEROMETER

In the 15 years since Burke and Franklin made their momentous discovery, many clues have been discovered about the Jovian decametric radiation. The probability of receiving radiation at earth is determined in part by the longitudes on Jupiter facing the earth and by the position of the satellite Io. Also important has been the determination of the radiation's dynamic spectra, polarization, pulse duration, and apparent anticorrelation with the sunspot cycle. However, the source size (angular extent of the sources) has not been determined. As stated in Chapter I, recent measurements indicate source diameters as small as .72 arc sec. The average source diameter yielded by these measurements is 1.33 arc sec or about 1/34 the angular diameter of Jupiter at the time of observation.[5] The average value is probably an upper limit to source size since scattering in the interplanetary medium may cause an apparent broadening of the sources and Faraday rotation may cause a loss of correlation in the signals received by the interferometer elements.[5] The exact sizes of the decameter sources are still unknown and if they could be determined, still another clue could be added to the list needed to solve

the basic problem confronting radio astronomers - understanding the mechanism which is responsible for the intense bursts of decameter wavelength radiation originating at Jupiter.

Special techniques are employed to determine the sizes of the decameter sources. Because of the wave nature of electromagnetic radiation, the "image" of a point radio source formed by a large dish type antenna is really a diffraction pattern analogous to the image of a star formed by an optical telescope. The central maximum of this pattern is of width λ/D radians, where λ is the wavelength of the radiation being received and D is the effective width of the antenna. (3) Two small sources will appear as a single source if their angular separation is significantly less than λ/D, and they cannot be resolved. Because of the long wavelengths used in radio astronomy, the resolving power of a single antenna could never equal that of an optical telescope unless its effective width was perhaps hundreds or thousands of miles. While it is impossible to construct an antenna this large at the present, resolution comparable to that obtained with optical instruments can be produced by the method of radio interferometry. Instead of one large antenna, two or more antennas are used to receive different parts of the same wave front generated at the source. If the two signals received by the antenna elements are combined, a high degree of resolution is obtained. The effective width D of the interferometer is the distance between the

elements and is commonly referred to as the "baseline". The
resolving power of such an interferometer is the same as that
of a giant antenna of effective width D, but the gain is much
less. If a source is equidistant from the antenna elements
and the propagation delays are negligible, then a given wave
front will arrive at each element simultaneously. The com-
bined signal contains information relating to source size. If
the elements are widly separated, transmission lines over the
length of the baseline are impractical. One method of circum-
venting this problem is to record the signals received by each
(12)
element on magnetic tape. If accurate time information is
placed on the tapes along with the Jovian noise, the signals
may be combined at a later time. Propagation delays and path
differences upset the simultaneous arrival of different parts
of the same wave front at each antenna and correction for each
must be made in aligning the signals in real time. This tape
recording interferometry technique is being used at the Univer-
sity of Florida and Western Kentucky University in an attempt
to determine the sizes of the decameter sources. Prior to 1969,
signals were recorded at each observing station on a dual track
magnetic tape recorder, with WWV absolute time references inter-
rupting the Jovian noise track at regular intervals. A local
oscillator provided a continuous time reference on a second
track. The local oscillator pulses were converted to absolute
time by aligning them with the WWV pulses. In this manner

simultaneity was established at each station and the separate signals were combined to produce an interference pattern.

However, when such factors as the geometric path difference, the signal delay in each station's receiver, and the propagation delay of the WWV signals to each station were taken into account, correlated parts of the same pulse on each observatory's tape were apparently shifted in time. If the time shift was real, it indicated that the pulses were actually arriving earlier at one end of the interferometer. (13)

The use of WWV as an absolute time reference was recognized as a probable source of error. These timing signals on the 5 MHz or 10 MHz carrier would arrive at each end of the interferometer as skywaves. Variation in the height of the reflecting layer in the ionosphere made it difficult to determine the propagation delay accurately. The apparent time delay which was on the order of a millisecond or less, could result from uncertainty in the propagation delay. To determine if this condition was introducing a timing error, the signal from a Loran C station was placed on the Jovian noise track immediately following the WWV signal. This procedure was initiated at the beginning of the 1969 apparition. The Loran C signals (100 kHz) are received primarily as groundwaves due to their frequency and the proximity of a transmitter to each end of the interferometer. The propagation paths to the ends of the baseline and thus the propagation delays can be accurately

determined. The use of both WWV and Loran C as absolute time references, results in a more accurate time alignment. The outcome of such an investigation using an 880 km baseline is the subject of this paper.

2.1. A Brief Description of the Florida-Kentucky Interferometer. The south element of the interferometer was located at the already extensive radio observatory operated by the University of Florida. The north element, operated by Western Kentucky University, was the first radio observatory established in Kentucky. See Figure 4.

A 21 acre field near Alvaton, Kentucky, was selected for the location of the Kentucky observatory. The primary reason for the selection was a range of low hills lying between the proposed location and the city of Bowling Green. Because of their location, the hills would shield the antenna from man-made interference. Also the flatness of the land made it suitable for the future construction of large antenna arrays. Trammel Creek, lying about 4 to 8 feet below the level of the rich bottom land, formed the south boundary of the field. No trouble was expected from the creek except an annual flood of a foot or two when the spring rains came.

The probability of reception of Jovian pulses falls off rapidly above 20 MHz and the earth's ionosphere acts as an opaque mirror for low frequency signals, blocking incoming radiation and reflecting terrestrial static and radio signals
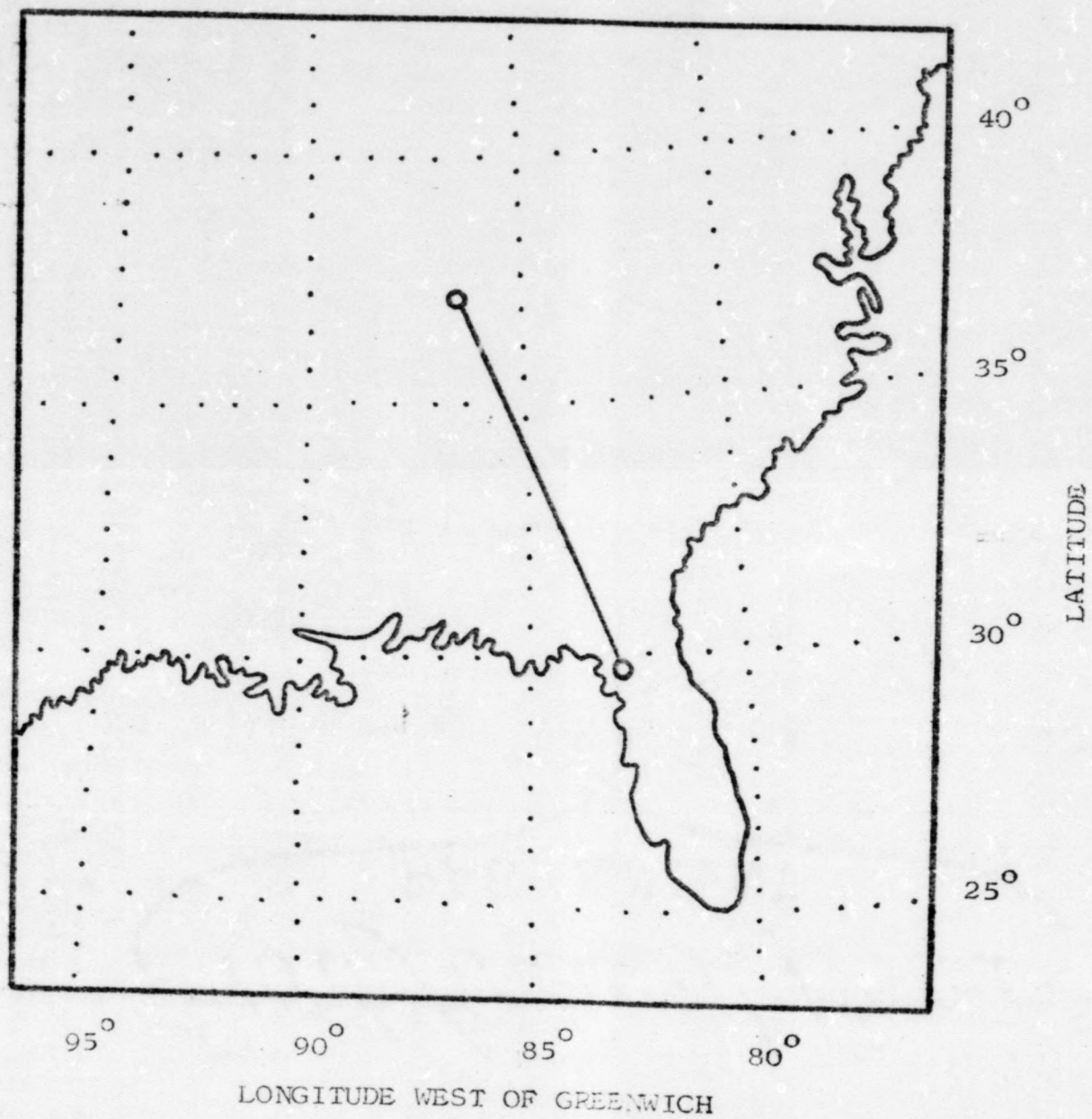
Figure 4 - The Florida-Kentucky Interferometer.

(3)

on to the antenna. For these reasons, data was recorded in the frequency band between 17.9976 and 17.9997 MHz. This frequency band had given good results in the past.

In order to combine relatively low cost with the desired maneuverability and directional properties, identical yagi type antennas were used at each station. Motorized equatorial mounts were used to keep the antennas pointed at Jupiter. To provide shelter for the observers and to protect the equipment, a small building was constructed and placed about 3 feet above the ground on concrete blocks in anticipation of the spring floods. Figure 5 shows the Western Kentucky University Radio Observatory. A log was kept at both stations containing a record of each watch. Observer comments on the receiving conditions, the weather, the time of reception of Jovian pulses, and any unusual interference, were always placed in the log. This book proved very useful in analyzing the data, for nights when strong Jovian storms had occurred were easily determined.

Standard instrumentation was employed at each station. To minimize receiver delay effects, identical Collins 75-S1 receivers were used by both stations. The delay in each re-
(14)
ceiver was measured and found to be identical. It should be pointed out that the 18 MHz pulses were not actually detected, but merely heterodyned down to a frequency between 300 and 2400 Hz. This gave a receiver bandwidth of 2.1 kHz. Magnicord 1022 dual track tape recorders were used to record the
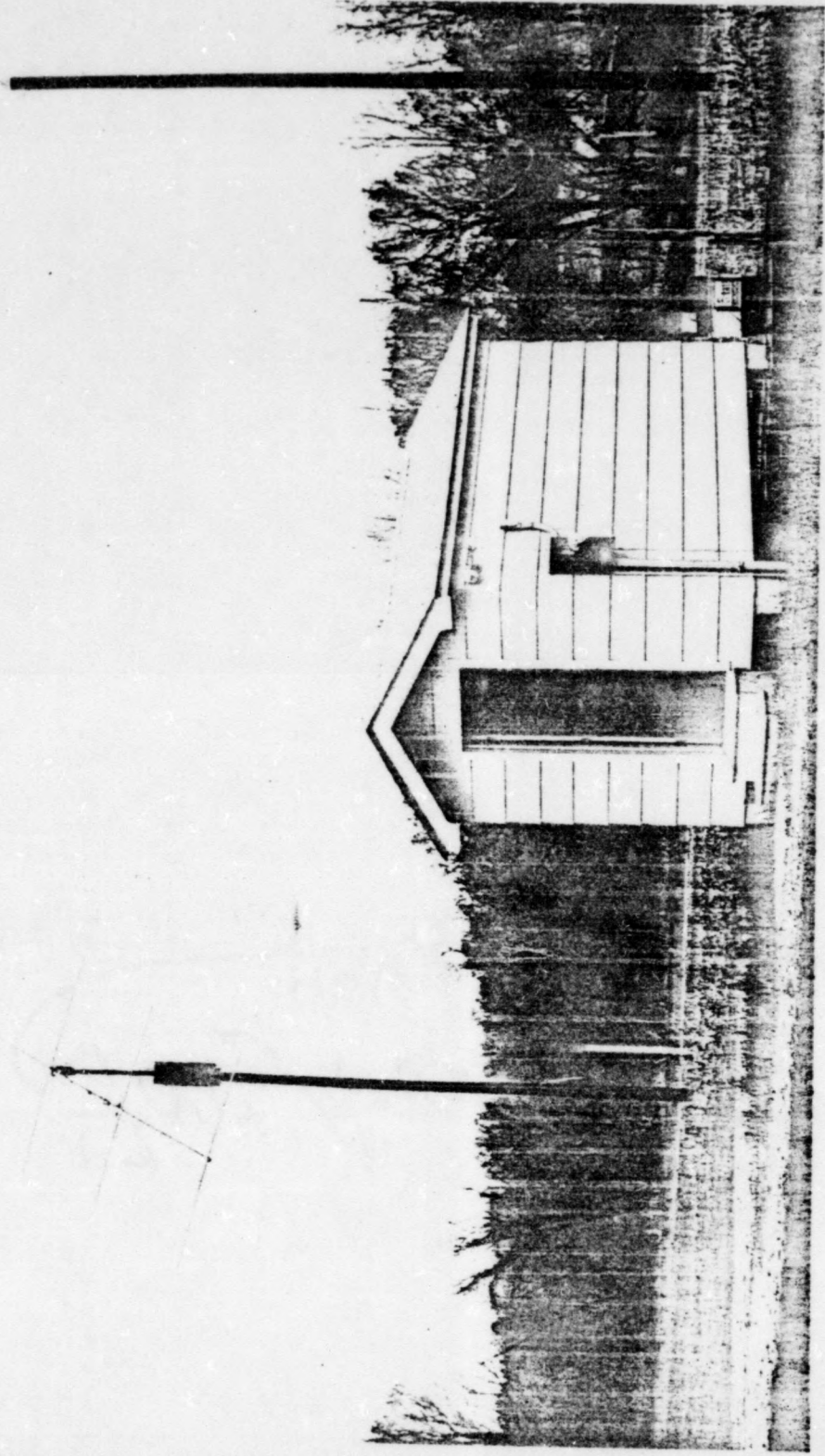
Figure 5 - Western Kentucky University Radio Observatory.

Jovian noise on ordinary magnetic tape at a speed of 7½ inches per second. The tape used to record the Jovian noise was 3600 foot reels of Scotch series 290. An audio amplifier and speakers allowed the observer to monitor what was being recorded on each channel. For placing time information on the magnetic tapes, each station was provided with a crystal oscillator, and WWV and Loran C receivers. The description and interpretation of this information will follow. Graphical records were provided by Texas pen recorders operating at a speed of 6 inches per hour. The Texas records proved very useful in deciding whether Jupiter signals or terrestrial interference had been received. Figure 6 shows the interior of the observatory.

