TIMING POTENTIALS OF LORAN-C

by

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ABSTRACT

The Loran-C navigation system is capable of synchronizing and setting clocks to a relative accuracy of better than one microsecond throughout the system's service area. The East Coast Loran-C chain will be synchronized with the national frequency standards and uniform time source located at Boulder. Time synchronization and time distribution will be demonstrated on the Atlantic Missile Range. Inter-range time synchronization and precise time for large areas of the world could be provided in the future.

A Loran-C receiver functions as a slaved oscillator and a trigger generator. The generated triggers bear a time relationship to the triggers at the master transmitter, which is known to within a microsecond. Clocks operating from these sources are compared with clocks operating from independent free-running oscillators.

A fundamental relationship between time and position is considered. Loran-C as a navigation and timing system can provide both position and time simultaneously.

TIMING POTENTIALS OF LORAN-C

I. Introduction

In the majority of timing applications a problem exists in setting two or more clocks to agree with one another. The greater the requirement for precise agreement between these clocks, the more difficult the problem becomes and if the clocks are in widely separated locations the difficulty is further increased. The reading of a single clock is meaningful only as it relates to its own frame of reference. For example, a clock may gain or lose with respect to the periodicity of the earth as it revolves about its own axis or about the sun.

Accurate astronomical time depends on long-term observations, but is ultimately limited by unpredictable variations in the earth's rotation. Furthermore, any astronomical time can be determined only to an accuracy of several milliseconds for a single set of observations. The initial settings of individual clocks may, therefore, differ by amounts of the order of milliseconds. These differences combined with the gains or losses of individual clocks are of such magnitude that independently operating clocks or clocks synchronized by existing radio timing signals are unable to make measurements more precise than a millisecond at different locations.

When it is necessary to measure time at two or more locations to an accuracy of one microsecond or better, such measurements must all be made within the same frame of reference, that is within a single clock system. The term "clock system" as used in this paper means a master clock at a convenient central location and other clocks at widely separated locations which are slaved to the master in such a way that each will track the master. Such a clock system must also provide for a means to synchronize or set each slave clock to agree accurately with the master clock. A number of Loran-C clocks will function as such a clock system with initial setting or synchronizing accuracies of one microsecond or better.

The National Bureau of Standards at Boulder, Colorado maintains the nation's primary frequency standard. A fail safe clock operating from this standard would provide an extremely uniform time source that could be related in retrospect to any astronomical time measurements. This uniform time source is the proposed means for controlling the aforementioned master clock.

II. Loran-C Operation and Its Timing Application

Loran-C [1] is an operational pulse navigation system operating on a basic frequency of 100 kc and normally consisting of a master station and two or more slave stations. Several Loran-C chains are operational or under construction. The U. S. East Coast chain and its primary navigational coverage areas are shown in Fig. 1. The master station is located at Cape Fear, North Carolina and the two slave stations at Marthas Vinyard, Mass. and Jupiter Inlet, Florida. The area over which a ground wave could be received for timing purposes would extend approximately 2,000 miles seaward or 1500 miles landward from any one transmitter.

The Loran-C system utilizes synchronous detection techniques and methods for determining a fixed sampling point early on the pulse independent of pulse amplitude. By this means the ground wave is completely resolved from the sky waves. See Fig. 2. To a first approximation the ground wave transmission time is proportional to distance. Secondary corrections, however, usually have a magnitude in the range of 1 to 10μs. This correction is determined largely by the conductivity of the path and to a much smaller extent by the dielectric constant and the index of atmospheric refraction. [2, 3] Both the conductivity and the dielectric constant of sea water are accurately known. Consequently, the transmission time over sea water can be computed accurately. Transmission times over paths involving land can not be as accurately calculated since the conductivity of land is not well known. However, experience in correlating time difference measurements[1] with generalized assumptions of ground conductivity is valuable. For example, it has been demonstrated [4] that the best single value which can be assigned to the eastern half of the U. S. is 0.005 mhos/meter. The average error between time differences computed using this conductivity and those measured was approximately 0.8μs. The algebraic average was nearly zero and the maximum error among all sites was 2.5μs. The largest errors were associated with sites located in mountainous terrain. Until better prediction methods are developed it must be assumed that systematic errors of the order of one microsecond may exist in land and mixed paths unless the transmission time has been measured by use of two transmitters.

1. All time difference measurements are determined by phase differences at 100 kc.

The East Coast Loran-C chain operates on a basic repetition rate of twenty pulse groups per second[2]. A pulse group consists of eight phase coded pulses with a uniform spacing of one millisecond. The Loran-C system, as presently operated, does not resolve time increments larger than the repetition period or 50 milliseconds. Larger increments could be resolved without interference to the system, but at this time there appears to be no pressing requirement for such a change. The 50-millisecond interval between pulse groups can be resolved conveniently by the WWV seconds' pulses. In order to use WWV and Loran-C in such a manner the two transmitting systems must be geared together. They would be since WWV is transmitting the aforementioned uniform time. [5] See Fig. 3.

The Loran-C navigation system operating on a basic frequency of 100 kc performs the vitally important function of slaving all oscillators in the system to the oscillator at the master transmitter.

By virtue of the technique of slaving a number of relatively cheap oscillators to a master oscillator, all clocks operated from such oscillators will, by definition, have an average drift rate of zero. The instantaneous deviation of any one clock from the average is primarily determined by the factors listed below:

1. Signal-to-noise ratio.
2. Relative and absolute quality of slave and master oscillators.
3. Integration time.
4. Tightness of coupling of the slave oscillator.

The positioning system requires a means for selecting a given cycle and a point on that cycle. It is obvious that this criteria for the positioning system satisfies the requirements for synchronizing a timing system. The instrumentation being utilized in the navigation system has a resolution of a few hundreths of one microsecond. The time variations in propagation due to changes in refractive index, conductivity, etc. are substantially less for all times than the previously mentioned predictabilities. (typical standard deviations at any given site were .2 to .3 μs [4])

2. Fractional Loran rates can also be used for the operation of a clock by gating the received pulses and using only those transmitted on the second to set the clock.

In order to relate the Loran-C system to the primary frequency standard it is proposed to install an extremely high quality secondary frequency standard at the Loran-C master and then monitor the master transmissions at Boulder to provide periodic adjustments.

Measurements of Loran-C signals from the East Coast made in Boulder in 1953 and 1955 [6] showed that the propagation time can be determined to an absolute accuracy of about one microsecond with an integration time of less than one minute. The standard deviation of such measurements (daytime) is less than 0.5μs. A better receiving antenna might make it possible to use the ground wave signal and achieve a substantially better measurement of the Loran-C master oscillator frequency.

A somewhat more sophisticated proposal is to locate a fourth station and the secondary standard in Illinois. The East Coast chain would then be synchronized with this station and good ground wave signals would be available at Boulder.

III. Setting a Loran-C Clock

In order to set a slave clock to agree with the master clock it is first necessary to determine the amount by which the apparent time at the slave is slow with respect to the master.

After the signal has reached the antenna, additional time is required for it to pass through the receiver and produce a trigger suitable for starting or synchronizing the clock. This time depends solely on the receiver design. For timing purposes the Loran-C receiver should be designed in such a way that the transmission time through it remains constant over a wide range of environmental conditions.

