MOON-BOUNCE TIME SYNCHRONIZATION

by Dr. Walter H. Higa*
and
Samuel C. Ward**

This report contains a brief discussion of the time synchronization experiment performed during the summer of 1970 with the Moon-Bounce Time Synchronization (MBTS) technique.

Within the last decade, the Jet Propulsion Laboratory became involved, first, with the RANGER series of spacecraft, which cruised near the moon and took pictures as they approached, and, later, with the SURVEYOR spacecraft series, which were landed on the moon. Several kinds of detailed lunar maps were made for the RANGER and SURVEYOR series; numerous radar studies using an X-band radar were required.

When a spacecraft merely cruises in space, a good stable oscillator is necessary to ensure doppler quality, but there is no real requirement on timing. The spacecraft in cruise mode has very little information to send, so the computers can be used to double-check and calculate the trajectory without having to resort to any exotic time synchronization between tracking stations. However, when the lunar orbiter series evolved several years ago, it required that the spacecraft be essentially stopped in space, which demanded very accurate navigation. The Jet Propulsion Laboratory was assigned the tracking duties for this series and was asked to provide an accuracy of 30 μsecs between tracking stations.

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*Technical Staff, Telecommunications Division, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91103, (213) 354-4240.

**Mr. Ward was primarily responsible for data analysis.

The locations of the tracking stations--Spain, California, Australia, and South Africa--made it very difficult to utilize the LORAN-C technique; the possibility of utilizing the skywave at some of these remote tracking stations is now being investigated.

As a result of the lunar orbiter requirements, the use of the lunar bounce radar method of synchronizing clocks at the tracking stations was proposed. This method is a bi-phase modulated X-band radar. The objective was to derive an operational system that required very few technical personnel at the remote tracking stations. In other words, an X-band signal is transmitted to the moon from the Goldstone, California tracking station, and the signal is modulated so that it can be used at other tracking stations to provide 20 μsecs of time synchronization. Thus, all the complicated computations of such a system are performed at the transmitting site, and the remote tracking stations have only a very simple receiving system. This system recognizes that the computer is needed to figure the doppler correction for the relative motion between the tracking stations and the moon. It also recognizes that any measurements made at the receiving site should be very, very simple. The receiver is reduced to its bare essentials; thus,

- The pseudo-noise (PN) modulated X-band transmission is frequency compensated for all the doppler shifts from station-moon-station.
- The unique PN code is advanced in time by the known propagation delay and then scans ±30 μsecs each minute in 1 μsec steps.
- The local oscillator at the receiver is bi-phase modulated by the same PN code as the transmitter and is synchronized to the station clock.