2.2. Data Tapes. Each data tape consisted of a 3600 foot reel of Scotch series 290 recorded at a speed of 7½ inches per second. Channel one contained the Jovian noise interrupted every minute by 5 seconds of WWV followed by 5 seconds of Loran C. Contained in the 5 seconds of WWV were the 59th and 60th second of each minute and the voice announcement of the Universal time every fifth minute. In the minute preceding the WWV voice announcement, a known impedence for signal calibration was connected to the receiver for 3 seconds. Channel two contained the pulses generated by the local oscillator. The Kentucky observatory's timing track consisted of 1/600, 1/60, and 1 second pulses while Florida's timing track consisted of
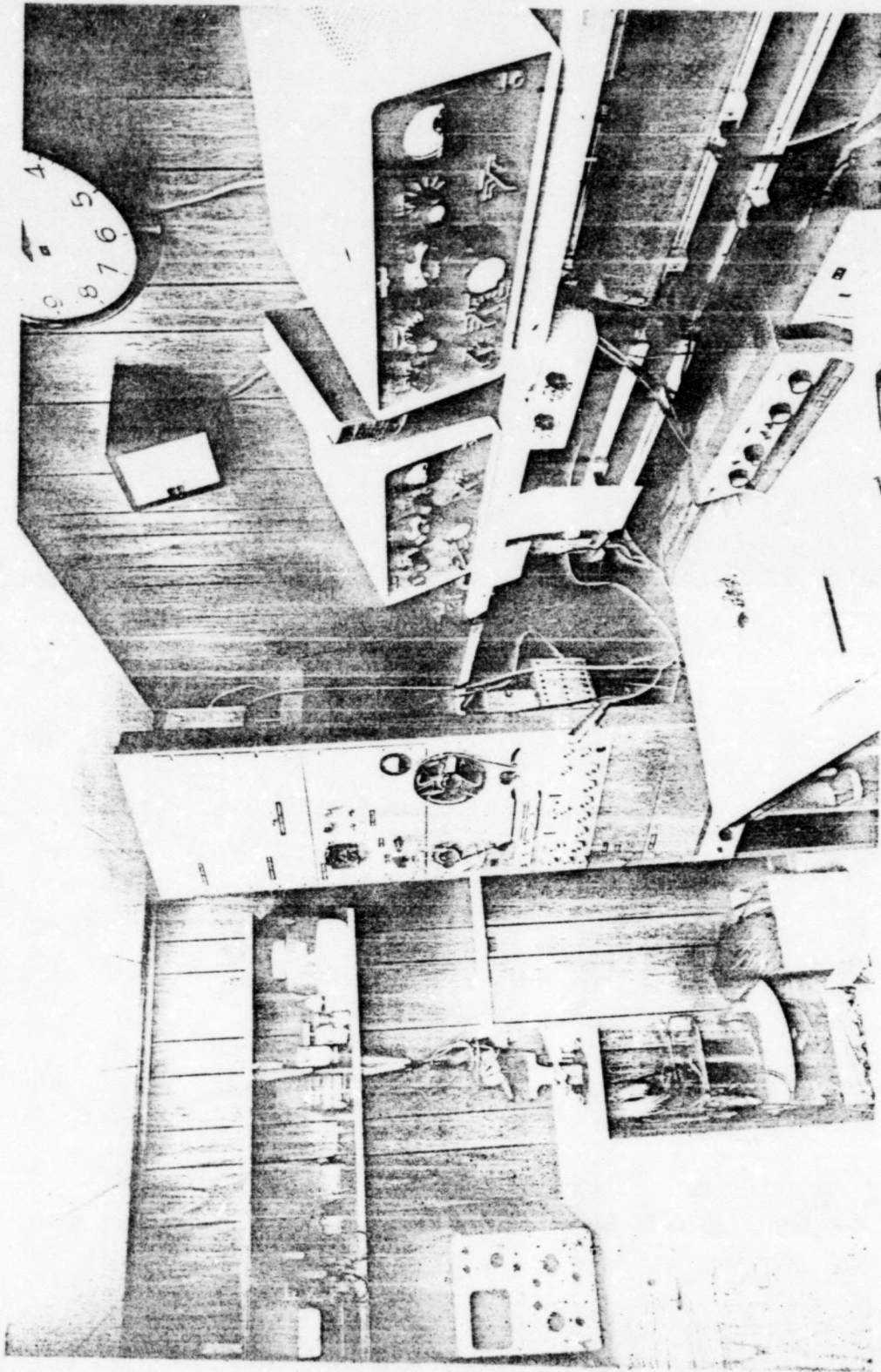
Figure 6 - Interior of Western Kentucky University Radio Observatory.

1/960, 1/60, and 1 second pulses. See Figure 7. The Loran C
transmissions consisted of 8 pulses, 1 millisecond apart, re-
peated every 99.300 milliseconds and transmitted at a frequency
of 100 kHz. All records made since January 6, 1969, include
Loran C signals. The Kentucky observatory was receiving the
Dana, Indiana, station while Florida received the station lo-
cated at Jupiter, Florida. The Loran C transmitters are synchro-
nized to the master station in Cape Fear, North Carolina.

2.3. Procedure. It was decided to employ a graphical
method of analysis in this investigation. The first step was
to examine the data tapes in order to locate Jovian pulses
that appeared to have been received by both stations simul-
taneously. This was accomplished by listening to the tapes
and referring to the Kentucky observatory's Texas records and
logbook. When it appeared that both stations were receiving
the same pulse group, the position of the pulse group on each
tape was determined to the nearest second, relative to WWV.
This was accomplished by counting the number of local oscillator
pulses between the start of a noise burst and the first second
of the same WWV minute on each tape.

Next, 5 seconds of the Jovian signal was cut from each
tape. By using WWV as a reference, the two sections of tape
were taken from the same real time interval. Each section of
tape including the Jovian signal was then spliced to 3 seconds
of Loran C and 2 seconds of WWV taken from the same reel of

CHANNEL 2 - TIMING TRACK

1/60 second pulse

1 second pulse

1/600 second Ky. or 1/960 second Fla.

TIME

CHANNEL 1 - DATA TRACK

Dummy noise load
every 5 minutes

Galactic background

Loran C   WWV

1 minute

1 minute — 1 minute

"next tone
begins at
X hrs. GMT"

WWV voice announcement
every 5 minutes

Jupiter
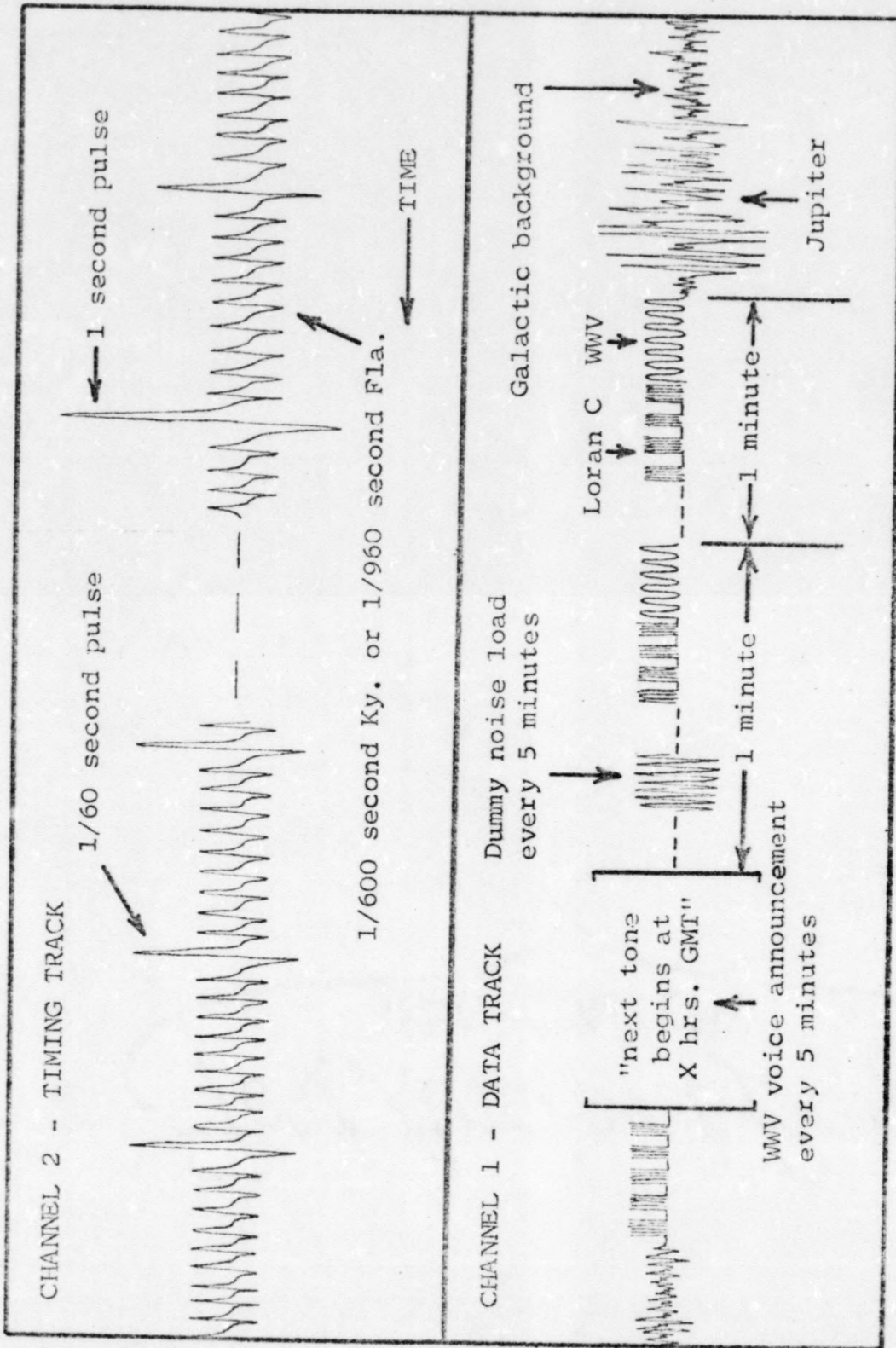
Figure 7 - The data tapes (not to scale).

tape as the noise itself. The WWV and Loran C selections were taken from the same time interval on each tape, and as close as possible to the selected signal. The data from each station was then spliced together giving a strip of tape representing approximately 20 seconds of time. Figure 8 shows the spliced data ready for examination.

In order to obtain a time dialated graphical record, the spliced data was played into a General Electric model PM-20 recording oscillograph. See Figure 9. This machine consists of a mechanical device to run photosensitive paper rapidly past a tungsten-illuminated reflecting galvanometer. The model PM-20 has a frequency response of 6 kHz and uses Dupont Lino-Write Spec. No. 1 photo-recording paper. Rolls of paper 300 feet long and 6 inches wide were used in this investigation. The paper was developed in a Consolidated Engineering Corporation oscillograph processor type 23-109-P4.

The actual measurements were made using the graphical records obtained with the oscillograph. The examination consisted of the following four steps:

(a) First, determine corresponding local oscillator seconds pulses on each station's record by aligning them with the WWV pulses on each record.

(b) Second, determine corresponding Loran C master pulse positions on each station's record by aligning corresponding

Figure 8 - Data after splicing (not to scale).
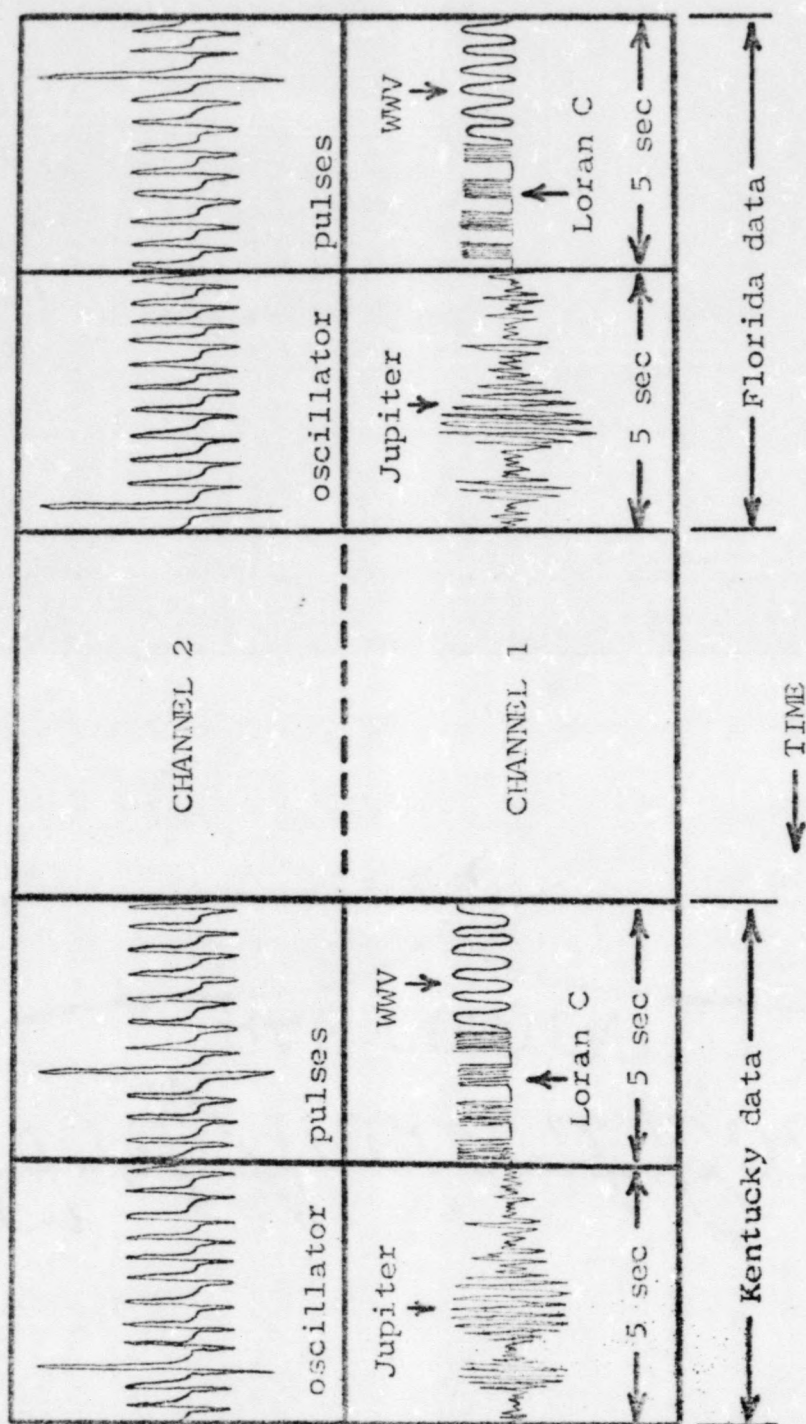
TAPE RECORDER

STEREO
AMPLIFIER

OSCILLOGRAPH

Channel 1

Channel 2
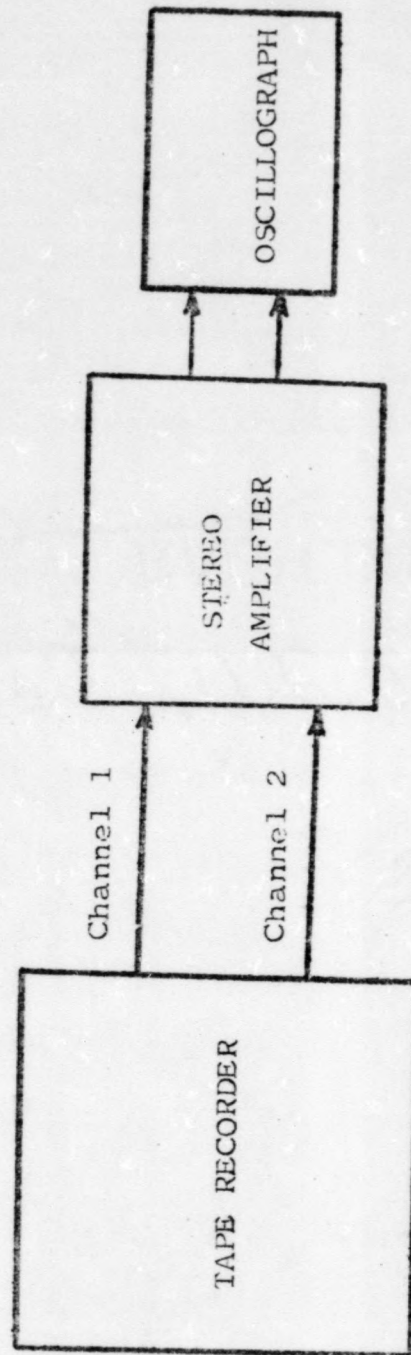
Figure 9 - Method of producing the time dialated graphical record.

local oscillator seconds pulses with the Loran C signals received by each observatory and using the Loran C propagation and transmission delays.