The apparent time at the receiver is slow by the amount of time required for the signal to propagate from the master transmitter and through the Loran system to the receiver, plus the transmission time through the receiver plus any additional systematic delays such as the coding delay normally used in a Loran system. This is illustrated by the following example:

Given:
1. Receiver 1000 miles from Jupiter
2. Sea water path
3. Receiver delay 25.0 μs

Propagation time 1000 mi. sea water	5373.1 μs
Propagation time Cape Fear to Jupiter	2711.8
Jupiter coding delay	12000.0
Receiver delay	25.0
Total Delay	20109.9 μs

It is assumed that a pulse is transmitted from the master station at Cape Fear precisely at each second. The corresponding pulse from the slave station at Jupiter would produce a time trigger at the receiver output 20,109.9 μs later. Therefore, the clock at the receiver should read .020110 sec. when this time trigger is used as a read command. The calibration of this clock to read the correct fraction of a second is accomplished by adding counts to the divider chain.

Therefore this clock will maintain the same uniform time as the master clock. A one second or one minute output from the clock will occur within one microsecond of the respective output from any other Loran-C clock in the system. Fig. 4 is a front view of the developmental model of a Loran-C clock. The panel immediately above the oscilloscope contains a 15 digit visual display covering one microsecond to hundreds of days. When the clock is given a read command this display reads out the time and holds until the next read command is received. A photographic display that will read out within 200 microseconds after receipt of a read command utilizes "Nixie" neon tubes. (Fig. 4 & 5) Fig. 5 shows some mechanical and packaging details of the clock. Solid state techniques were utilized wherever possible on the clock construction.

IV. Slaved Clocks vs. Independent Clocks

The comparison of Loran-C clocks (slaved clocks) with independent clocks running from oscillators of different qualities is shown in Fig. 6. This comparison assumes that two independent clocks are drifting apart at a drift rate equal to the maximum rate indicated. The independent clocks must be initially synchronized and must run continuously without interruption. The Loran-C clocks may be interrupted and resynchronized at random without effecting the accuracy.

Assume a clock operating from the slaved oscillator of a Loran-C receiver is correctly set. If that clock and receiver are moved a distance of 983 feet toward the Loran-C transmitter the clock will then be one microsecond fast. Similarly, if the clock is moved 983 feet in the opposite direction it will be one microsecond slow. In contrast, if the same clock were operating from an independent oscillator it would neither gain nor lose as a result of motion.

If a Loran-C clock is used in a moving vehicle its position must always be taken into account. In either ships or aircraft the fixes available from the Loran-C navigation system can provide the necessary information. However, the computations required to convert the time difference readings to distance from the transmitters are rather involved and would necessitate a computer in most cases. However in a stationery ship or remote location the time and position can be obtained simultaneously.

On the surface it might appear that an independent clock would be more satisfactory in a moving vehicle. This may be true occasionally provided the clock does not have to maintain the correct time for a long period. Even the best clocks (or oscillators) will drift with respect to other clocks. In cases where drifts of the order of a microsecond are important, the slaved clock is a virtual necessity.

As the accuracy of clocks within a timing system is increased, the location of each clock becomes correspondingly more important. Fig. 7 illustrates this simple relationship. The timing precision of Loran-C and WWV are also shown for an integration time of approximately one minute. Much longer integration times would improve the accuracies obtainable with WWV. [5]

V. Atlantic Range Timing

The National Bureau of Standards is furnishing the engineering services to design and build Loran-C clocks and a UHF timing distribution system to demonstrate timing feasibility on the AMR. After the feasibility demonstrations the AMR may elect to time synchronize all of the down range stations with Loran C. The clocks consist of the modified Loran-C receivers and counting and read-out circuits. WWV is used to resolve increments of time larger than 50 milliseconds.

This clock is of necessity a rather complex device. Where a large number of equipments requiring time are operated in close proximity, a single clock can serve them all by means of an appropriate UHF timing distribution system. This basic system of time measurement and distribution can be duplicated at any number of mainland and down-range sites within the coverage area of the East Coast Loran-C chain. See Fig. 8.

The UHF distribution system utilizes a single channel to transmit several time codes with pulse position modulation techniques. A 1000 pulse per second rate is obtained from the clock and transmitted to give accurate millisecond time. A total of eleven time codes and seven repetition rates are transmitted by dividing the 1000 microsecond period into 18 short intervals. Pulses are positioned within these intervals to transmit the codes and repetition rates. The information is sent in the interval preceding the indicated time and all codes or repetition rates are generated on time coincident with the next pulse. In this manner all codes and repetition rates have the same time accuracy as the millisecond pulse, which is nominally one microsecond.

Assured Loran-C ground wave coverage extends down range at least as far as Trinidad and perhaps beyond. The various down-range sites to that distance can be provided with absolute timing accuracy of approximately one microsecond. It is important to note that the absolute accuracy involves an allowance for systematic propagation errors which cannot be measured independently by any existing system or method. The repeatability of time measurements at any one station, however, will in general be better than 0.1 μs. In some cases repeatability may be at least as important as absolute accuracy. For example: The trajectory of a missile could be determined by transmitting very short pulses at UHF or microwave frequencies from the missile and recording their time of arrival at a number of time synchronized stations. See Fig. 9. Systematic time errors among the observing stations would result in a corresponding error in the absolute position of the trajectory, but the changes from reading to reading would be influenced only by the stability of the individual clocks and the stability of the propagation medium between the missile and the ground stations.

On the basis of theory [7] and measurements [6] there is little doubt that Loran-C clocks can be synchronized at Fernando and Ascension Islands on second and/or third hop sky waves. Second hop sky wave time differences from the Cytac transmitters (Forestport, New York, Cape Fear, North Carolina, and Carrabelle, Florida) were measured at distances up to 3000 miles. Standard deviations of these differences were less than two microseconds day and night. Sunrise and sunset effects corresponding to 18 to 20 km change in ionospheric height were observed. Since only the first reflected signal was utilized these sunrise and sunset effects rarely lasted more than 30 minutes. The height variations agree well with other observations for oblique incidence. [8, 9] At distances beyond ground wave range there is no satisfactory way to accurately measure sky wave delays. But there is no reason to distrust computed values based on theoretical calculations, former observations and recent electron density rocket information. [7, 8, 9, 10] With generous allowance for error, it should be possible to establish time at Fernando and Ascension within 10 microseconds.

VI. Inter-Range Synchronization

The Atlantic and Pacific missile ranges can be linked with a common timing system which will provide one microsecond accuracy. The link between the two ranges requires the installation of additional Loran-C stations in a generally East-West direction across Continental U. S. Possible locations for these stations are shown in Fig. 10. Such a configuration would provide inter range synchronization as well as excellent navigational coverage over Continental U. S.