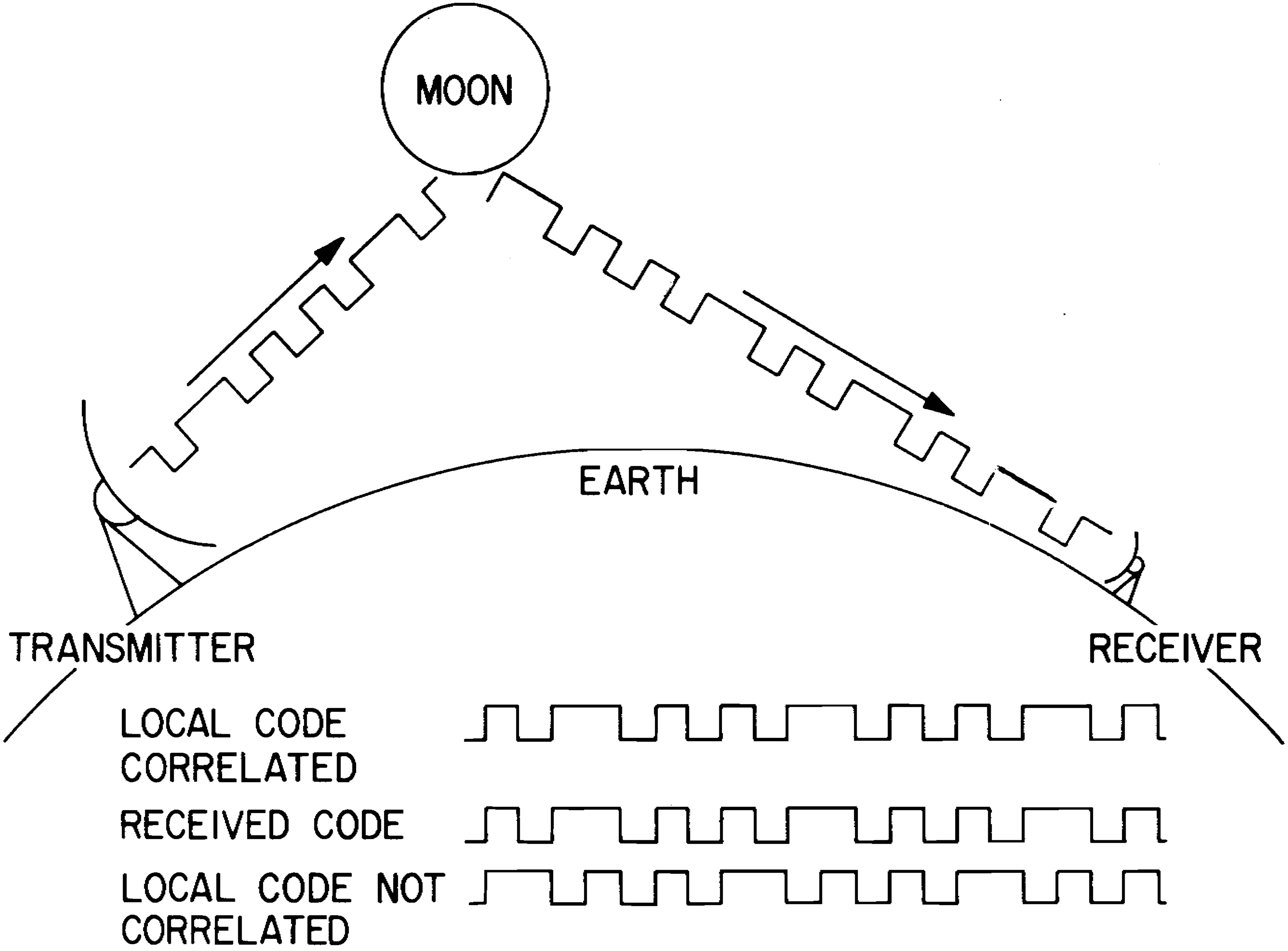
- The cross correlation of the received signal and locally generated code is recorded by a strip chart recorder to provide visual real-time measurement of the station clock error relative to the master clock at Goldstone.

The MBTS method was used successfully for ± 20-μsec clock synchronization between Deep Space Networks (DSN) stations during the Mariner '69 mission. Understandably, the originators of the concept of MBTS did not have the time to investigate the full capabilities of the method. The present experiment was undertaken to complete the investigation.

Figure 1 illustrates schematically how time is synchronized. In the X-band radar, a programmed transmitter takes care of the doppler shift and is so modulated with a unique pseudo-random noise code that the signal going up contains a modulation that is also generated by the receiver, and the two are, in effect, correlated between the received modulation and the locally generated one. The offset is then measured in terms of the correlation function.

If the transmitter signal were really advanced by the propagation delay and the local clock were indeed in synchronization with the transmitter site clock, the result would be both a perfect coherence and a strong signal output. Since the local clock is not expected to be in perfect synchronization with the transmitter clock, the code is advanced by the 2- or 3-sec propagation delay time and then retarded to 30 μsecs. For each second thereafter, the code is advanced 1 μsec until it is ahead of the propagation delay by 30 μsecs. Thus, if the local clock is within 30 μsecs of the transmitter clock, one should be able to observe it directly on a recording of the correlation function.

A typical trace on the strip chart recorder would show the two modulations coming into coincidence as maximum correlation was reached from a start of minimum or 0 correlation. If the correlation function were



DSN TIME SYNCHRONIZATION

FIGURE 1

the correlation of two square waves, it should actually be a triangular-shaped correlation response. But, because of the time constant in a capacitor that is charging up, there is a gradual decay of the signal.

If there were no noise and if the moon were a very smooth sphere, one would get an idealized response; however, noise will be superimposed because the moon is indeed a very rough surface, and one finds that there is an effective subradar point--the point at which reflection occurs.

The subradar point does not remain stationary but due to liberation, it moves from hills to valleys within a 28-day period. The effective front cap thus consists of a complex surface, roughly 180 km in diameter, which moves from day to day. By tedious calculations, it is possible to compute the average deviation from sphericity of the varying subradar points. Figure 2 shows a graph of the varying altitudes of the effective front cap of the moon. Distance has been converted into equivalent propagation delay times for convenience.