(c) Third, align the records from the two stations to produce the best correlation between the Jovian pulses recorded at each observatory and measure directly on each record, the time interval between corresponding Loran C master pulses and correlated peaks of the same Jovian noise pulse.

(d) Fourth, make corrections for the optical path difference between Jupiter and the two stations, and for receiver delay.

Any difference in the measurements made on each station's record in step (c) after all corrections are made, will constitute an apparent time shift in the arrival of Jovian pulses at each end of the interferometer. The determination of the Loran C propagation delays and the delay at the Kentucky observatory due to optical path difference are outlined in Appendices I, II, III, and IV.

A detailed description of steps (a), (b), and (c) will now be presented. Figure 10 is a reproduction of a section of the Kentucky observatory's oscillograph record. Channel one contains a WWV seconds pulse group and channel two contains the timing track generated by the local oscillator. In splicing

Figure 10 - Aligning the local oscillator pulses with WWV (to scale - tracing).

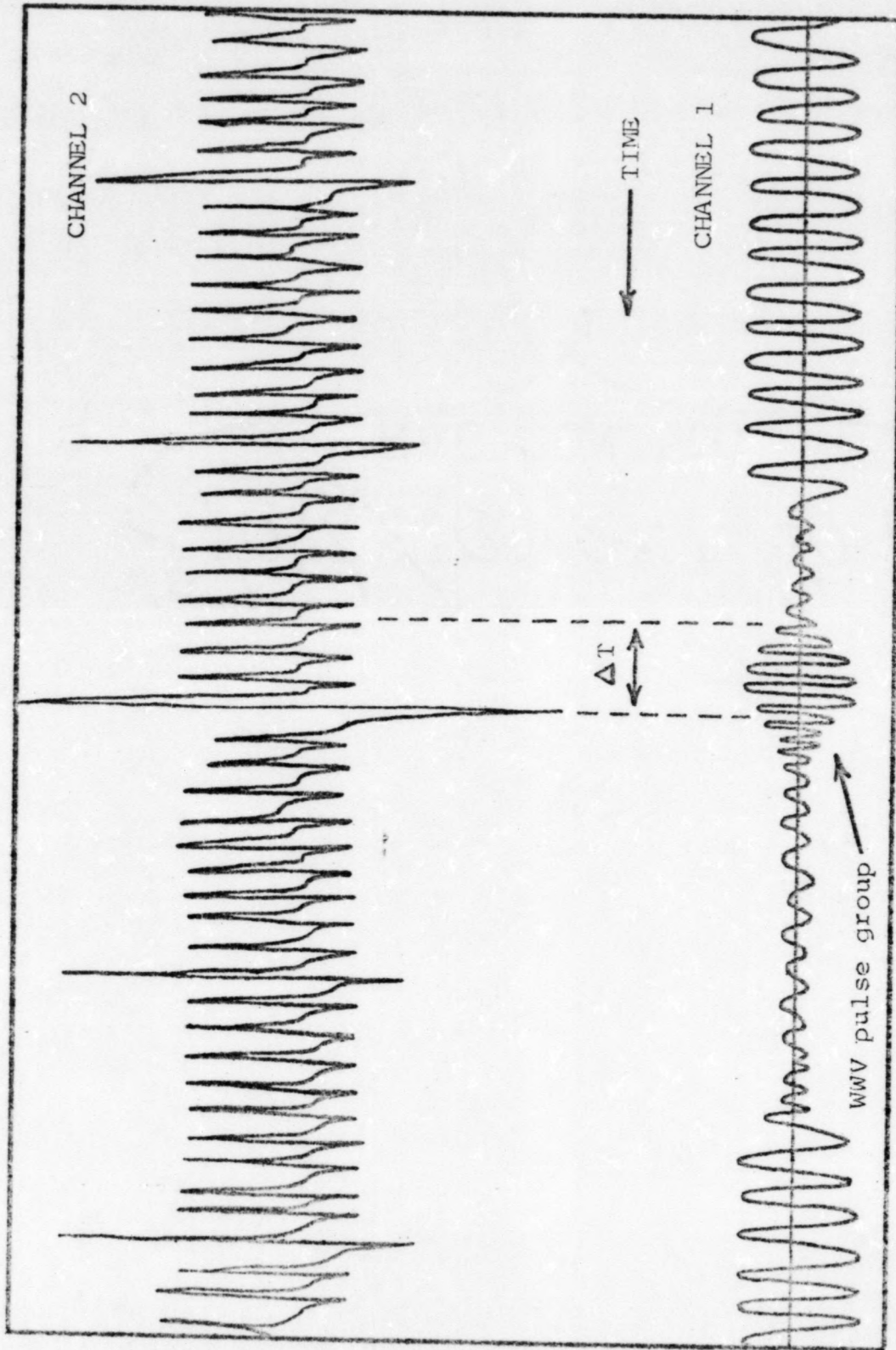the data, care was taken to insure that the same WWV seconds pulse group occured on the sections of data removed from each station's tape. This made it easy to locate corresponding WWV seconds pulse groups on the graphical records. The seconds pulses of each observatory's local oscillator had been aligned with the WWV seconds pulses when the Jovian noise was recorded. However, a small correction was needed to correctly position the local oscillator pulses, since the initial alignment was made by listening to the WWV pulses and the oscillator pulses simultaneously, and adjusting the oscillator. It was arbitrarily decided that the beginning of a WWV seconds pulse group would be the point where the WWV pulse first crosses the zero axis. In order to align the local oscillator pulses with WWV, measurement was made from the peak of a local oscillator seconds pulse to the beginning of a WWV seconds pulse group. In Figure 10, the Kentucky observatory's seconds pulse lags the WWV seconds pulse group by an amount ΔT. A piece of plexiglas with a hairline ruled on it was used to read ΔT from the local oscillator timing track. To align any of the Kentucky observatory's seconds pulses with WWV, it is only necessary to move them forward in time the increment ΔT. A similar procedure was used on Florida's graphical record.

Figure 11 illustrates step (b). Channel one contains the Kentucky observatory's local oscillator pulses and channel two, Loran C pulses from the transmitter at Dana, Indiana. The
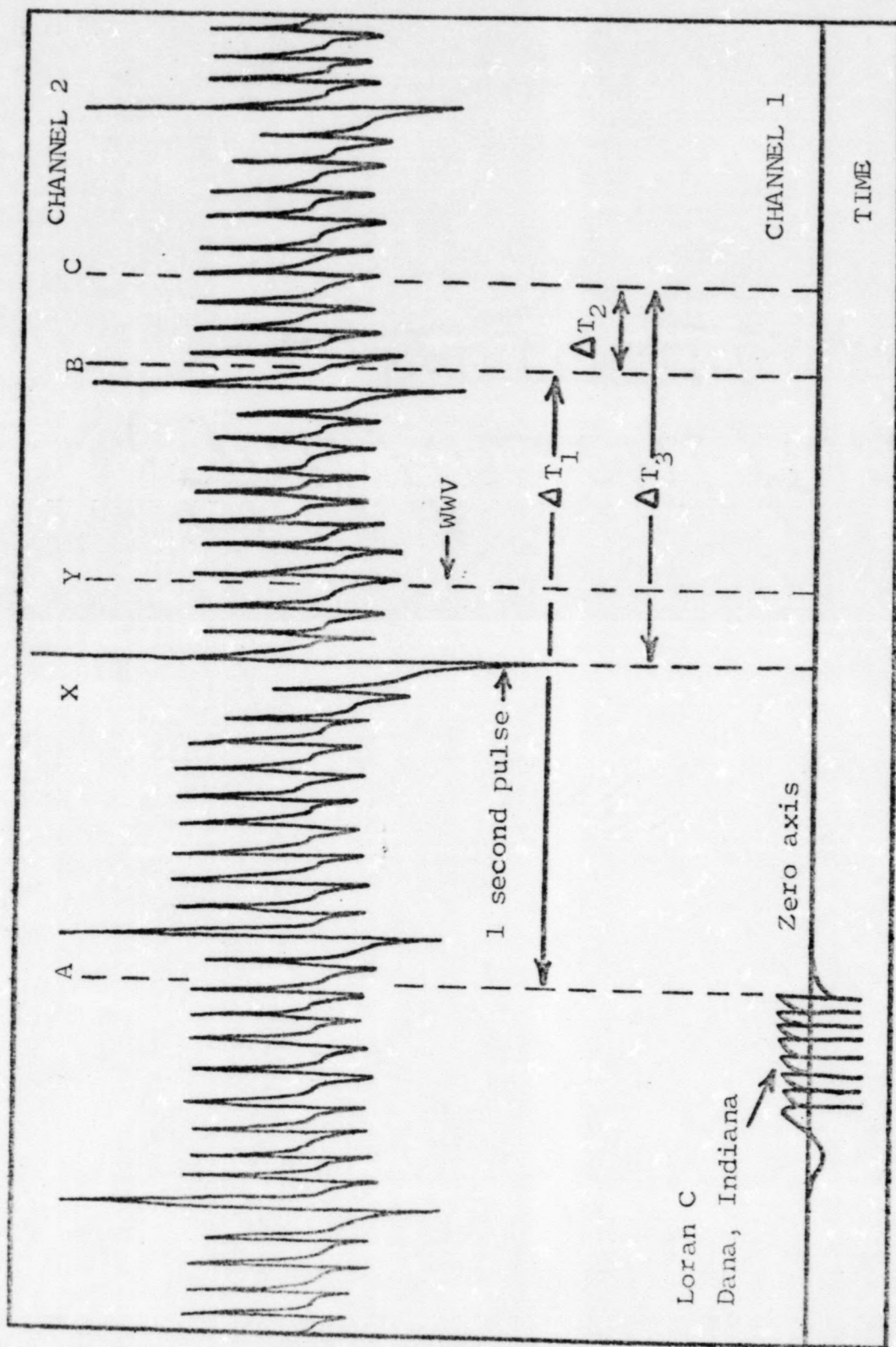
Figure 11 - Locating the position of a Loran C master pulse relative to a local oscillator seconds pulse (tracing but time intervals not drawn to scale).

positions of a local oscillator seconds pulse and a WWV seconds pulse are represented by points X and Y respectively. The beginning of a Dana, Indiana, Loran C pulse is represented by point A, and was arbitrarily determined to be the projection of the first positive Loran C peak upon the zero axis. The transmission delay of the Dana, Indiana, transmitter relative to the master station in Cape Fear, North Carolina, is represented by ΔT_1. At the time the data was taken, ΔT_1 was .0685607 second. The propagation delay of the Dana, Indiana, transmitter relative to Alvaton, Kentucky, is ΔT_2. The value of ΔT_2 is .001151 second (see calculation in Appendix I). Therefore, C represents the start of the master pulse. The position of the master pulse relative to any local oscillator seconds pulse can now be determined by moving the oscillator pulse forward in time an amount ΔT_3. A similar process was carried out to determine the position of the Loran C master relative to the Florida observatory's local oscillator seconds pulses. Care must be taken to insure that the position of the Loran C master is determined from the same local oscillator seconds pulse on each station's record. Since the master pulses are repeated every 99.300 milliseconds, the Loran C pulse chain will gain 7 milliseconds on the local oscillator pulses every second. A large error would result if measurements were not made from the same local oscillator pulse on each record.

Figure 12 illustrates step (c). Here reproductions of each observatory's graphical record are aligned to produce maximum correlation between a burst of Jovian noise received simultaneously. Channel one on each record contains the Jovian noise and channel two the pulses generated by each observatory's local oscillator. A and B represent the positions of a Loran C master pulse as recorded in Florida and Kentucky respectively. These points in time have been located with respect to the local oscillator seconds pulses as indicated by ΔT_3 in Figure 11. C and D are the projections of an apparently correlated peak in the Jupiter burst received by both stations. The correlation is determined by pulse shape and the pattern of the pulse group. After all corrections are taken into account, any difference between ΔT_4 and ΔT_5 will constitute a time delay in arrival of the assumed identical pulse at stations in Florida and Kentucky.

At this point it seems proper to say a few words about the measurements made in steps (a), (b), and (c). Since the oscillograph paper speed was not completly uniform, care was taken to make all measurements from a localized part of the time track and not to transfer linear distances from one part of the record to another. Points were projected upon the time track using a piece of plexiglas containing two perpendicular hairlines. One hairline was superimposed on the zero axis of the data track, the other passed through the point to
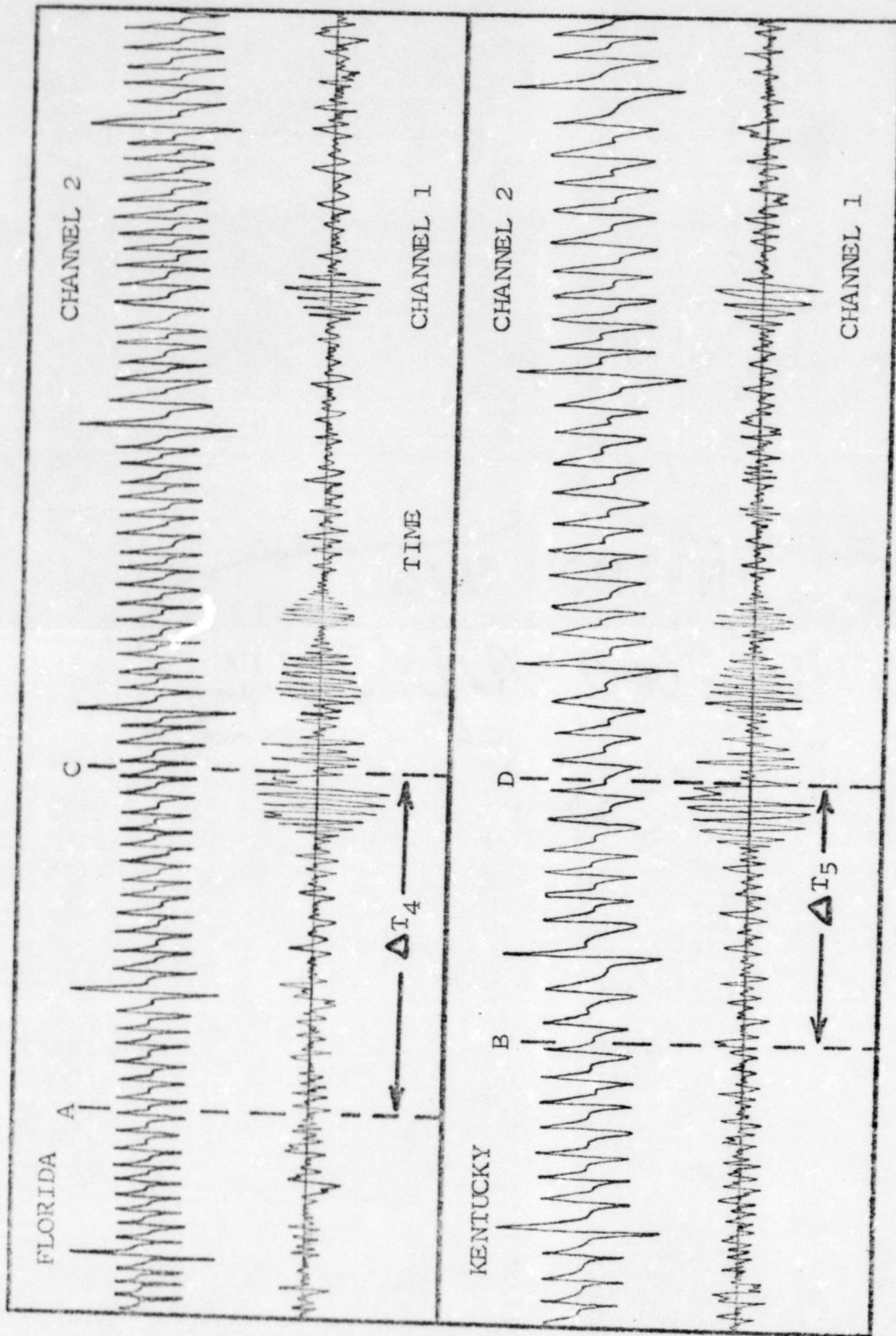
Figure 12 - Determination of the time delay (not to scale).

be projected on the time track. The width of the hairline was .24 mm which was equivalent to .010 milliseconds on the record time scale. With care, measurements could be made to the nearest .2 millisecond and possibly to the nearest .1 millisecond. See Figure 13.