The inter range synchronization only could be obtained on a very reliable basis by providing the previously mentioned transmitter in Illinois and another transmitter and secondary frequency standard near the West Coast. The western transmitter would be located within ground wave range of Boulder and steered along with the East Coast chain by the primary frequency standard. If a number of Loran-C chains were synchronized, one to another, in order to provide coverage over very long ranges, the synchronization accuracy would be degraded to some extent. As far as is known, synchronization errors are of a random nature and therefore can be expected to add as the root-sum-square. For example: If the synchronization error in each transmitter is 0.03 microsecond, the accumulated error in synchronizing six stations would be $\sqrt{6(.03)^2}$ or 0.073 microseconds.

The synchronization accuracy of the present Loran-C system could be improved by the use of better oscillators and longer integration times. It is not obvious, however, how much improvement could be achieved before reaching the point of diminishing returns.

The total noise or synchronization errors which can be expected in synchronizing a chain in the Hawaiian Islands should be substantially less than the prediction error in a land or mixed path.

VII. Additional Uses of Precise Time

Some scientific and commercial uses of a precise timing system that may have direct or indirect military applications are:

1. The positioning of high-altitude aircraft from the ground by using the UHF pulse technique.

2. The location of thunderstorms by precisely measuring the location of the lightning discharge.

3. The accurate position-fixing of nuclear detonations by a similar means.

4. A precise evaluation of the fluctuations of the periodicity of the earth's rotation and other astronomical phenomena by relating observations made at widely separated points.

5. The precise measurement of time variations on high frequency transmissions such as WWV as an aid to better understanding of propagation phenomena.

6. Similar measurements on forward scatter communication links and other types of communication could also be made.

7. The surveying of offshore islands and remote areas.

8. The investigation of Loran-C sky waves to give a better understanding of LF ionospheric conditions.

9. The precise time from a single Loran-C clock could be made economically feasible for a variety of users in industry and research by the application of a VHF or UHF distribution system. Relatively inexpensive receivers would result if sufficient users were located within range of the distribution system. Existing facilities such as television transmitters could be utilized for this purpose.

VIII. Acknowledgements

Special acknowledgement is given to Mr. P. J. Kiser, of the Air Force Eastern GEEIA Region, for his engineering contributions to the Loran-C clock and his assistance in the preparation of this paper.

The entire Loran-C clock and UHF distribution system is being developed by the National Bureau of Standards, Boulder Laboratories under the sponsorship of Headquarters, Eastern GEEIA Region.