Figure 3 shows the results of the MBTS experiment superimposed on the graph of Figure 2. The excellent correlation for May and June leaves little doubt that the lunar topography is the principal cause for fluctuations in the method. The month of July shows the same kind of correlation as for previous months, but a systematic error of approximately 10 secs was observed. These points are denoted by circled triangles. The exact causes for these systematic errors have not yet been determined, but either equipment failure or operator error, or both are suspected. The July experiments were carried out at a very low angle of elevation at either the transmitting site or the receiving site; this was the only operational factor that differed consistently from those of the preceding months.

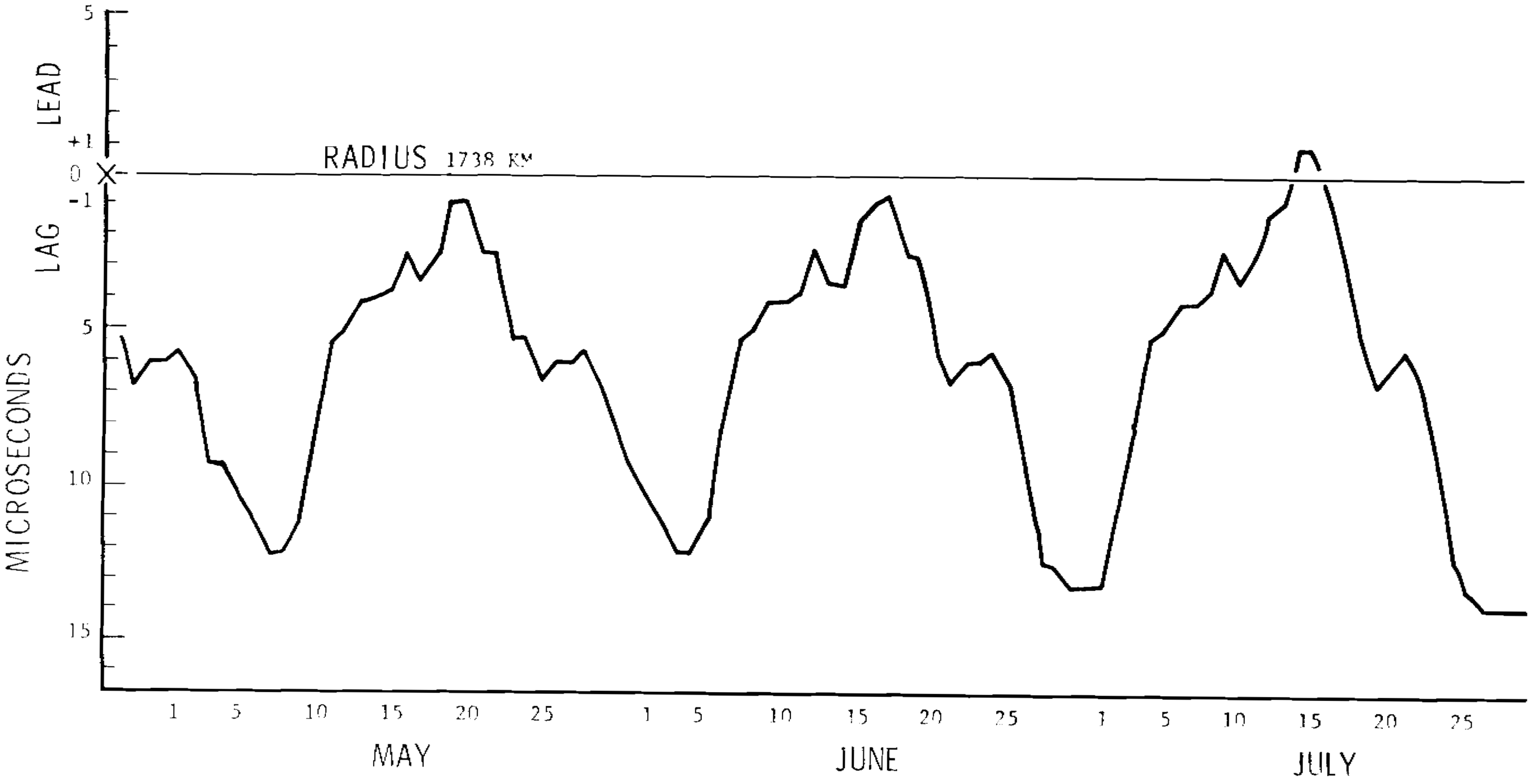
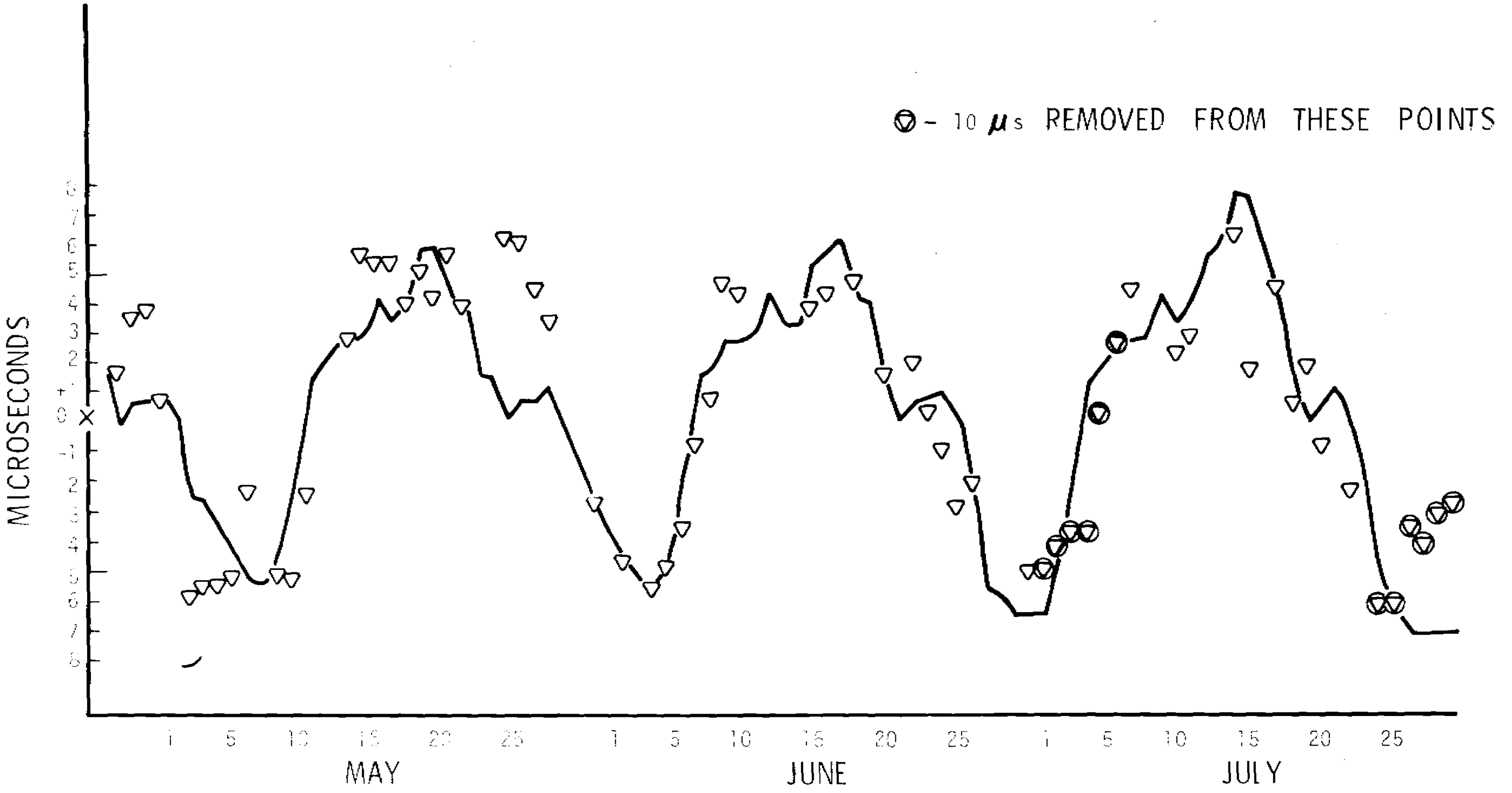

5
LEAD
+1
0
-1
LAG
5
MICROSECONDS
10
15
RADIUS 1738 KM
1
5
10
15
20
25
MAY
1
5
10
15
20
25
JUNE
1
5
10
15
20
25
JULY

FIGURE 2



USNO CLOCK 36 OFFSET FROM NBS CLOCK 8 AS MEASURED BY X BAND MOONBOUNCE SYSTEM

FIGURE 3

CONCLUSIONS

The precision of the MBTS scheme can be improved from around ±10 μsec to around ± 3 μsec by correcting for lunar topography. The systematic errors must first be explained and removed.