It should be pointed out that the determination of peak correlation was purely subjective in nature. The criteria for correlation was pulse shape. The records from the two stations were superimposed over an illuminated screen and peaks that appeared to be correlated were marked. It is not likely that accuracy greater than .1 millisecond could be obtained by this method.

Figure 13 - Projecting points from the data track to the time track. Axis X is superimposed on the data track's zero axis and Axis Y is used for alignment purposes.

CHAPTER III

EVALUATION OF RESULTS

Three separate Jovian noise bursts received at each observatory were isolated on the oscillograph records. The bursts were carefully examined, and peaks which appeared to be identical on the two records were marked. The three pulse groups were of short duration: 50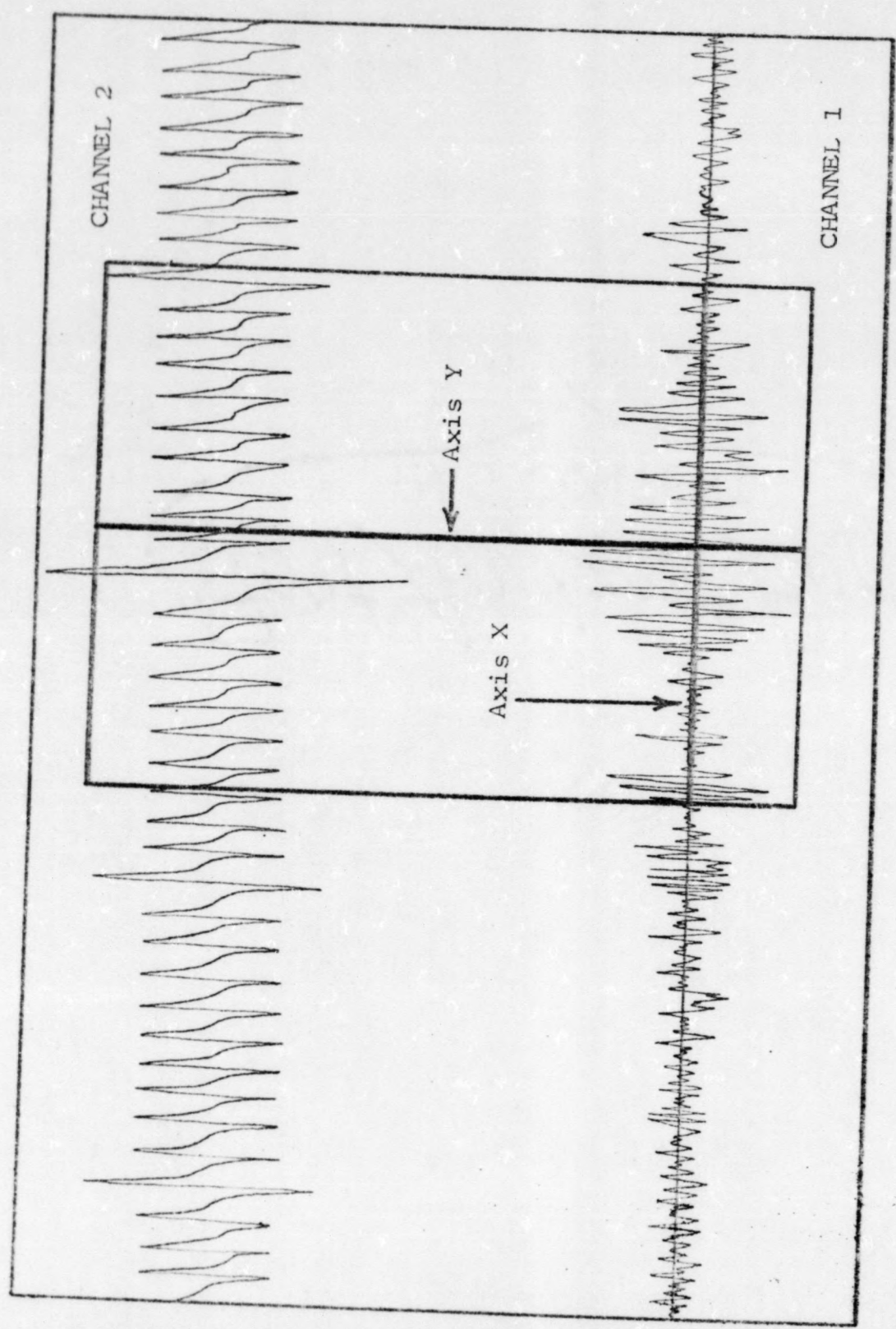, 16, and 8 msec (milliseconds); hence, were classified as Jovian S-bursts. When the longest pulse group was examined, the average duration of pulse correlation was found to be approximately 8 msec. Eight peaks were found in the 50 msec pulse group which appeared to exhibit correlation or anticorrelation, two in the 16 msec pulse group, and three in the 8 msec pulse group, giving a total of 13 peaks from which measurements could be made. The measurements are plotted in Figure 14 on page 35. The abscissa is an event axis, the letters A, B, and C referring to the pulse groups. Apparent time delay is plotted on the ordinate in tenths of a msec. A positive time delay Δt, means that a pulse arriving at the Florida station at time T, does not arrive at the Kentucky station until a later time $T + \Delta t$.
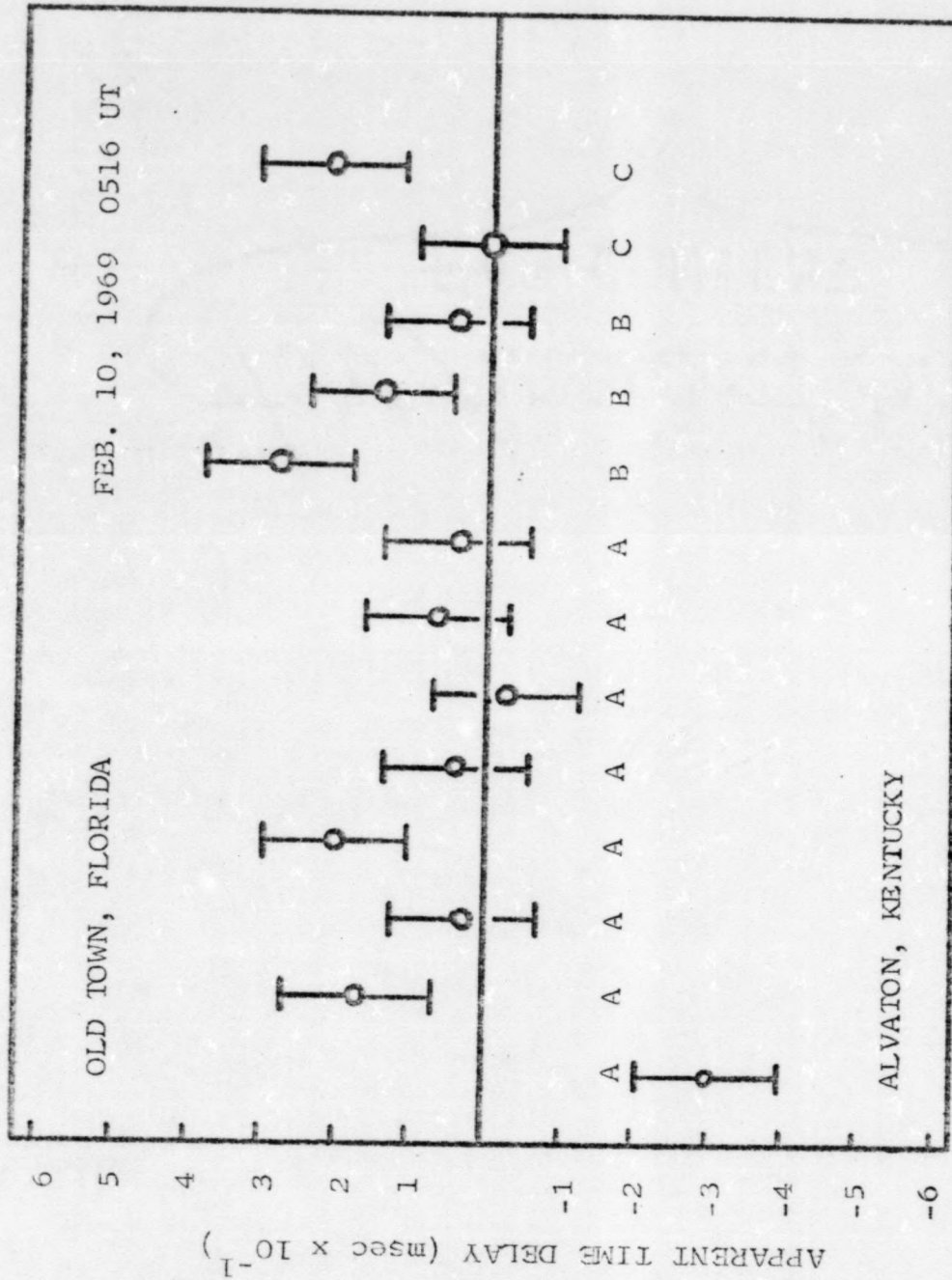
Figure 14 - The apparent time delay for correlated peaks in pulse groups A, B, and C, after correcting for the optical path difference, receiver delay, and Loran C transmission and propagation delays.

The average time delay is 0.06 ± 0.14 msec. The error ± 0.14 msec is the standard deviation of the mean. The error ± 0.1 msec shown in Figure 14, is the estimated maximum error in a single measurement. The optical path difference (1.819 msec), receiver delay, and Loran C transmission and propagation delays were all taken into account.

3.1. Sources of Error. In order to reduce the measuring error, each measurement was repeated several times and averages were taken. The results are plotted in Figure 14.

Another possible source of error could be a slight oscillation of the tape as it crossed the play-back head. The data tapes used in this investigation were first copies of original data tapes recorded at the Florida and Kentucky observatories. The Florida and Kentucky tapes were copied on different recorders. While no conclusions can be drawn, oscillation of the tape could have occurred when the data was first recorded, copied, or played into the oscillograph.

It is unlikely that error could have been introduced by a misalignment of the play-back head on the recorded used to play the tapes into the oscillograph. If the play-back head was misaligned, the timing track generated by the local oscillator would be displaced in time relative to the data track containing the Jovian noise. However, the absolute time references WWV and Loran C were also on the data track. The time displacement would be cancelled out when the local oscillator

pulses were aligned with WWV.

The most probable source of experimental error was the method used to estimate pulse correlation. The width of the trace line itself on the oscillograph records averaged about 0.1 msec. Moreover, the speed of the paper through the oscillograph, about 8.2 ft/sec, was not great enough to resolve the fine structure of the pulses. The records were aligned so as to match up the greatest number of individual peaks in a pulse. Often, the records could be shifted slightly to the left or right and a new set of peaks would line up. Individual pulse shapes and the pulse envelope were studied to indicate which was the proper alignment.

3.2. Possible Explanations of a Time Delay. It must be remembered that the data used in this investigation represents only three seconds of signal recorded on February 10, 1969, at 0516 UT. This leads one to suspect that a time delay might be introduced by some transient phenomenon such as a difference in the electron density in the ionosphere above the two stations. Even though the observed time delay in this investigation was well within the measuring error (considerably less than one standard deviation), calculations were performed to determine if a time delay of this magnitude could reasonably be attributed to ionospheric effects. These calculations are included in Appendix IV. The results show that it is possible to obtain a

time delay of 0.06 msec by increasing the maximum electron density along the Alvaton, Kentucky, propagation path by a factor of approximately 3. However, since the observed time delay is so small compared with the estimated measuring error, the results should not be considered as an explanation of the observed time delay, but rather as helpful information for future investigations.

Others have postulated that a time delay could be the result of a "shadowing effect" upon the earth by the interplanetary media. According to this theory, the structure of the pulses is a result of the interplanetary plasma between earth and Jupiter casting interference patterns upon the earth. Just as the speed of a cloud determines how long it takes its shadow to travel between points on earth, the speed of this interplanetary media could introduce a time delay in reception of a Jovian pulse between the two observatories. However, if this were true, the wave form of the Jovian radiation would have to be simple, and constant in time or the "pulse structure" would appear different when received at each observatory. Not enough is known about the structure of the interplanetary plasma between earth and Jupiter to determine if the pulse structure observed could be caused by such an effect.

3.3. <u>Summary of Conclusions</u>. The purpose of this investigation was to determine the magnitude of the apparent time delay using Loran C as an absolute time reference. The following conclusions are drawn:

(1) Based upon the analysis of data recorded on Feb. 10, 1969, at 0516 UT, the average value of the time delay Δt is 0.06 ± 0.14 msec.

(2) The observed value of the time delay is well within the estimated measuring error. There is no significant difference in the time of arrival of Jovian pulses at Old Town, Florida, and Alvaton, Kentucky.

(3) The method used to test correlation of pulse groups was purely subjective in nature, the criteria being visual comparison of pulse shape on the oscillograph records. Computer studies should be made with emphasis on a more objective method of determining pulse correlation. Using the computer, one can maximize the cross correlation function over an arbitrary interval for two pulse groups. This is a more objective way of defining pulse correlation than the method used in this investigation. The time dialation obtained with the recording oscillograph limits the accuracy of determining the time delay; however, the

expanded records are useful in selecting sections of data to be tested for pulse correlation by other techniques.

(4) Loran C is much superior to WWV as an absolute time reference because the observatories are receiving it as a ground wave with little sky-wave contamination.

CHAPTER IV

FLOOD DAMAGE TO THE

WESTERN KENTUCKY UNIVERSITY RADIO OBSERVATORY

Western Kentucky University's radio observatory was located in a 21 acre creek bottom field near Alvaton, Kentucky. See Figure 15. On the morning of June 23, 1969, the Bowling Green area was receiving heavy rainfall and 6 inches had fallen over the past 36 hours. Normally tranquil streams were raging torrents, threatening to overflow their banks. At approximately 9:30 AM CDT, a secretary in the Dept. of Physics and Astronomy received a call from Mr. Burford from whom the university had leased the observatory site. He reported that someone had broken into the observatory the previous night and that Trammel Creek, which formed the south boundary of the site, was flooding the observatory access road.