LIST OF FIGURES

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Loran-C Coverage

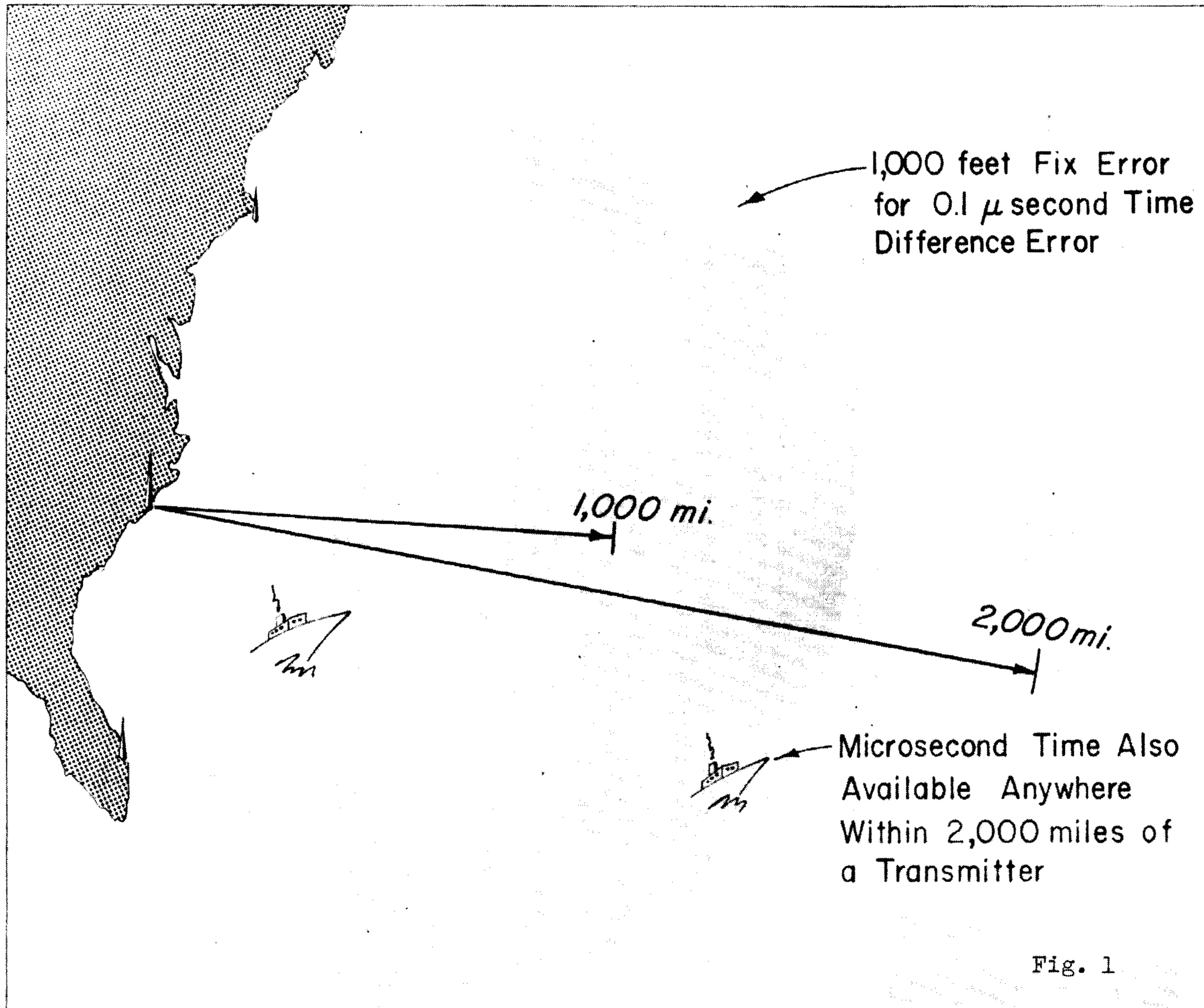

Fig. 1

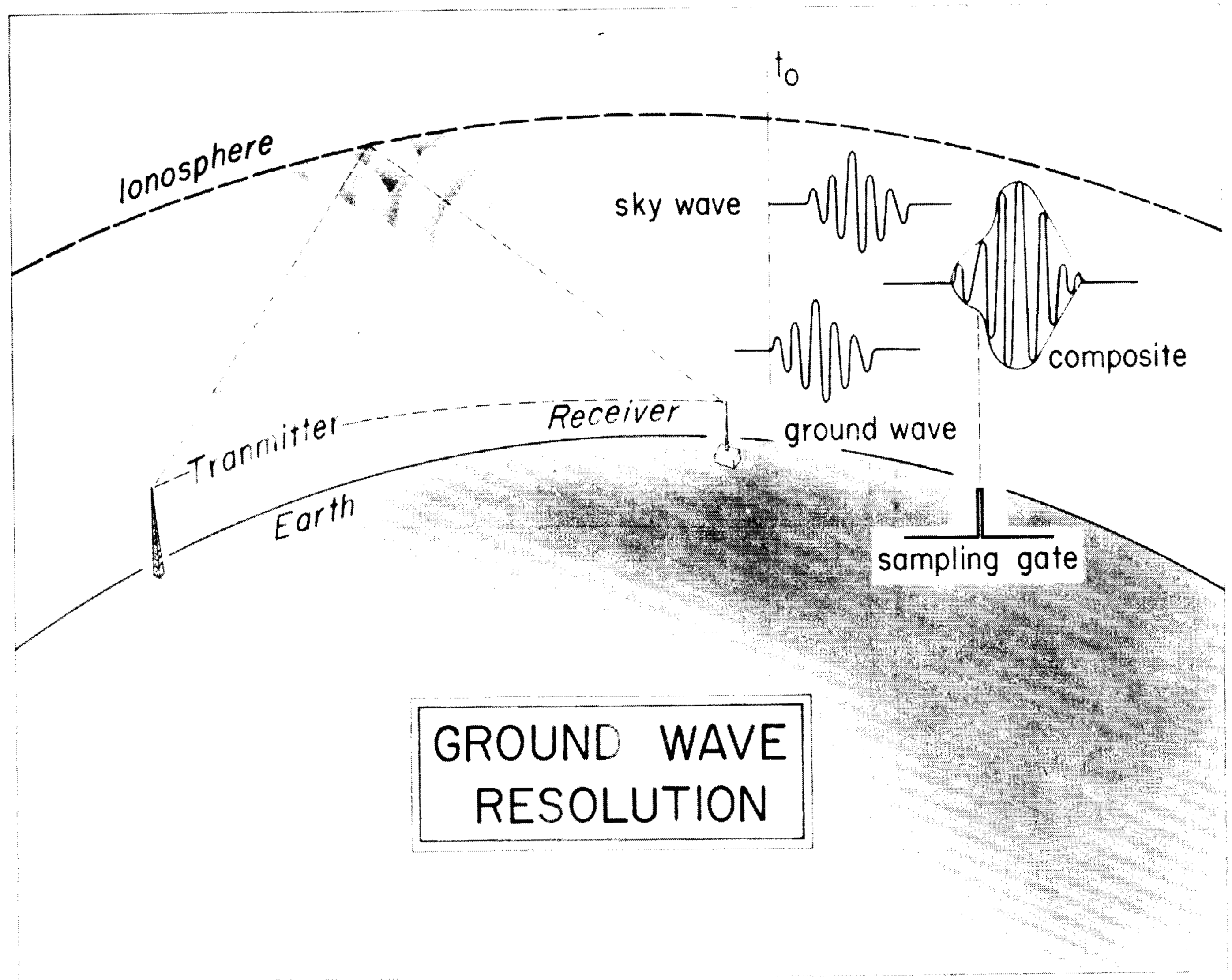
t$_0$
Ionosphere
sky wave
composite
Trannitter
Receiver
ground wave
Earth
sampling gate
GROUND WAVE
RESOLUTION