Acknowledgement: The authors would like to thank F. Borncamp and R. Wells for assistance in coordinating the experiment. The help of NBS (Boulder) and the USNO is gratefully acknowledged.

TIME DISSEMINATION METHODS FOR NETWORK AND LOCAL TELEVISION - ABSTRACT

by George Kamas*

The National Bureau of Standards is conducting experiments in the utilization of television for the dissemination of time and frequency. The long-term objective of these experiments is to develop a television time dissemination system for the United States. Various techniques of television time dissemination and display are discussed. The paper will be available from the National Bureau of Standards Time and Frequency Division in Boulder, Colorado in the near future.

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*Time and Frequency Division, National Bureau of Standards, Boulder, Colorado 80302, (303) 447-1000, Ext. 3378.

MICROWAVE, OPTICS, LASERS, AND OTHER EXOTIC SYSTEMS

by Robert Stone*

It is good to work in a real world if possible, and the real world in time and frequency has had a look over the years as shown in Figure 1. NRL has been active in this field since the early 1920's. The solid curve represents what the real need has been over the years in precision time and frequency, and the dotted curve represents the state-of-the-art. In the beginning years of electronics, time and frequency were thought of separately. Tuning forks, crystals, etc. were used to control frequency; pendulums and other similar devices were used to control time. For the greater part of the time, the state-of-the-art in time and frequency has been a factor of 10 greater in accuracy than was actually needed. Communication during this period was very simple and the time/frequency problems could be very easily met.

A major breakthrough in time/frequency techniques occurred with the advent of the ring crystal in 1930. By 1940, standards capable of maintaining frequency to 10^8 and time to 1 msc were available. During this period, operational requirements for precision time and frequency were also increasing. Navigation systems, such as LORAN, were coming into being and digital communication systems required in teletype systems were being introduced. In the 1940's, a number of 0 temperature coefficient crystals were being developed, such as the GT cut crystal in 1942 and the AG cut in 1950.

About 1960, frequency synthesizers were developed which allowed a much more precise control of transmission frequencies. Concurrent with

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*Head, Radio Time and Frequency Section, Naval Research Laboratory, Washington, D.C. (202) 767-3454.