About 10:30 AM, V. M. Robinson and R. L. Scott arrived at the observatory site. The creek had flooded the surrounding bottom land to an estimated depth of 3 feet and was rising rapidly. The instrument building could be seen about 1000 feet to the northwest, washed off its concrete block foundation by the swift flood current. The water was rising so rapidly that no immediate attempt was made to reach the building.
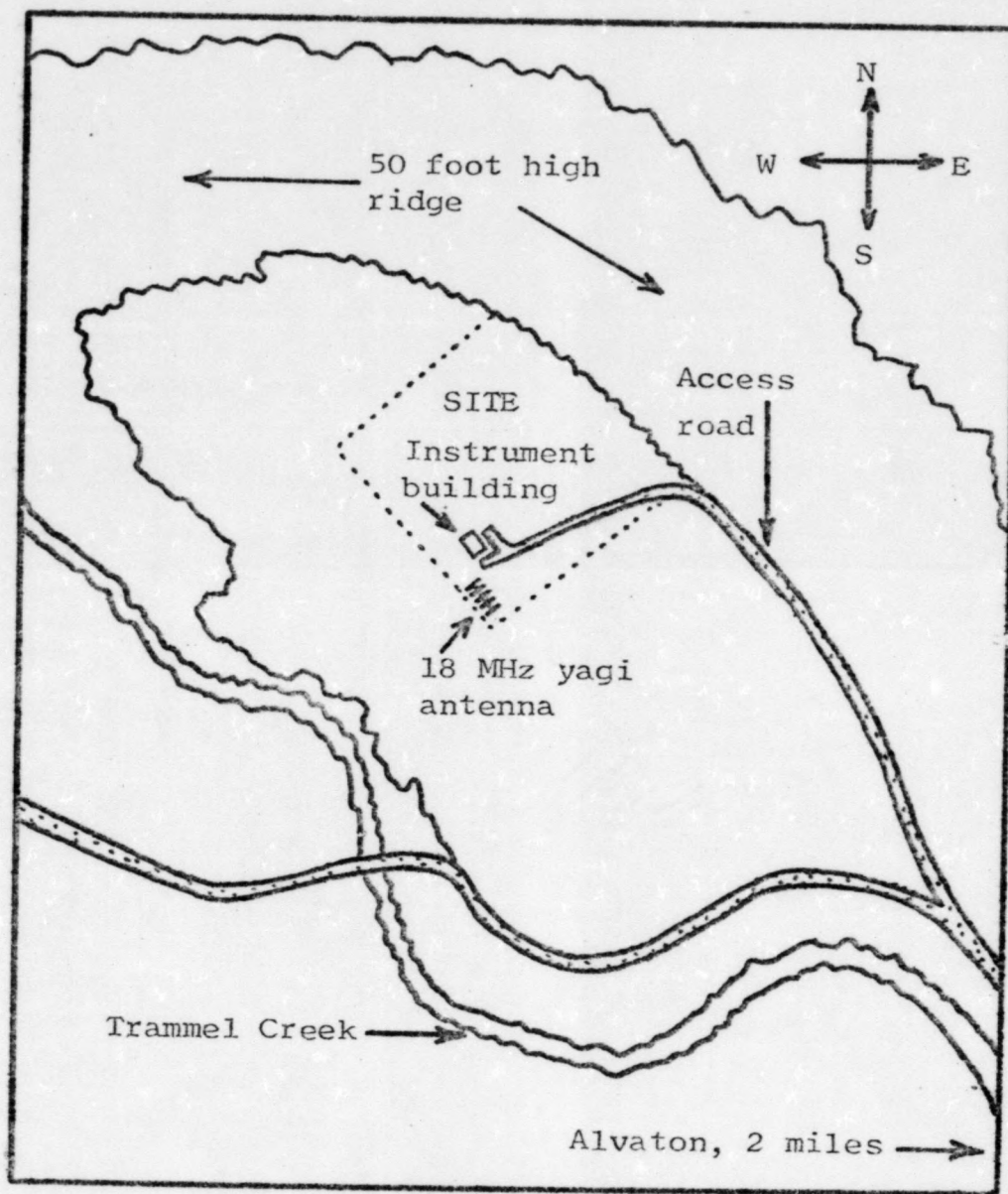
41

Figure 15 - The location of the Kentucky observatory.

At 12:30 PM, Robinson and Scott returned to the observatory site along with I. E. Collier who had borrowed a small motor boat belonging to the Biology Dept. The water had already advanced another 100 yards along the access road toward Alvaton and had risen an estimated 12 feet since 10:30 AM. Collier, Robinson, and Scott, after putting on life jackets, proceeded in the boat over the road where Scott had parked his car only 2 hours before. The instrument building could not be seen and it was presumed washed away. The 18 MHz antenna was still standing but the water had risen to within an estimated 20 feet of the top of its 40 foot support pole. The tops of the WWV antenna support poles were visible but the antenna itself was completly submerged. No photographs of the actual flood other than Figure 16 are available, for the three members of the "rescue party" considered the flood waters too hazardous to take their cameras into the boat. After reaching safe ground, it was decided to return to the university as nothing else could be done at the site. The bridges on highway 231 between Bowling Green and Alvaton were now under water, and a detour to Scottsville, Kentucky, and then up highway 101 to U. S. 31 W had to be made in order to return to Bowling Green.

The next day, the flood waters had receded and the instrument building was found about 100 feet from its original location wedged up against a piece of farm machinery. See
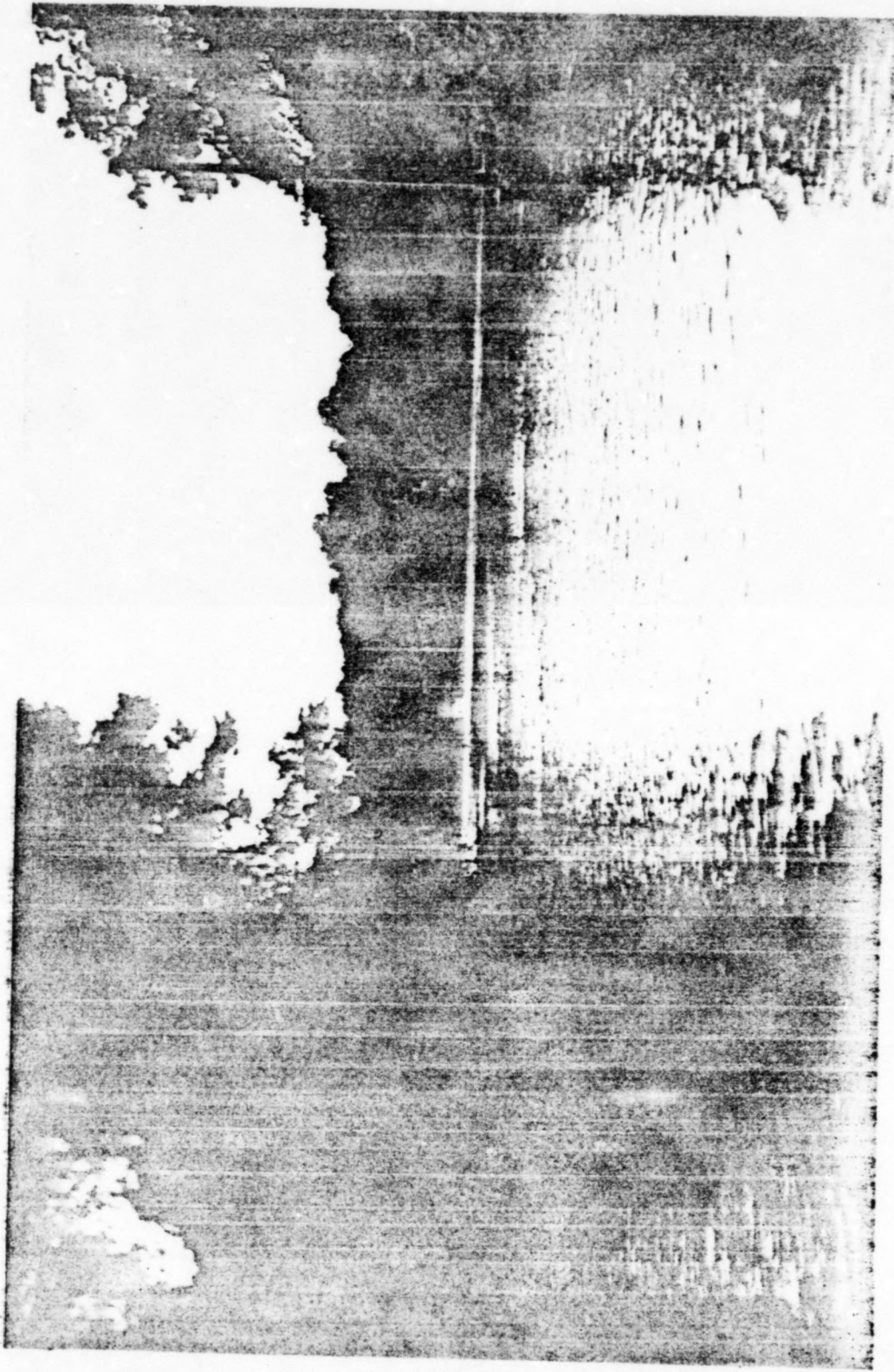
Figure 16 - Last view of the Kentucky observatory before
it was submerged.

Figure 17. All the equipment was found except two Collins receivers and an oscilloscope. It is believed that the receivers and the oscilloscope were stolen when the observatory was broken into. Most of the equipment was severly damaged and either discarded, returned to the factory, or cleaned and repaired by V. M. Robinson. The instrument building was badly waterlogged and was considered a total loss.

The Kentucky observatory is presently being rebuilt near Petros, Kentucky, about 11 miles west of Bowling Green on U. S. 68. The new site is on higher ground and no flooding of any kind is expected. The goal in mind is to have the Kentucky observatory rebuilt in time for the 1971 apparition.
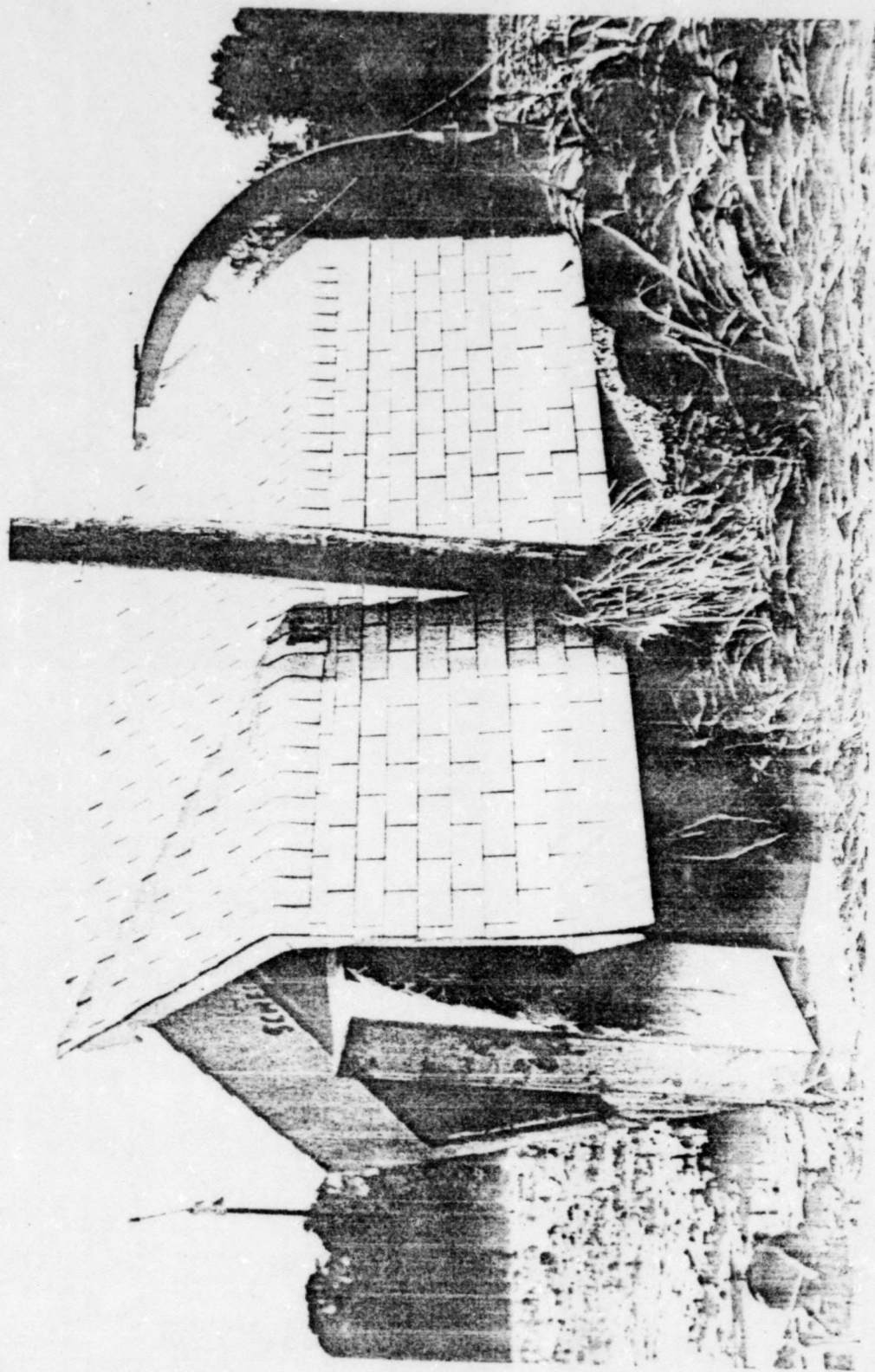
Figure 17 - The remains of the Western Kentucky University
Radio Observatory.

APPENDIX I

THE PROPAGATION DELAYS BETWEEN THE LORAN C STATIONS

AND THE RADIO OBSERVATORIES

In order to calculate the time elapsed between the transmission of a pulse by the Loran C station and the arrival of that pulse at the radio observatory, it is necessary to determine the path length. The arc length α between two points on a sphere is given by Smart.

(15)

$$\alpha = \cos^{-1}\left[\sin\phi_A\sin\phi_B + \cos\phi_A\cos\phi_B\cos(\lambda_A - \lambda_B)\right]$$

where, ϕ_A and ϕ_B are the latitudes of points A and B, and λ_A and λ_B are the longitudes of points A and B. See Figure 18.
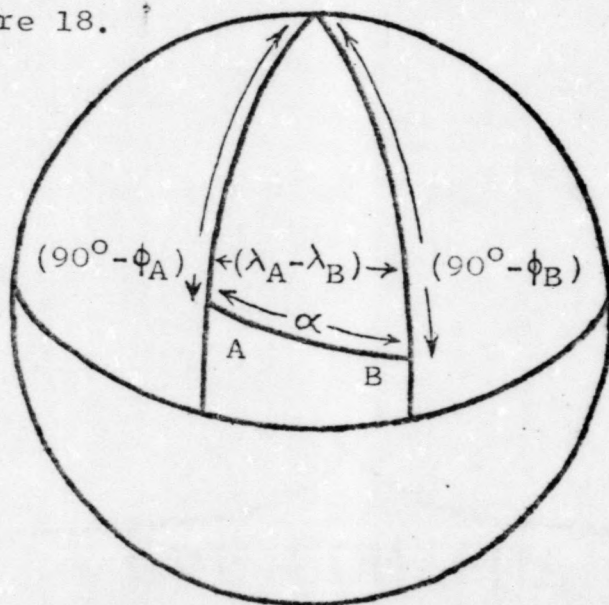

Figure 18
The arc length between two points on a sphere.