Fig. 2

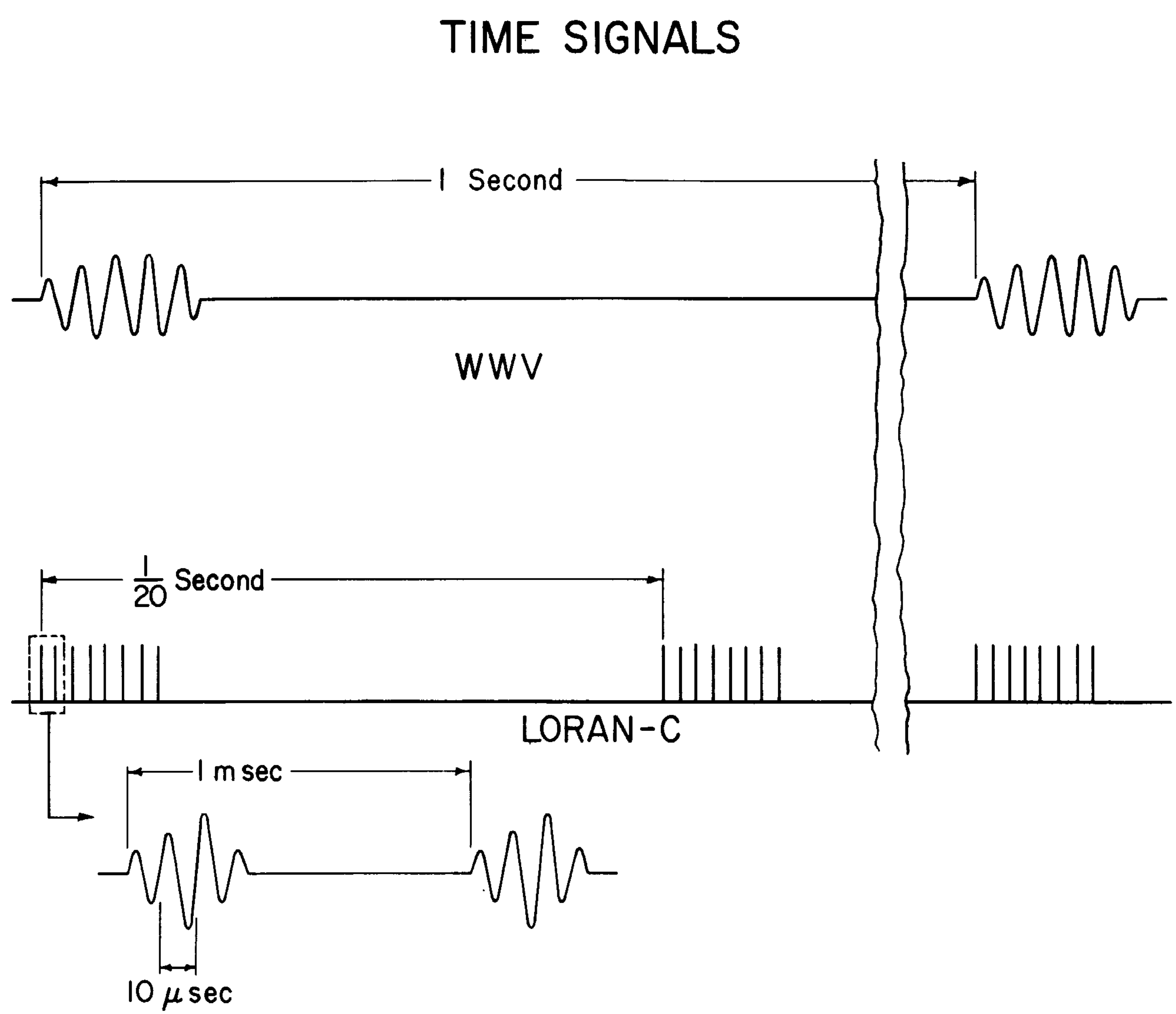

Fig. 3

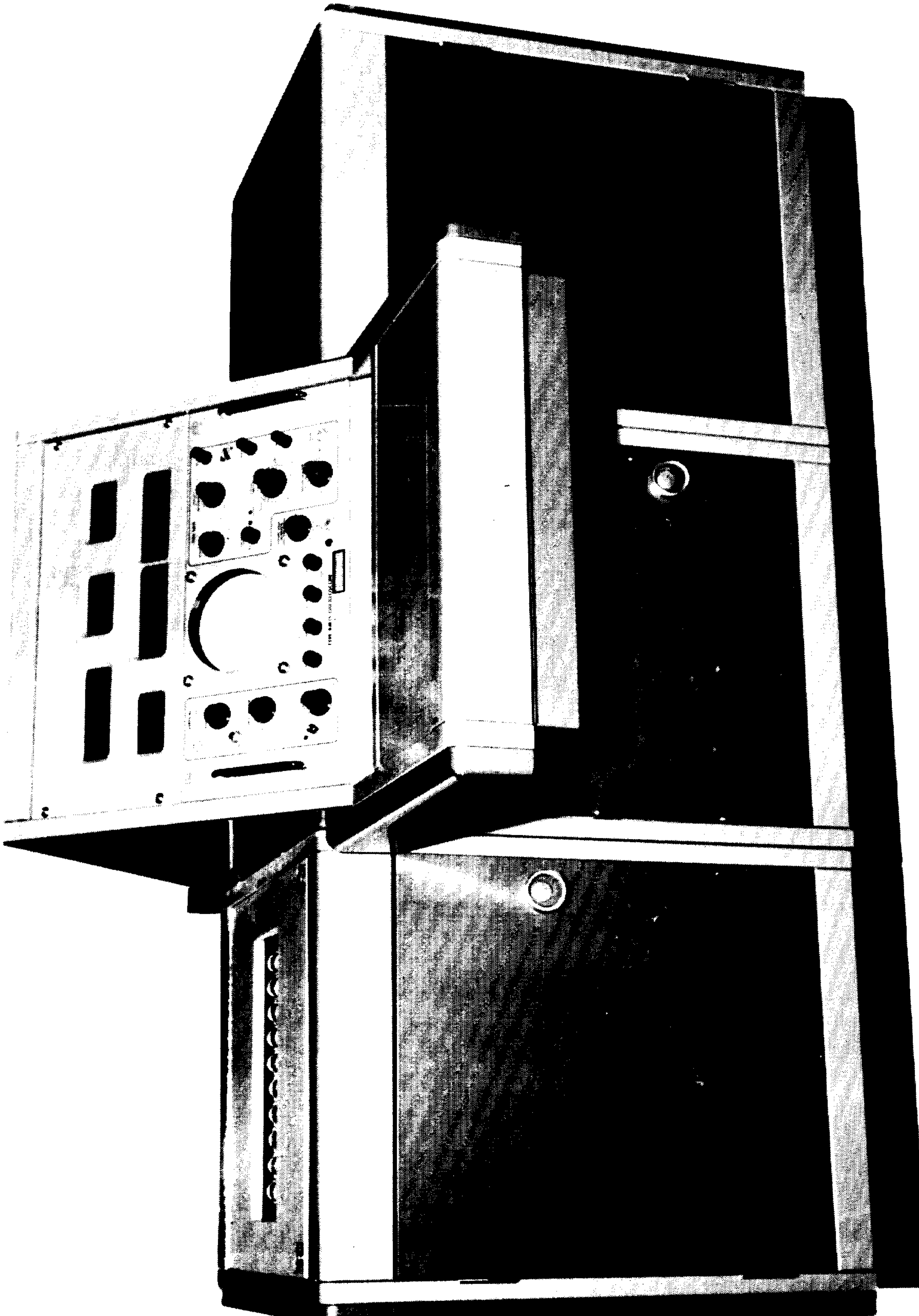

Fig. 4

Loran-C Clock (Front View)

Loran-C Clock (Rear View)