TIMING - NEED VERSUS TECHNOLOGY

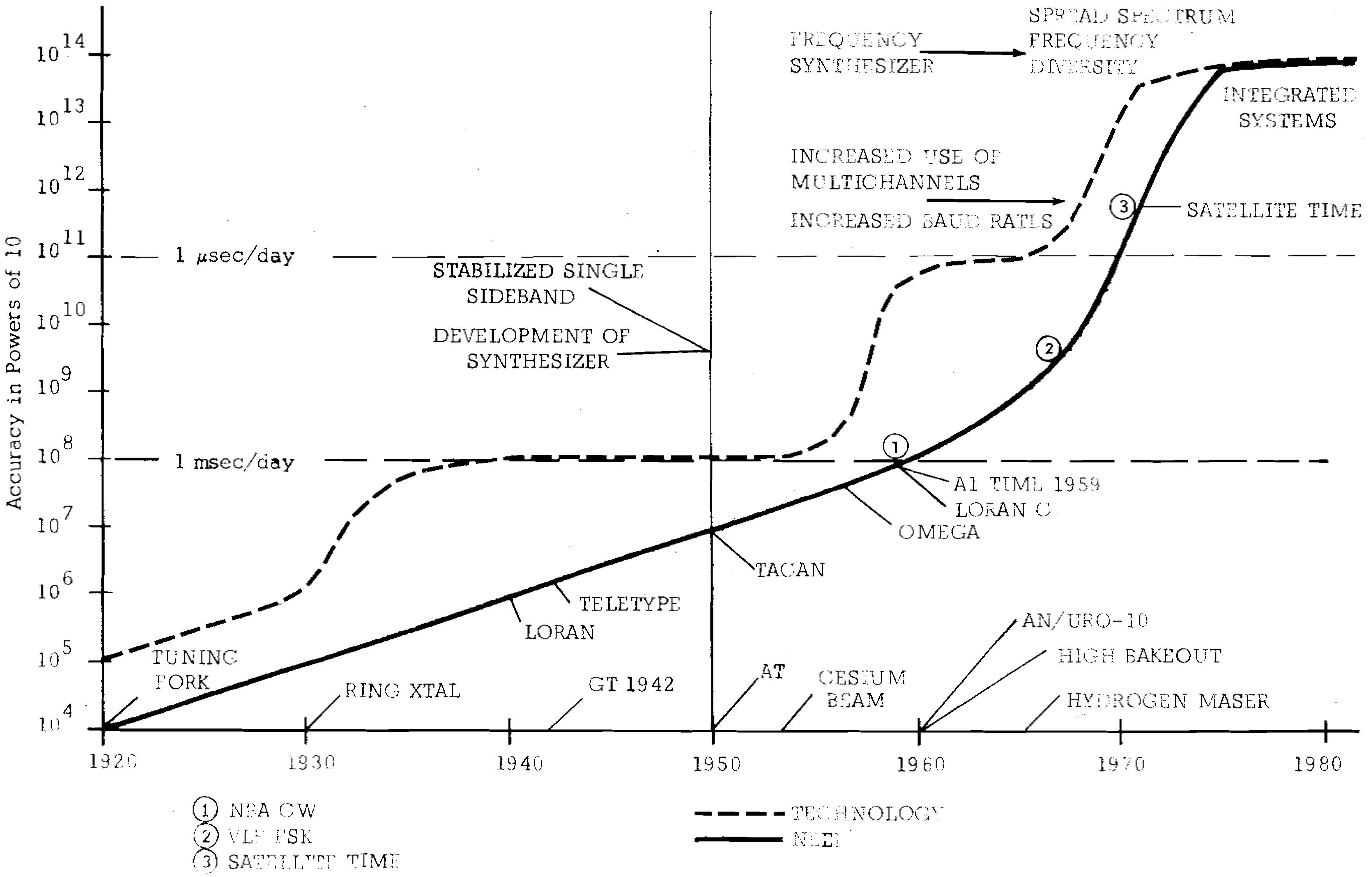


FIGURE 1

this was the development of stabilized single-side band systems. Prior to this point in history, the techniques which were used were simple and easily understood. Operation and maintenance were performed through intuition. All that was needed of precision time and frequency was sufficient frequency control to hold the signal within the band passes of the system employed.

About 1950, things began to change. More and more precision was being required in frequency and time. The intuitive approach to electronic operation and maintenance began to give way to a greater use of instrumentation. As more systems were developed (such as TACAN, OMEGA, LORAN-C in the navigation area; and use increased of the teletype, stabilized single-side band, higher baud rates, and the use of multichannel operation in the communications area), the demand for more precision in time and frequency increased. Figure 1 shows an increase of about an order of 10 in precision for each decade up to about 1950. Somewhere between the 1950's and 1960's, there was an upswing, until in the decade between 1960 and 1970 there was an increase of about three orders in the operational need of precision time and frequency. This need is still increasing. With the advent of satellite communication, spread spectrum frequency diversity, and integrated systems, it can be expected that eventually a time will come in which all the precision time and frequency which can be provided by the state-of-the-art will be utilized in operational systems. If the present rate of increase continues, this point may be reached at some time in the next decade.

The aim of the time and frequency program at NRL is to provide a practical path by which users of precision time and frequency can refer to a common worldwide standard at the Naval Observatory. A hierarchy is envisioned, such as is shown in Figure 2, in which the standards are maintained at the Naval Observatory; a long-range means of transfer is provided to various parts of the world; then, branching from these points,