47

The latitude and longitude of the Loran C transmitters and the radio observatories are given in Table 1.

STATION	LATITUDE ϕ	LONGITUDE λ
Loran C Dana, Indiana	39° $51'$ $07''.70$ N	87° $29'$ $11''.19$ W
Loran C Jupiter, Florida	27° $01'$ $59''.09$ N	80° $06'$ $52''.92$ W
Western Kentucky University Radio Observatory	36° $52'$ $32''$ N	86° $22'$ $15''$ W
University of Florida Radio Observatory	29° $32'$ N	83° $02'$ W

Table 1 - The coordinates of the Loran C transmitters and the Florida and Kentucky observatories.

The arc length between Dana, Indiana, and Alvaton, Kentucky, is calculated as follows:

$$\alpha = \cos^{-1}\left[\sin(39^\circ 51') \sin(36^\circ 53') + \cos(39^\circ 51')\cos(36^\circ 53')\right.$$
$$\left.\cos(87^\circ 29' - 86^\circ 22')\right]$$

$$\alpha = \cos^{-1}\left[(.60019)(.64078) + (.79986)(.76772)(.99981)\right]$$

$$\alpha = \cos^{-1}(.99854)$$

$$\alpha = 3\overset{\circ}{.}10$$

To convert into linear measure, multiply the arc, expressed in radians, by the radius of the earth $(s = r\alpha)$:

$$s = (6378.24 \text{ km})(3\overset{\circ}{.}1)(\pi \text{rad.}/180^\circ)$$

$$s = 345.10 \text{ km}$$

The time elapsed between the transmission of a pulse at Dana, Indiana, and its arrival at the radio observatory in Alvaton, Kentucky, is then:

$$t = s/c$$

$$t = \frac{345.10 \text{ km}}{2.9979 \times 10^5 \text{ km/sec}}$$

$$t = 1.151 \text{ msec}$$

The arc length between Jupiter, Florida, and Old Town, Florida, is calculated as follows:

$$\alpha = \cos^{-1}\left[\sin(29^{\circ}32')\sin(27^{\circ}02') + \cos(29^{\circ}32')\cos(27^{\circ}02')\cos(83^{\circ}02' - 80^{\circ}07')\right]$$

$$\alpha = \cos^{-1}\left[(.49293)(.45451) + (.87007)(.89074)(.99870)\right]$$

$$\alpha = \cos^{-1}(.99804)$$

$$\alpha = 3.\!^{\circ}58$$

To convert into linear measure, multiply the arc, expressed in radians, by the radius of the earth ($s = r\alpha$):

$$s = (6378.24 \text{ km})(3.\!^{\circ}58)(\pi\text{rad.}/180^{\circ})$$

$$s = 398.53 \text{ km}$$

The time elapsed between the transmission of a pulse at Jupiter, Florida, and its arrival at the radio observatory in Old Town, Florida, is then:

$$t = s/c$$

$$t = \frac{398.53 \text{ km}}{2.9979 \times 10^5 \text{ km/sec}}$$

$$t = 1.329 \text{ msec}$$

APPENDIX II

THE LENGTH OF THE BASELINE

The next two appendices contain an outline of the
calculation of the geometric path difference between the
planet Jupiter and the ends of the interferometer for the
morning of February 10, 1969 at 0516 UT. Once the path
difference is known, the geometric time delay can be found.

Before the actual calculations are presented, a brief
explanation of the problem is in order. Figure 19 defines
the geometric path difference. The baseline is represented
by X and the path difference by D. The paths of Jovian emis-
sions received by the Kentucky and Florida observatories are
represented by R_1 and R_2 respectively. The paths R_1 and R_2
are considered parallel. The path difference is $R_1 - R_2$ and can
be found by extending a perpendicular from the Florida observ-
atory to R_1. Since Old Town lies at a more southerly latitude
than Alvaton, R_1 is always longer than R_2. From Figure 19, it
is seen that the path difference D is equal to $X \cos \phi$. The
problem of calculating the path difference is thus reduced to
finding the length of the baseline and the angle between
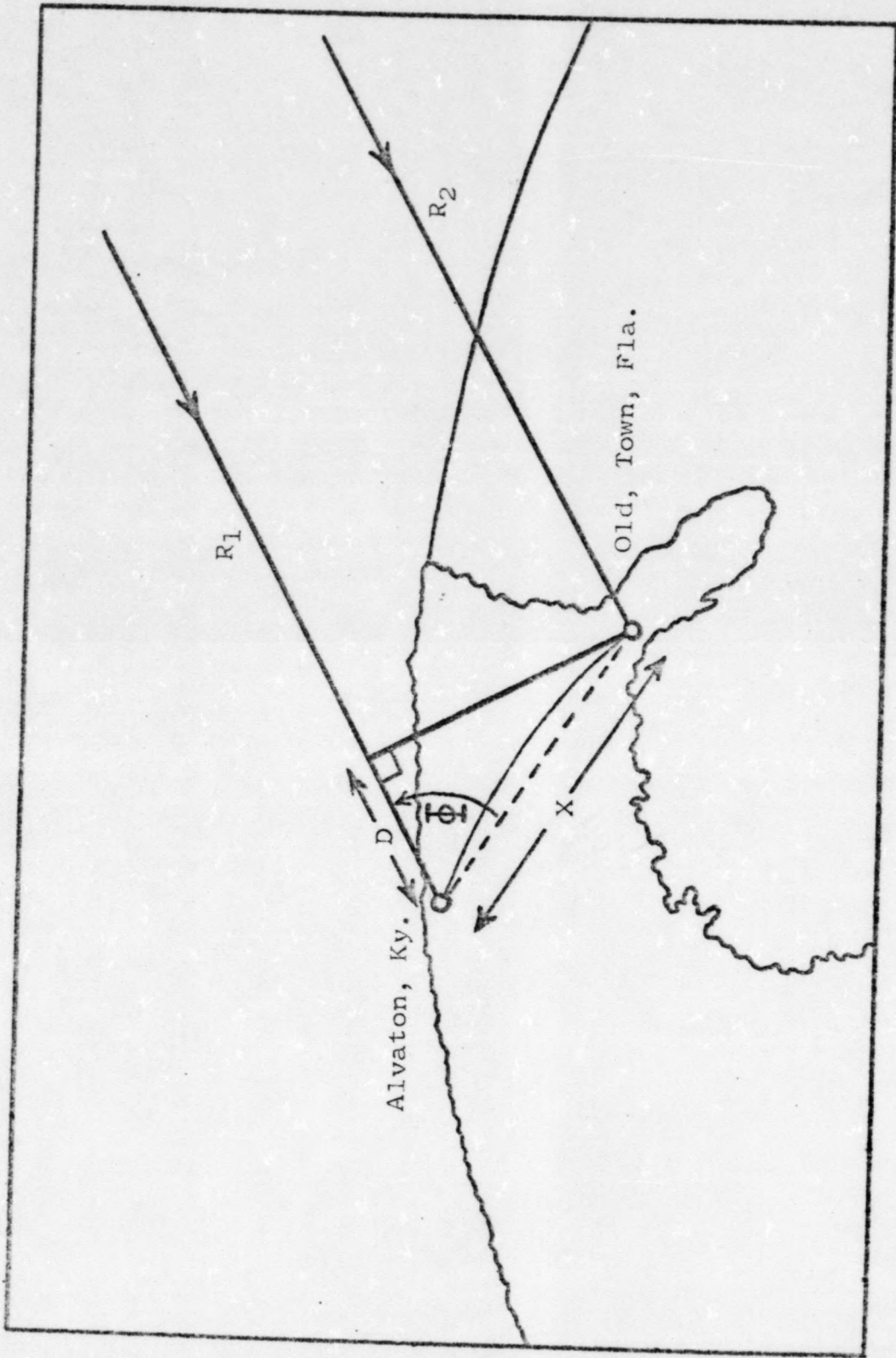Jupiter as seen from Alvaton, Kentucky, and the baseline at

51

Figure 19 - The geometric path difference D.

0516 UT on February 10, 1969.

The length of the baseline is determined by first finding the arc length between the two observatories and then calculating the included chord. The formula for finding the arc length between any two points on a sphere is to be found in Appendix I. The determination of the included chord length is illustrated in Figure 20.
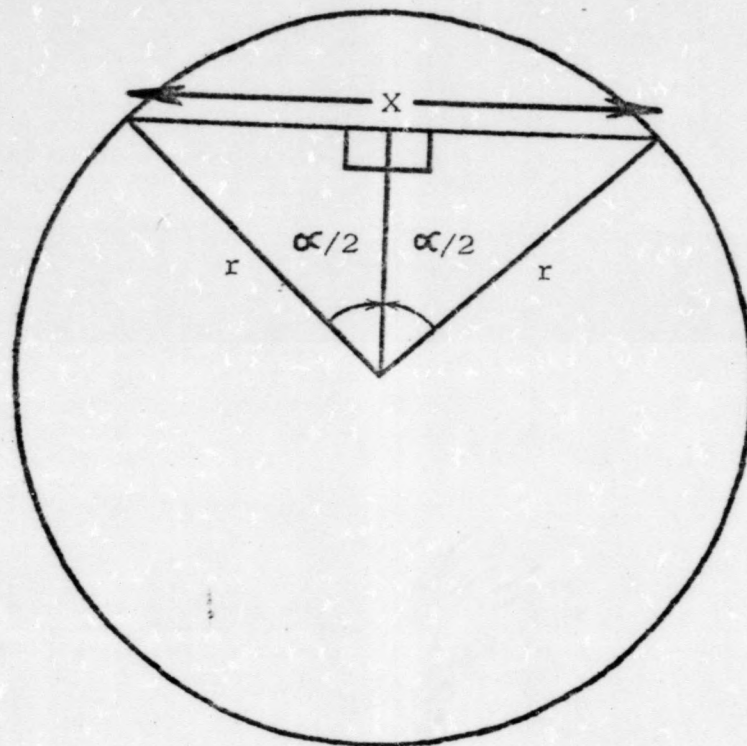
Figure 20
Determining the length of the baseline.

X = chord = baseline

α = length of arc in degrees

r = radius of earth

$X/2 = r\sin \alpha/2$

Therefore, $X = 2r\sin \alpha/2$

The arc length between the two stations at Alvaton, Kentucky, and Old Town, Florida, is calculated as follows:

$$\cos \alpha = \sin(36^o53') \sin(29^o32') + \cos(36^o53') \cos(29^o32')$$
$$\cos(86^o22' - 83^o02')$$

$$\cos \alpha = (.60019)(.49293) + (.79986)(.87007)(.99831)$$
$$\alpha = \cos^{-1}(.99055)$$
$$\alpha = 7^o53'$$

The baseline is the chord X in Figure 20, and can be found as follows:

$$X = 2r\sin \alpha/2$$
$$X = (2)(6378.24 \text{ km}) \sin(7^o53'/2)$$
$$X = 12756.48 \text{ km}(.06889)$$
$$X = 878.79 \text{ km}$$

APPENDIX III

THE GEOMETRIC TIME DELAY BETWEEN JUPITER
AND THE TWO ENDS OF THE INTERFEROMETER

Now that the length of the baseline has been determined, the cosine of angle Φ must be calculated. In general, the cosine of the angle between any two lines may be found if the direction cosines of the lines relative to a particular coordinate system are known. Figure 21 illustrates this relationship. The cosine of angle Φ may be calculated if a coordinate system is defined so that the respective direction cosines of R_1 and X may be determined. Figures 22 and 23 on pages 57 and 58 describe such a coordinate system.

Using the formula given in Figure 21 and the coordinate system described in Figures 22 and 23, $\cos \Phi$ is:

$$\cos \Phi = (\cos \epsilon)(\sin B)(\cos \Theta)(\sin A) + (\cos \epsilon)(\cos B)(\cos \Theta)(\cos A) + (\sin \epsilon)(\sin \Theta)$$

$$\cos \Phi = (\cos \epsilon)(\cos \Theta)\left[(\sin A)(\sin B) + (\cos A)(\cos B)\right] + (\sin \epsilon)(\sin \Theta)$$

$$\cos \Phi = (\cos \epsilon)(\cos \Theta)\left[\cos(B - A)\right] + (\sin \epsilon)(\sin \Theta)$$

Thus if angles Θ, A, ϵ, and B are determined, $\cos \Phi$ may be found.

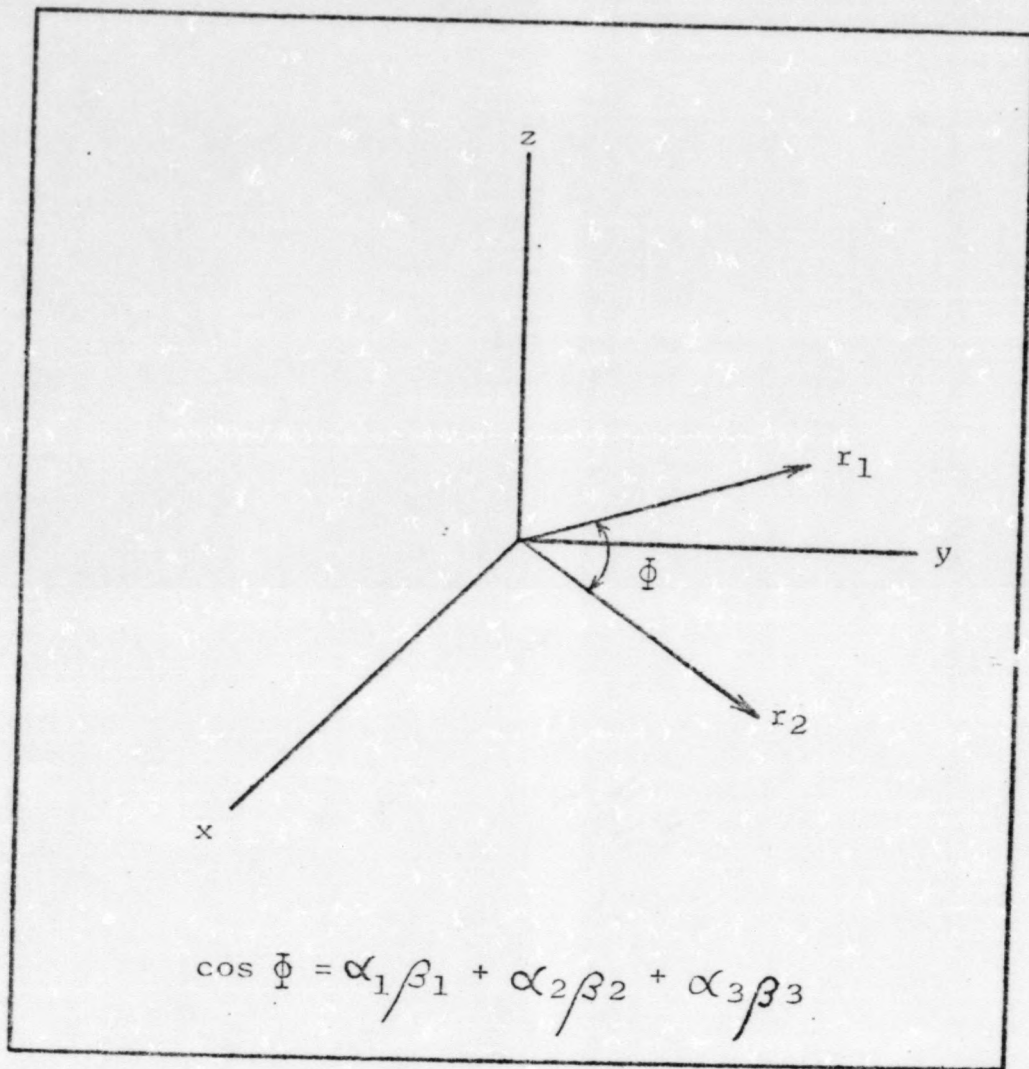$$\cos \Phi = \alpha_1 \beta_1 + \alpha_2 \beta_2 + \alpha_3 \beta_3$$

Figure 21 - The angle between two lines as a function of their direction cosines.