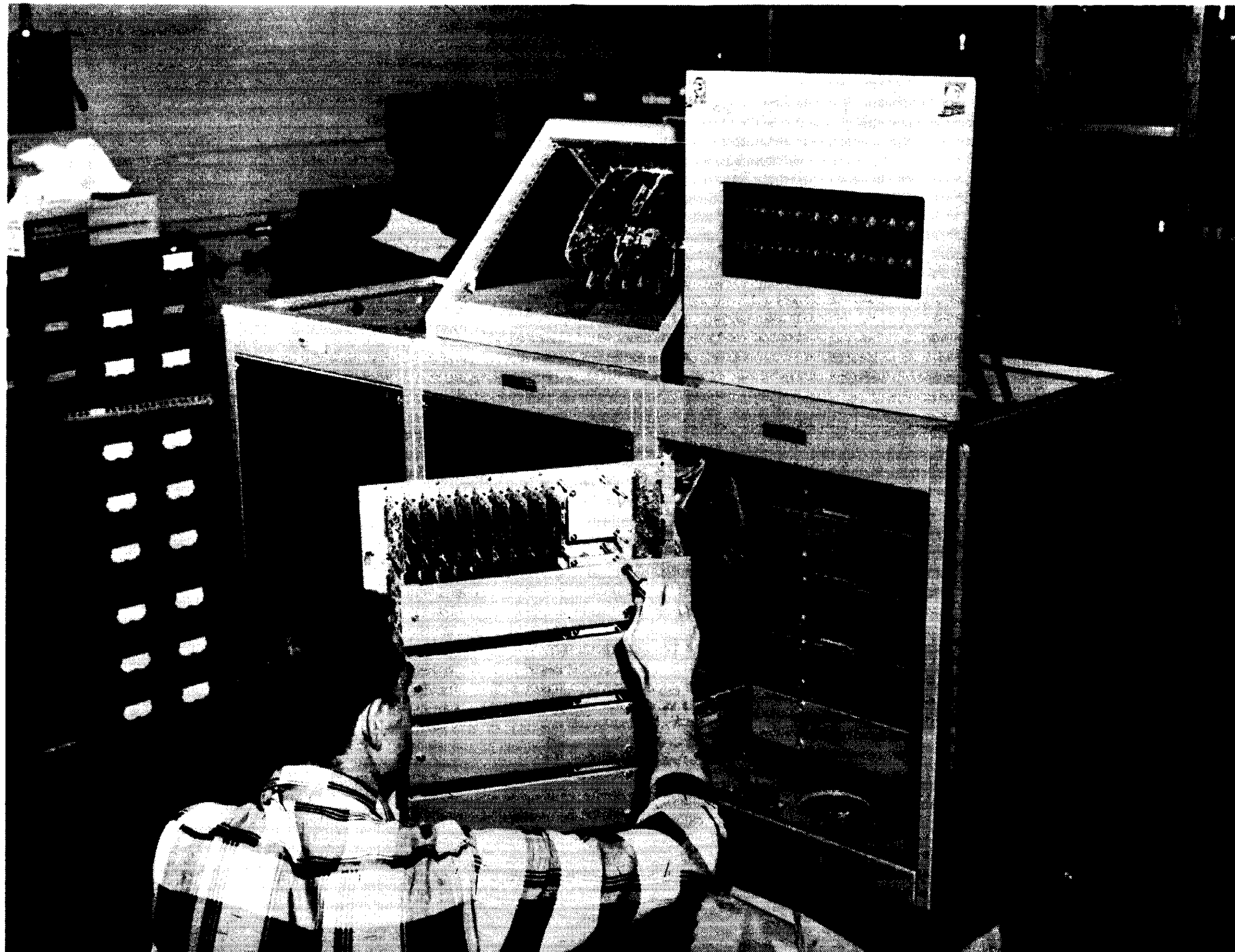

Fig. 5

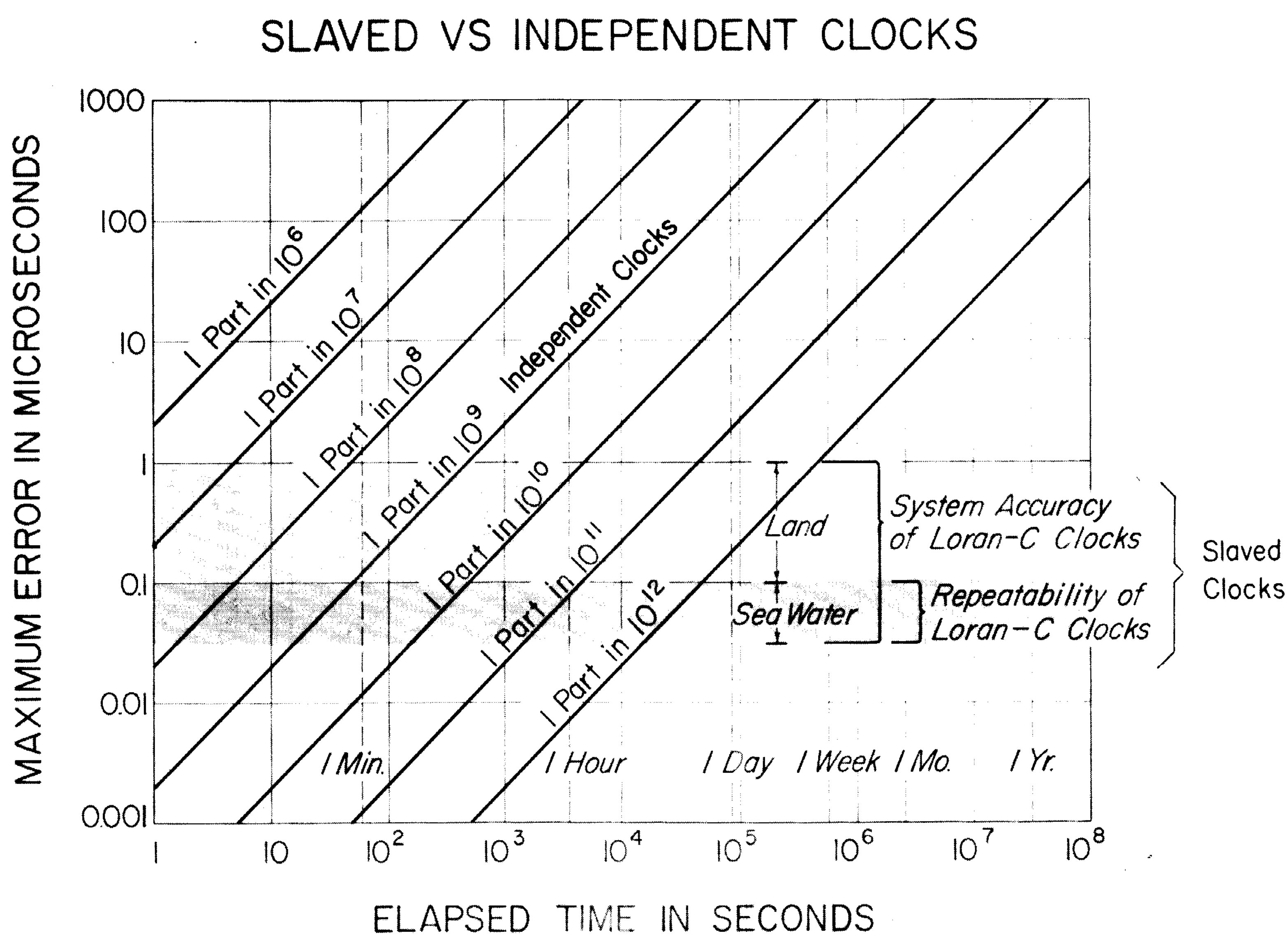
SLAVED VS INDEPENDENT CLOCKS
MAXIMUM ERROR IN MICROSECONDS
1000
100
10
1
0.1
0.01
0.001
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
ELAPSED TIME IN SECONDS
1 Min.
1 Hour
1 Day
1 Week
1 Mo.
1 Yr.
1 Part in 10^6
1 Part in 10^7
1 Part in 10^8
1 Part in 10^9
Independent Clocks
1 Part in 10^{10}
1 Part in 10^{11}
1 Part in 10^{12}
Land
Sea Water
System Accuracy of Loran-C Clocks
Repeatability of Loran-C Clocks
Slaved Clocks

Fig. 6

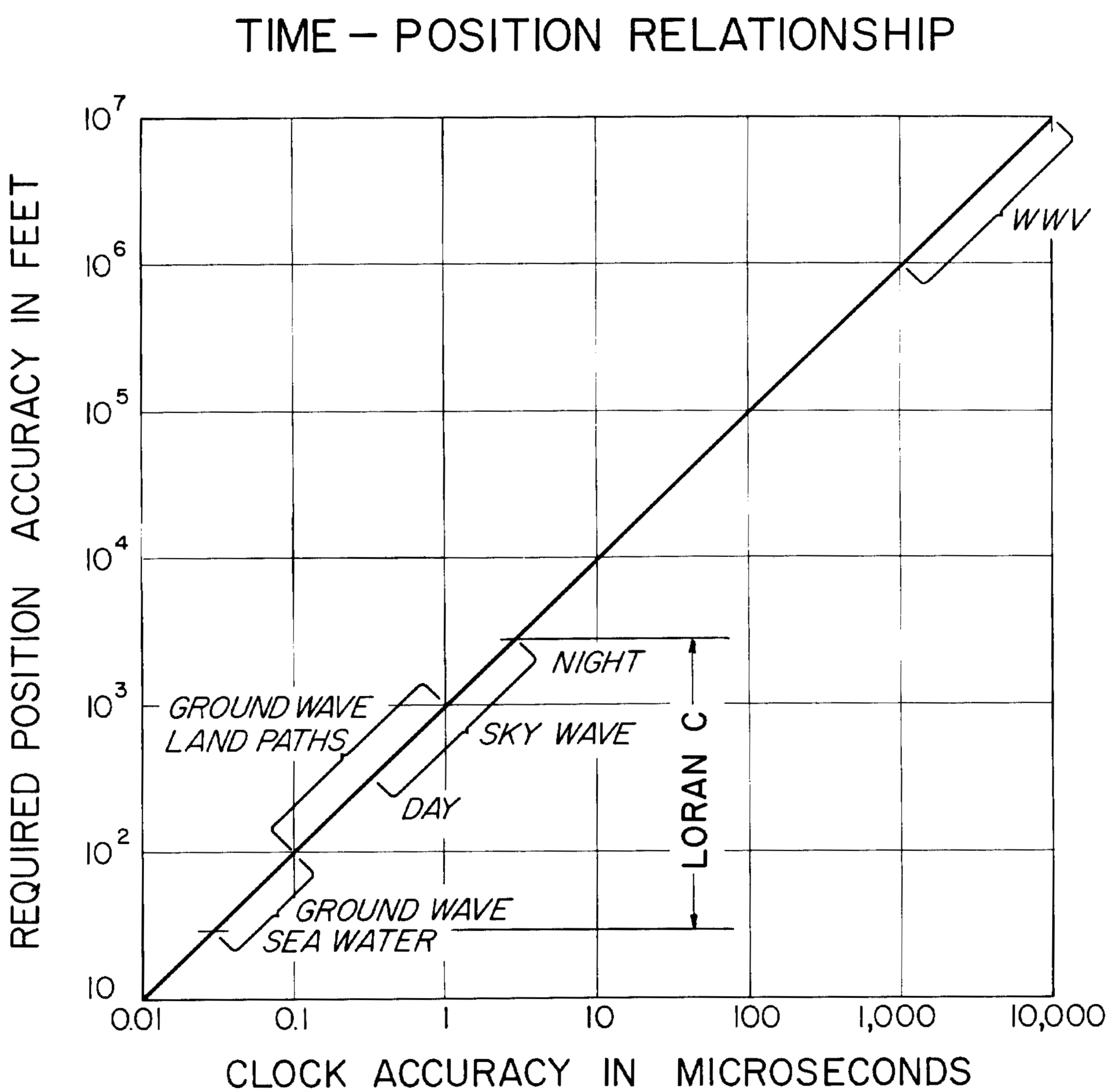
TIME – POSITION RELATIONSHIP
REQUIRED POSITION ACCURACY IN FEET
10^7
10^6
10^5
10^4
10^3
10^2
10
0.01
0.1
1
10
100
1,000
10,000
CLOCK ACCURACY IN MICROSECONDS
WWV
NIGHT
GROUND WAVE
LAND PATHS
SKY WAVE
DAY
LORAN C
GROUND WAVE
SEA WATER