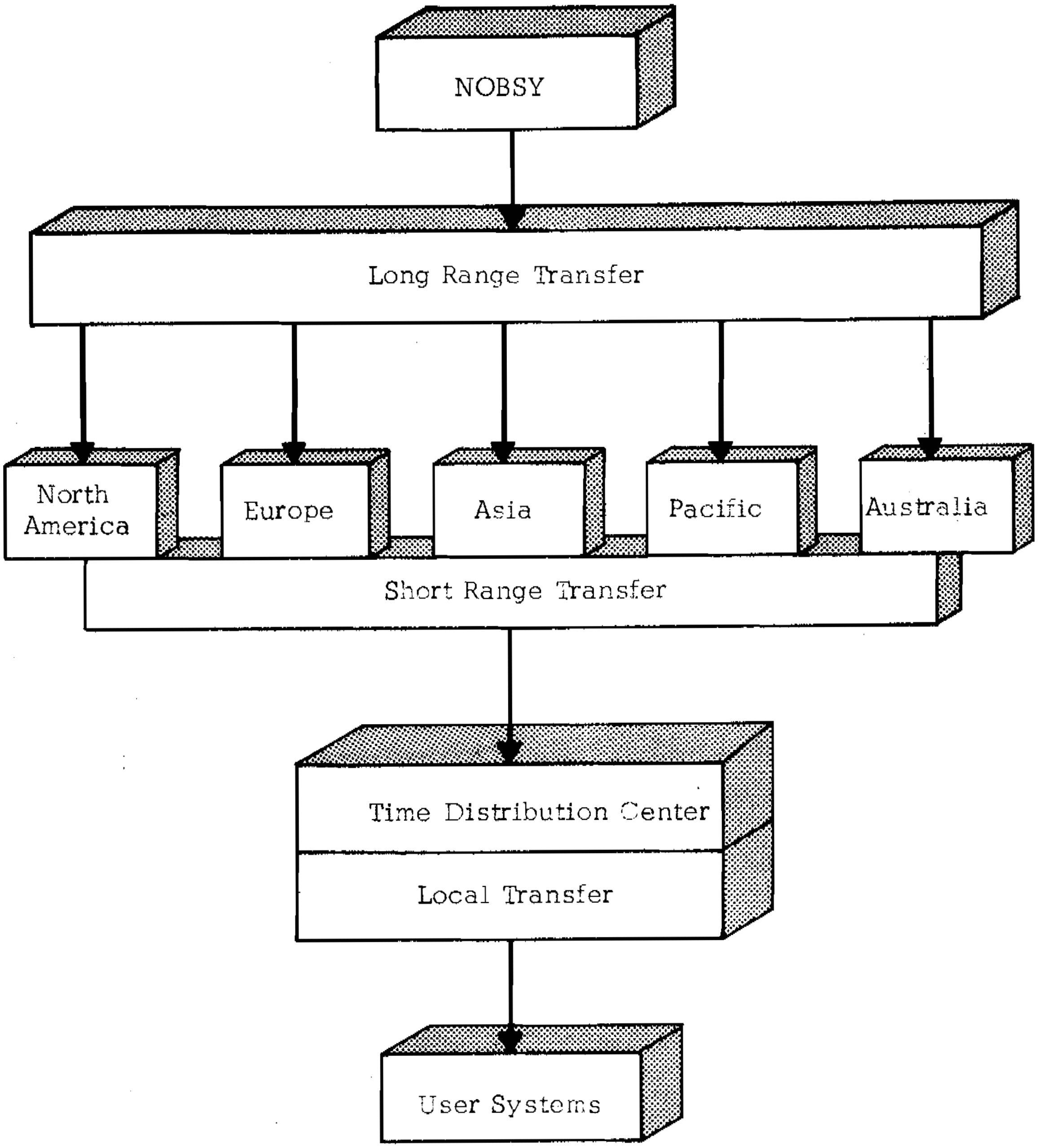

NOBSY
Long Range Transfer
North America
Europe
Asia
Pacific
Australia
Short Range Transfer
Time Distribution Center
Local Transfer
User Systems

FIGURE 2

there is a short range means of transfer to local time distribution centers which serve the user systems. This concept is shown another way in Figure 3. Any system which utilizes precision time or time interval also has a capability for the dissemination of time and time interval to the accuracy required in the system. The most economical way to transfer or disseminate time and frequency is to utilize those systems which require it. Such a system for long range transfer of time is the DSCS satellite system. Utilization of this system on a non-interfering basis will permit the transfer of precision time to about 1/10 msec anywhere in the world, which has the proper facilities. Following the same concept, short range and distribution of time and frequency would utilize available communication and navigation systems.

At present, the worldwide dissemination of precision time, as envisioned by NRL, appears as shown on Figure 4. Time will be introduced into the DSCS satellite system via a microwave link from the Naval Observatory. This link at present goes from the Observatory to NRL and Waldorf, but when the system becomes operational the link will go from the Naval Observatory to Brandywine, Maryland. Once in the DSCS satellite system, the transfer of time can be accomplished to virtually all major areas of the world. From these points, it is expected that other systems, such as LORAN-C, OMEGA, VLF, HF, etc., will be synchronized. Plans are being made to extend this hierarchy to the shipyard, the calibration center, and to ship and shore stations. One of the major problems in developing this hierarchy is to determine the users who should receive precision time and to set a system of priorities.