$\alpha_1, \alpha_2,$ and α_3 are the direction cosines of r_1.

$\beta_1, \beta_2,$ and β_3 are the direction cosines of r_2.
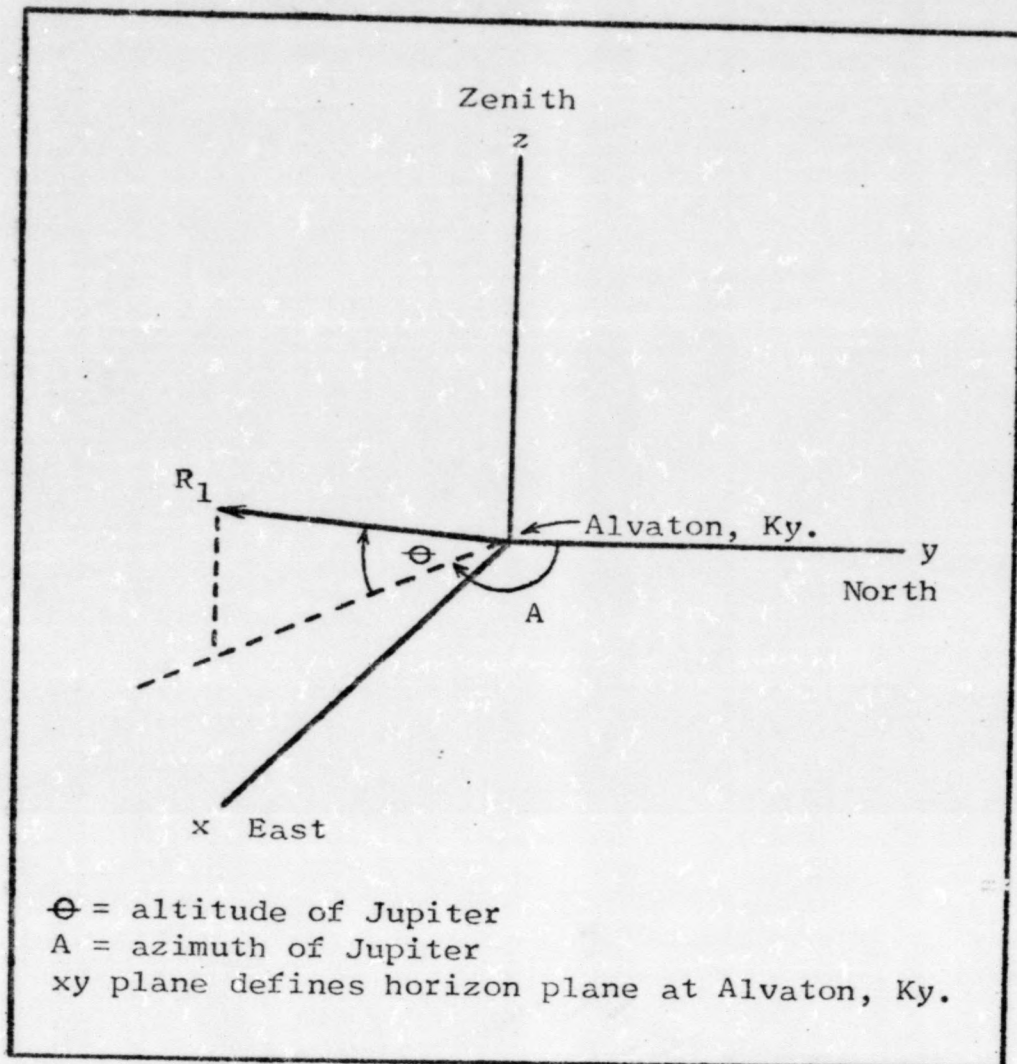
Figure 22 - Altitude and azimuth of Jupiter.

COMPONENTS	DIRECTION COSINES
$z = R_1 \sin\theta$	$\sin\theta$
$x = R_1(\cos\theta)(\sin A)$	$(\cos\theta)(\sin A)$
$y = R_1(\cos\theta)(\cos A)$	$(\cos\theta)(\cos A)$

Table 2 - Components and direction cosines of R_1.
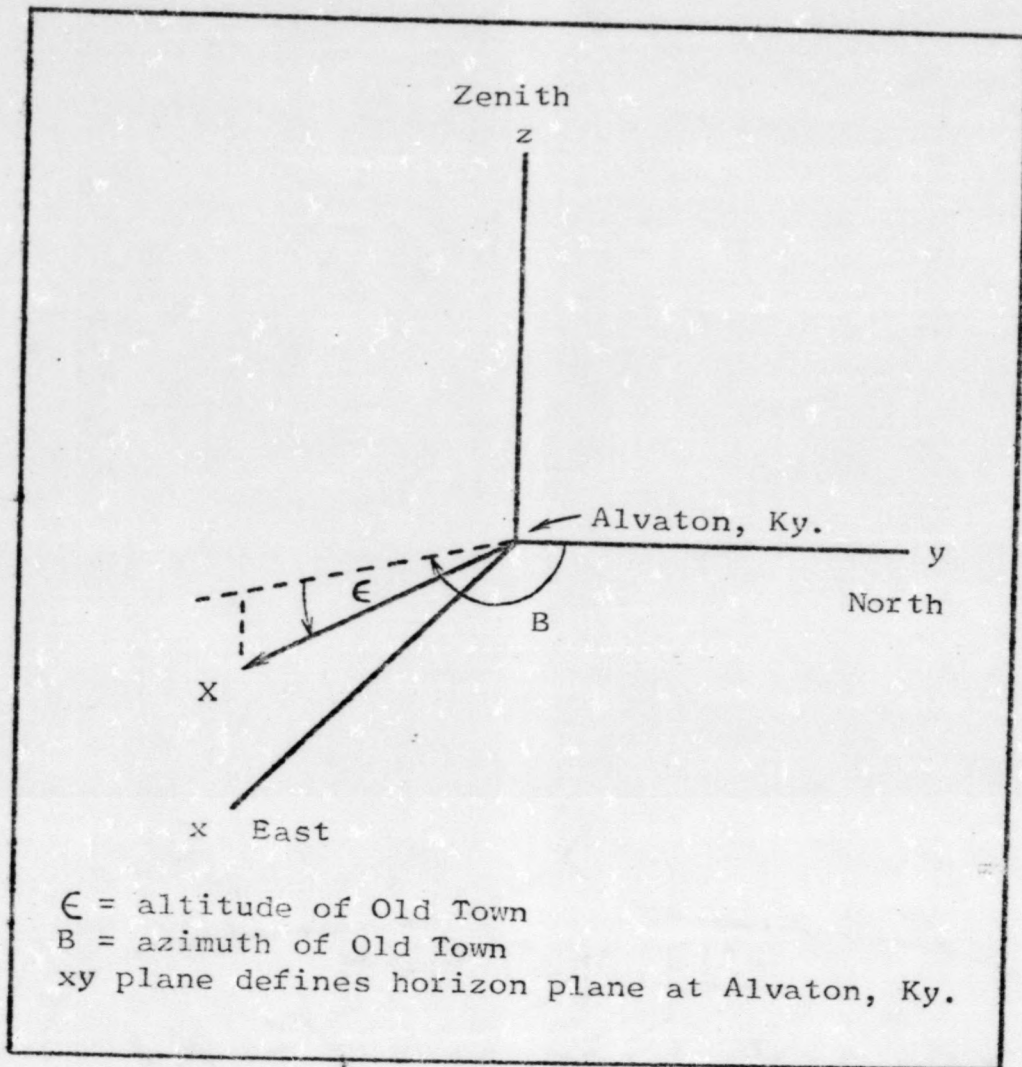
Figure 23 - Altitude and azimuth of Old Town.

COMPONENTS	DIRECTION COSINES
$z = X \sin \epsilon$	$\sin \epsilon$
$x = X(\cos \epsilon)(\sin B)$	$(\cos \epsilon)(\sin B)$
$y = X(\cos \epsilon)(\cos B)$	$(\cos \epsilon)(\cos B)$

Table 3 - Components and direction cosines of the baseline.

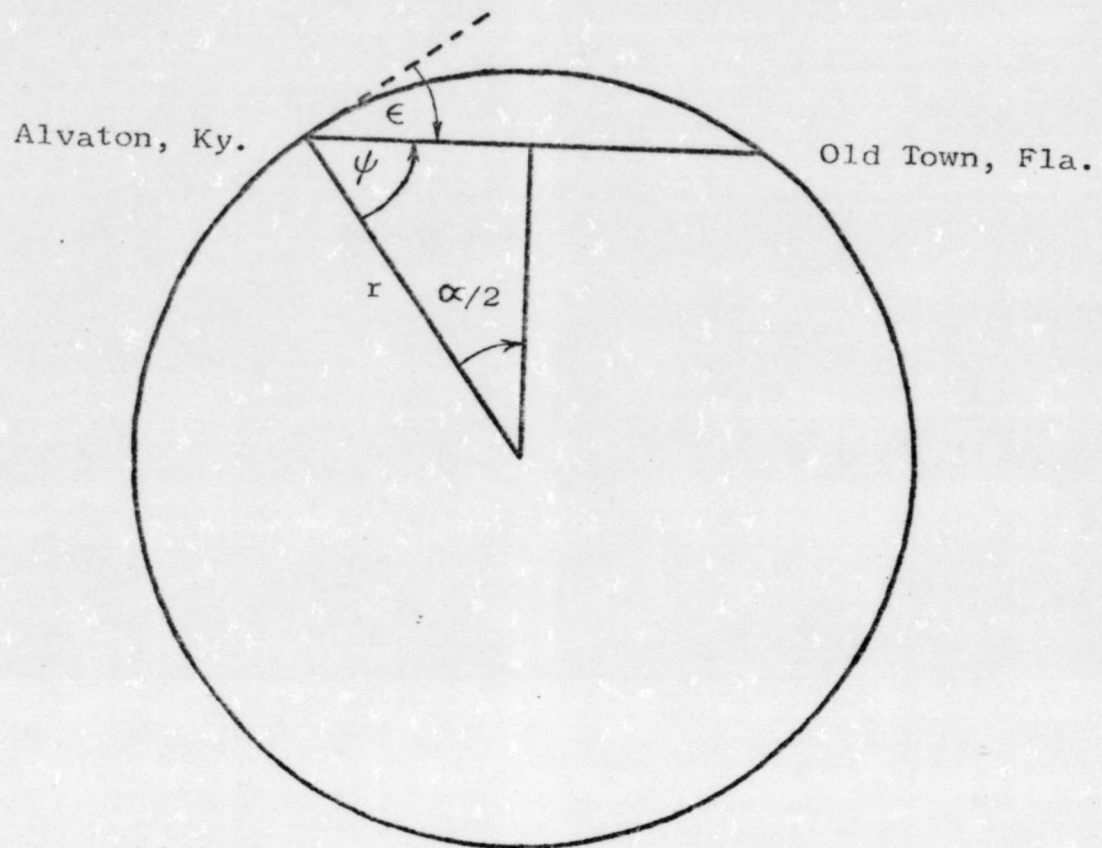Angle ϵ may be found by referring to Figure 24.

Figure 24

Determination of the altitude of Old Town.

$\alpha/2$ = half angle of arc between Alvaton and Old Town

ϵ = altitude of Old Town as seen from Alvaton

r = radius of the earth

$\epsilon = 90^\circ - \psi = \alpha/2$

$\epsilon = \frac{7^\circ 53}{2} = -3^\circ 57'$

Next we determine the azimuth of Old Town, Florida, for an observer at Alvaton, Kentucky. The law of sines for spherical triangles is: (15)

$$\frac{\sin A}{\sin(a)} = \frac{\sin B}{\sin(b)} = \frac{\sin C}{\sin(c)}$$, where A, B, and C are the three angles of the triangle, and a, b, and c are the arc lengths opposite angles A, B, and C. In Figure 25, B is the azimuth of Old Town as seen from Alvaton, and α is the arc length between Alvaton and Old Town. $\Delta\lambda$ is the difference in longitude of the two locations.
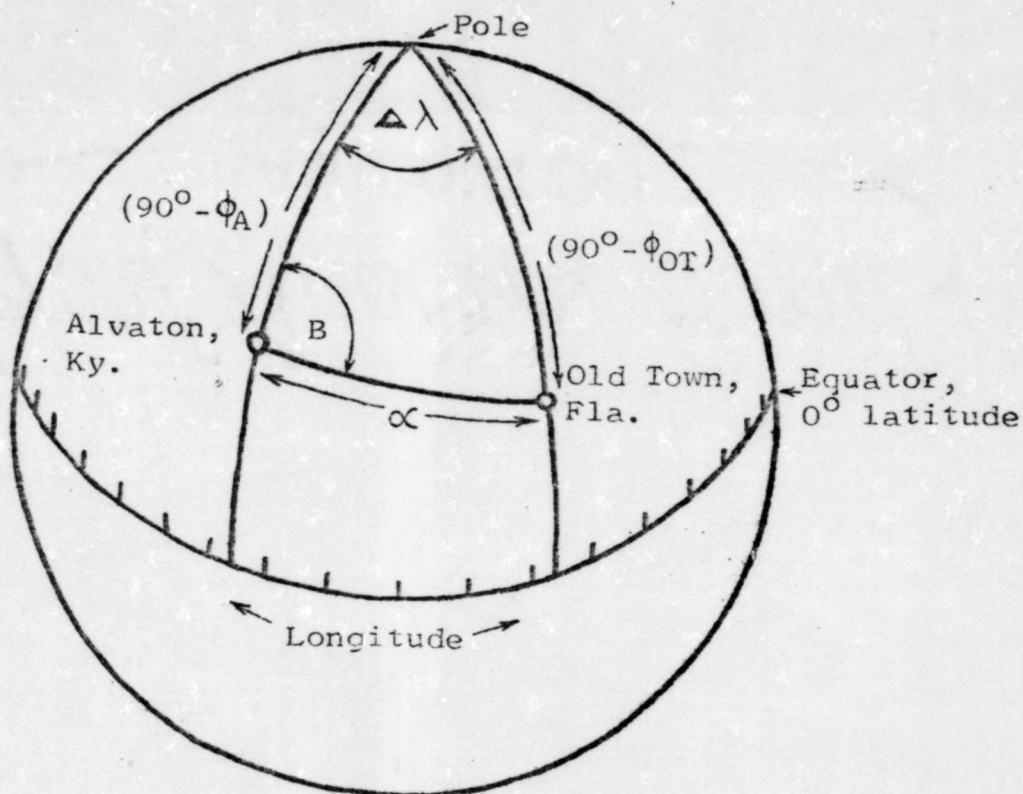

Figure 25

Determination of the azimuth of Old Town.