Fig. 7

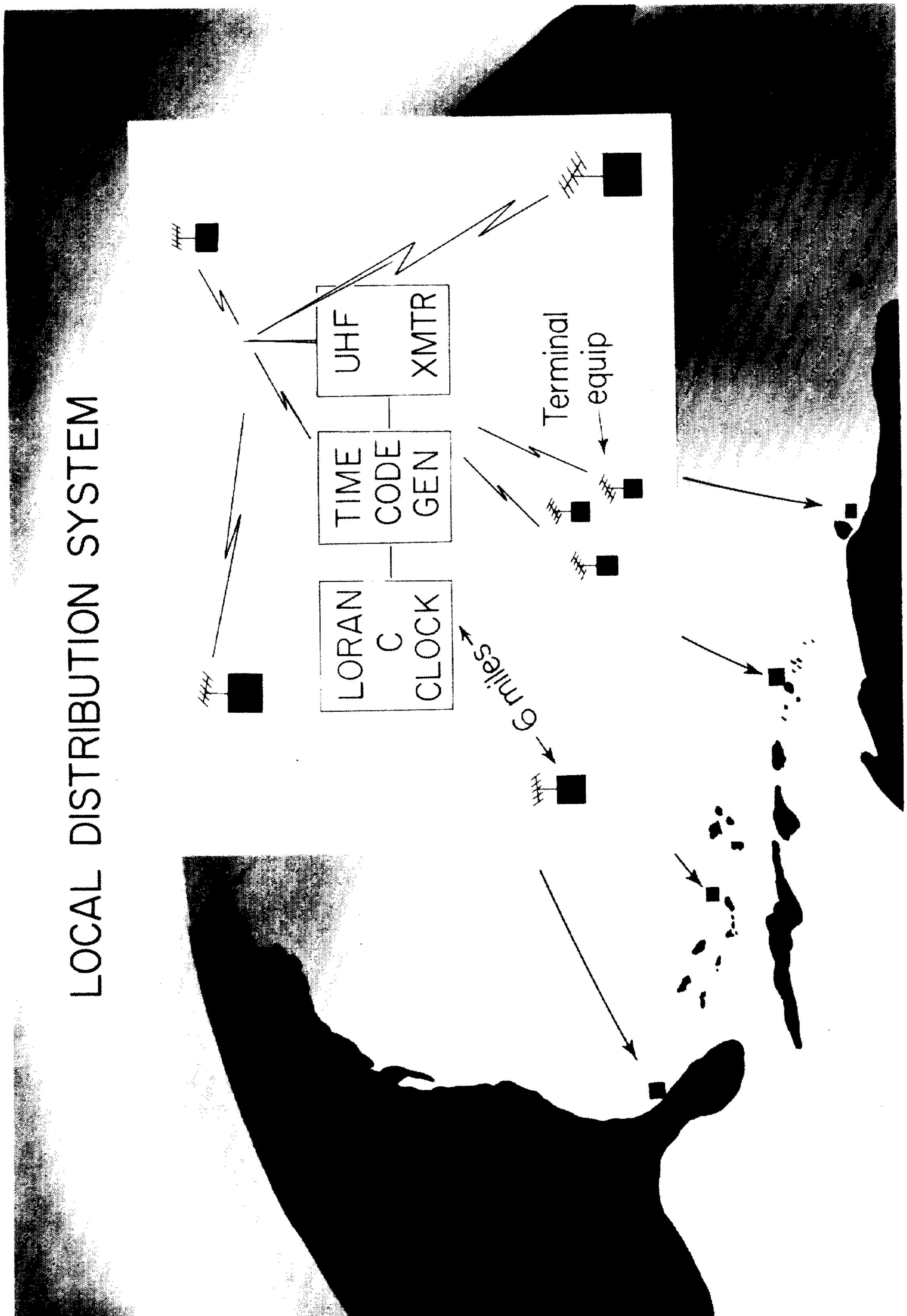
LOCAL DISTRIBUTION SYSTEM
LORAN C CLOCK
TIME CODE GEN
UHF XMTR
Terminal equip
6 miles

Fig. 8

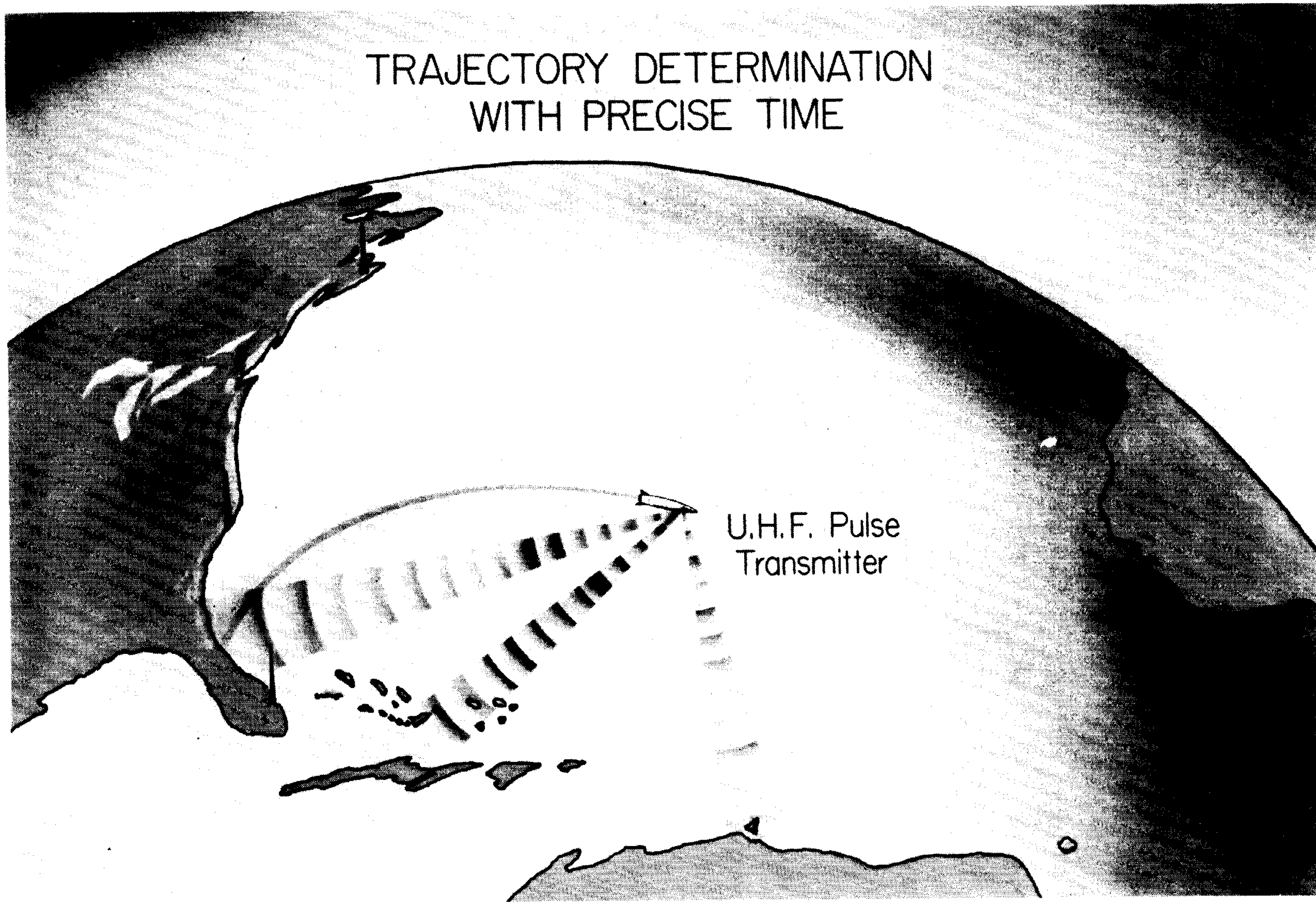
TRAJECTORY DETERMINATION
WITH PRECISE TIME
U.H.F. Pulse
Transmitter

Fig. 9

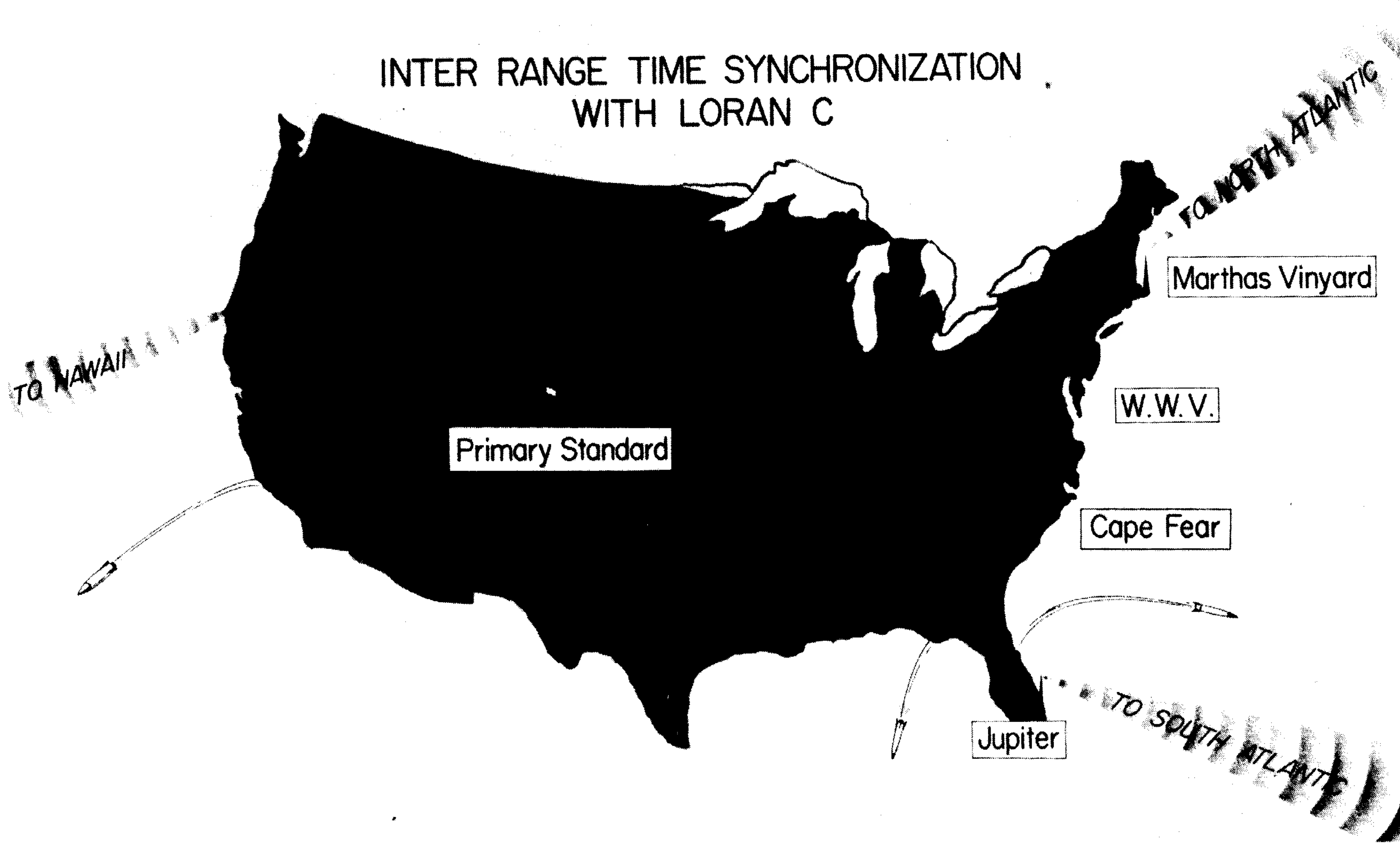
INTER RANGE TIME SYNCHRONIZATION
WITH LORAN C
TO NORTH ATLANTIC
Marthas Vinyard
W.W.V.
Cape Fear
Jupiter
TO SOUTH ATLANTIC
TO HAWAII
Primary Standard

Fig. 10