Using the law of sines:

$$\frac{\sin B}{\sin(90^\circ - \phi_{OT})} = \frac{\sin \Delta \lambda}{\sin \alpha}$$

$$\sin B = \frac{\cos(29^\circ 32') \sin(3^\circ 20')}{\sin(7^\circ 53')}$$

$$\sin B = \frac{(.87007)(.05814)}{(.13716)} = .36884$$

$$B = 158^\circ 22'$$

The altitude and azimuth of Jupiter for an observer at Alvaton can be calculated once the hour angle of Jupiter is determined. The coordinates of Jupiter for the morning of February 10, 1969, are given in Table 4.

DECLINATION	$-0^\circ 47' 03''.59$
RIGHT ASCENSION	$12^h 22^m 09^s.63$
MERIDIAN TRANSIT	$3^h 02^m 03^s$ Ephemeris time

Table 4 - Coordinates of Jupiter for the morning of February 10, 1969.

(15)

The hour angle of Jupiter is calculated as follows :

HA = Sidereal time -Right ascension

First determine the local civil time at $5^h 16^m 30^s$ UT.

$$LCT = 23^h 16^m 30^s \text{ CST} + 14^m 32^s \text{ longitude correction}$$
$$LCT = 23^h 31^m 02^s$$

The hour angle of the mean sun = $LCT -12^h = 11^h 31^m 02^s$

The right ascension of the mean sun on Feb. 10, 1969, was equal to $21^h 33^m 52^s$.

$$ST = HAMS + RAMS = 32^h 64^m 54^s$$

The right ascension of Jupiter on Feb. 10, 1969, was equal to $12^h 22^m 10^s$. The hour angle of Jupiter at $5^h 16^m 30^s$ UT on Feb. 10, 1969, was:

$$HA = 32^h 64^m 54^s -12^h 22^m 10^s = 20^h 42^m 44^s.$$ In angular measure the hour angle equals $310^o 41' 0''$

The altitude of any celestial body as seen from a particular location on earth is given by:

$$\sin\Theta = (\sin\delta)(\sin\phi) + (\cos\delta)(\cos\phi)(\cos HA)^{(15)}$$, where δ is the declination of the celestial body, HA is its hour angle, and ϕ is the latitude of the observer. On February 10, 1969, the declination of Jupiter was $-0^o 47'$ and its altitude at $5^h 16^m 30^s$ UT was:

$$\sin\Theta = \sin(-0^o 47')\sin(36^o 53') + \cos(-0^o 47')\cos(36^o 53')\cos(310^o 41')$$
$$\sin\Theta = (-.01367)(.60019) + (.99991)(.79986)(.65188)$$
$$\Theta = 30^o 53'$$

The azimuth of a celestial body at a given time and place on earth is given by:

$$cosA = \frac{(\sin\delta) - (\sin\phi)(\sin\theta)}{(\cos\phi)(\cos\theta)} \quad (15)$$

, where δ is the declination of the celestial body, θ is its altitude, and ϕ is the latitude of the observer. The azimuth of Jupiter at UT $5^h 16^m.30^s$ on February 10, 1969, for an observer at Alvaton, Kentucky, was:

$$cosA = \frac{\sin(-0°47') - \sin(36°53')\sin(30°53')}{\cos(36°53')\cos(30°53')}$$

$$cosA = \frac{(-.01367) - (.60019)(.51317)}{(.79986)(.85821)}$$

$$cosA = -.46859$$

$$A = 117°57'$$

Now that angles A, B, ϵ, and θ have been determined, the cosine of angle $\overline{\phi}$ and thus the geometric path difference and time delay can be found.

$$\cos\overline{\phi} = \cos(-3°57')\cos(30°53')\cos(40°25') + \sin(-3°57')\sin(30°53')$$

$$\cos\overline{\phi} = (.99762)(.85821)(.76135) - (.06889)(.51317)$$

$$\cos\overline{\phi} = .61649$$

The geometric path difference is:

$$D = (878.79 \text{ km})(.61649) = 541.76 \text{ km}$$

The geometric time delay is:

$$T = D/c = \frac{541.76 \text{ km}}{2.9979 \times 10^5 \text{ km/sec}} = 1.807 \text{ msec}$$

APPENDIX IV

OPTICAL PATH DIFFERENCE

A pulse from Jupiter will not arrive simultaneously at the two ends of the baseline if there exists an optical path difference. The effect of a purely geometrical path difference has been calculated in Appendix III. If the wave traverses ionized regions in space which are not homogeneous over the segment of the wavefront that strikes the interferometer, another delay is introduced. Such an effect is produced in the terrestrial ionosphere. The following calculation of the time delay caused by a difference in optical path length, includes both geometric and propagation effects. Since insufficient information exists concerning ionized regions in interplanetary space, the following calculations include the propagation delay introduced by the earth's atmosphere from ground level to 700 km, the assumed top of the ionosphere, and the geometric path difference in essentially free space. See Figure 26.
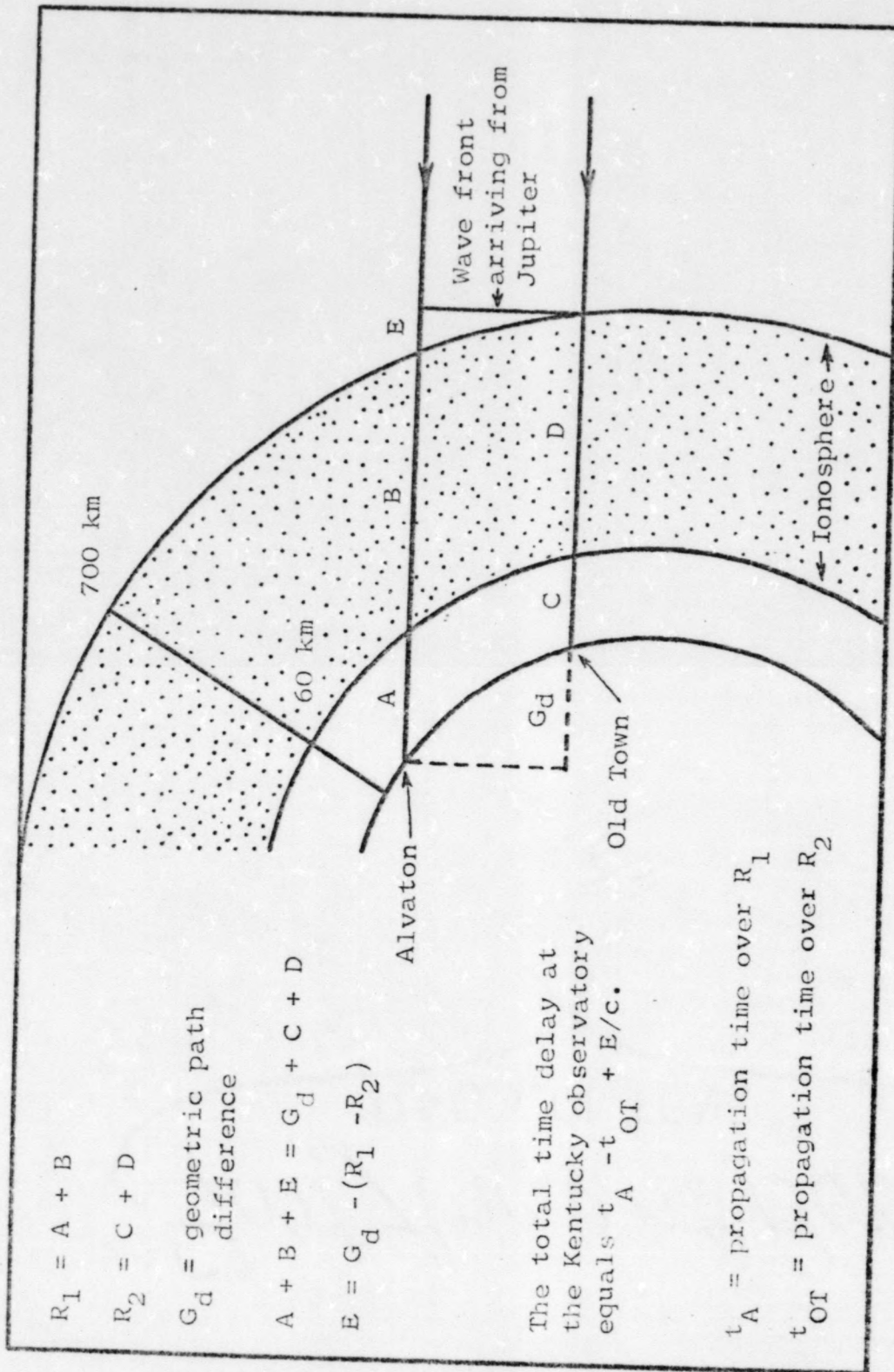
Figure 26 - The optical path difference.

$R_1 = A + B$

$R_2 = C + D$

G_d = geometric path difference

$A + B + E = G_d + C + D$

$E = G_d - (R_1 - R_2)$

The total time delay at the Kentucky observatory equals $t_A - t_{OT} + E/c$.

t_A = propagation time over R_1

t_{OT} = propagation time over R_2

The propagation time t of a pulse from the top of the ionosphere to the ground, may be found by evaluating the following integral:

$$t = \int \frac{dx}{\mu c}$$, where μ is the phase refractive index, c is the free-space velocity, and the integration is carried out over the path through the ionosphere. Using cgs units, μ may be expressed as:

$$\mu = \sqrt{1 - \frac{8.1 \times 10^{-5}N}{f^2}}$$ (17)   , where N is the electron

density in e/cm^3 and f is the frequency in MHz. Assuming a cosine model of the ionosphere (18), the variation of electron density with altitude can be written:

$$N = \tfrac{1}{2}N_m(1 + \cos\pi\frac{h - h_m}{a})$$, where N_m is the maximum electron

density, h_m is the height of the maximum electron density, h is the height where the electron density is equal to N, and a equals the half-thickness $(h_m - h_o)$ where h_o is the height at which the ionosphere begins. The value choosen for N_m is 3×10^5 e/cm^3 (17). Assuming $h_o = 60$ km (17) and $h_m = 380$ km (17) the value of a is 320 km. The altitude of Jupiter at the Kentucky observatory was $30^\circ 53'$ and at the Florida observatory, $36^\circ 43'$, when the data was recorded. The refractive effects due to the atmosphere are negligible, thus the propagation paths are considered to be straight lines. The effect of receiver bandwidth (2.1 kHz) was calculated and found to be negligible.

Making the above substitutions, the path integral from ground level to 700 km is:

$$t = \frac{1}{c\sin\Theta}\left[\int_{0\text{ km}}^{60\text{ km}} 1\, dh + \int_{60\text{ km}}^{700\text{ km}} \frac{dh}{\sqrt{1 - KB\left(1 + \cos\pi\frac{h - h_m}{a}\right)}}\right]$$

where $K = \dfrac{8.1 \times 10^{-5}}{(f = 18\text{ MHz})^2}$, $B = \frac{1}{2}N_m$, and Θ is the altitude of

Jupiter. Using the trigonometric identity $\cos^2\psi/2 = \dfrac{1 + \cos\psi}{2}$,

and letting $u = \pi\dfrac{h - h_m}{2a}$ and $k^2 = 2KB$, and using the symmetry of

the integrand, one obtains:

$$t = \frac{1}{c\sin\Theta}\left[60\text{ km} + \frac{4a}{\pi}\int_0^{\pi/2} \frac{d\phi}{\sqrt{1 - k^2\sin^2\phi}}\right],$$

which is a complete elliptical integral of the first kind.

Evaluating:

$$t = \frac{.002378}{\sin\Theta}\text{ sec}$$

Substituting:

$$t_A = \frac{.002378}{(\sin30°54)} = 4.6339\text{ msec}$$

$$t_{OT} = \frac{.002378}{(\sin36°44)} = 3.9780\text{ msec}$$

Δt = (total time difference due to optical path

difference) = $t_A - t_{OT} + \dfrac{G_d - (R_1 - R_2)}{c} = 1.819\text{ msec}$

The following calculation is performed to determine if a time delay of the same magnitude as the observed time delay of 0.06 msec (which is considerably less than one standard deviation) could be introduced by a difference in the ionospheric media along the propagation paths.

Suppose t_A = 4.6339 msec + 0.06 msec = 4.6939 msec. The value of the complete elliptical integral is now 1.6688.

$$\theta = 27^\circ 41'$$

$$\sin\theta = k = .46458$$

$$k^2 = 2KB = .21583$$

$$.21583 = \frac{(2)(8.1 \times 10^{-5})(\frac{1}{2}N_m)}{(18 \text{ MHz})^2}$$

$$N_m = 8.63 \times 10^5 \text{ e/cm}^3$$

Thus it is seen that if the maximum electron density along the Alvaton propagation path had been approximately 3 times the assumed value of 3×10^5 e/cm^3 along the Old Town propagation path, an additional ionospheric delay of 0.06 msec would have occurred at the Kentucky observatory. For the maximum electron density along the propagation paths to differ by a factor of 3 is not unreasonable. However, since the observed time delay is so much less than the measuring error, these results should not be considered as an explanation of the observed delay but rather as helpful information for use in future investigations.

LIST OF REFERENCES

1. Franklin, K. L., "An Account of the Discovery of Jupiter as a Radio Source", Astron. J. 64, 37-39 (1959).

2. Mayer, C. H., "Radio Emission of the Moon and Planets", Planets and Satellites , edited by G. P. Kuiper and B. M. Middlehurst (University of Chicago Press, Chicago, 1961).

3. Carr, T. D., and Smith, A. G., Radio Exploration of the Planetary System (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1964).

4. Radhakrishnan, V., and Roberts, J. A., "Polarization and Angular Extent of the 960 MHz Radiation from Jupiter", Phys. Rev. Letters 4, 493-494 (1960).

5. Block, W. F., Carr, T. D., Lebo, G. R., Paul, M. P., Robinson, V. M., and Six, N. F., "Interferometry of Jupiter at 18 MHz with a 52,800λ Baseline", Astrophysical Letters, Vol. 5, 133-136 (1970).

6. Carr, T. D., report before the December, 1958, meeting of the American Astronomical Society.

7. Warwick, J. W., "Theory of Jupiter's Decametric Radio Emission", Annals N. Y. Acad. Sci. 95, 39-60 (1961).

8. Goldreich, P., Lynden-Bell, D., "Io, a Jovian Unipolar Inductor", Astrophys. J. 156, 59-78 (1969).

9. Warwick, J. W., "Relation of Jupiter's Radio Emission at Long Wavelengths to Solar Activity", Science 132, 1250-1252 (1960).

10. Smith, A. G., "Jupiter, the Radio-Active Planet", American Scientist, 57, 2, 177-192 (1969).

11. Bigg, E. K., Nature, 203, 1008 (1964).

12. Carr, T. D., May, J., Olsson, C. N., and Walls, G. F., "Post Detector Correlation Interferometry of Jupiter at 18 MHz", IEEE NEREM Record, 7, 22 (1965).

13. Block, W. F., Brown, G. W., and Carr, T. D., "Long-Baseline Interferometry of S-Bursts from Jupiter", Astrophysical Letters, Vol. 1, 89-94 (1968).

14. Robinson, V. M., Private Communication, April 15, 1970.

15. Smart, W. M., Text-Book on Spherical Astronomy (Cambridge University Press, Cambridge, England, 1962).

16. The American Ephemeris and Nautical Almanac for the Year 1969 (U. S. Government Printing Office, Washington, D. C., 1967).

17. Glasstone, S., Sourcebook on the Space Sciences (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1965).

18. Davies, K., Ionospheric Radio Waves (Blaisdell Publishing Company, Waltham, Massachusetts, 1969).