Short range transfer of time will be accomplished by cable, optical link, or microwave link. It is expected that the most extensive method will be the microwave link. Such a link has been established between the Naval Observatory and NRL. Figure 5 shows the characteristics of this link. The hydrogen masers at NRL can quite effectively be compared

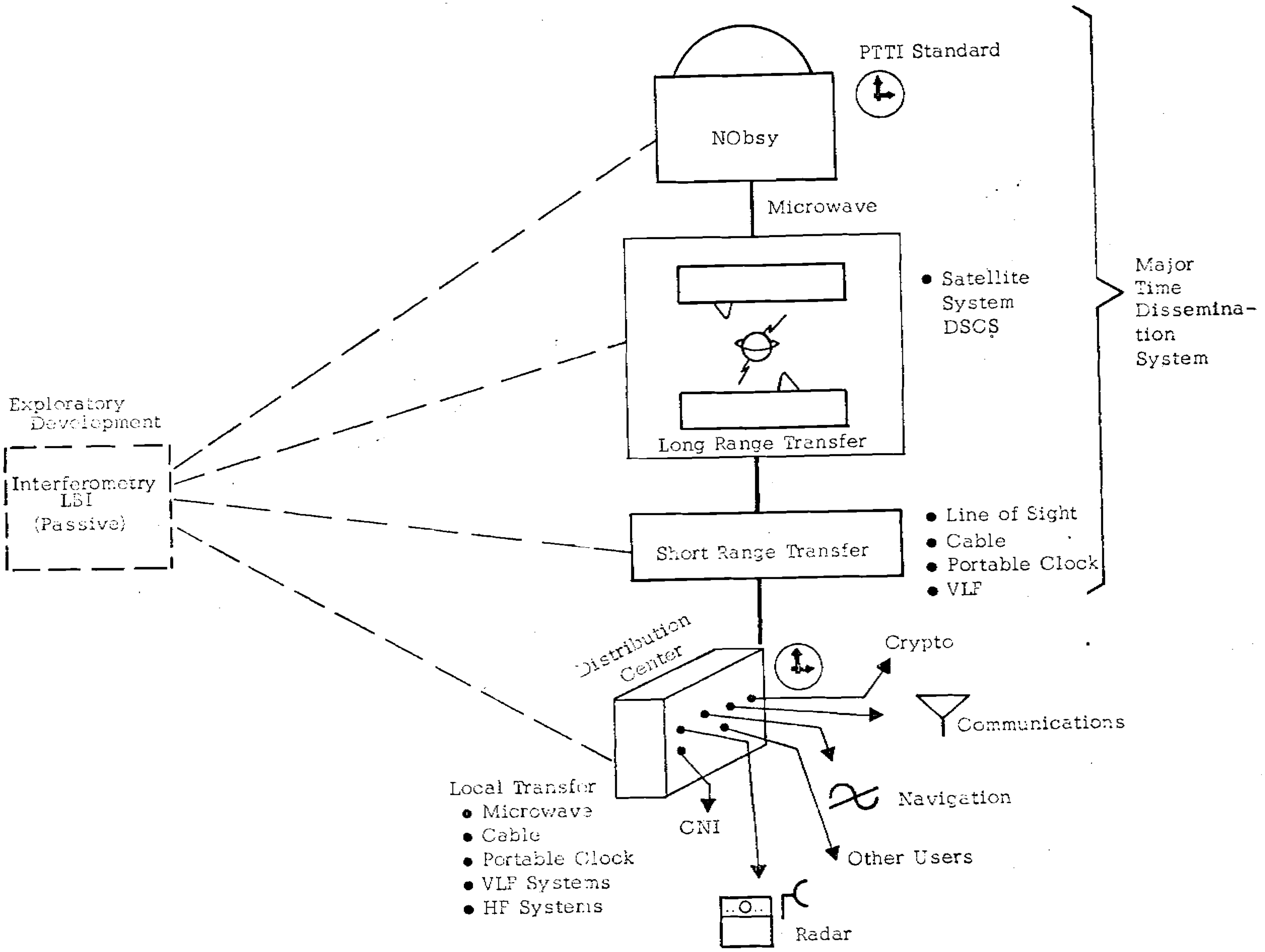

PTTI Standard
NObsy
Microwave
Satellite System DSCS
Long Range Transfer
Major Time Dissemination System
Exploratory Development
Interferometry LBI (Passive)
Short Range Transfer
Line of Sight
Cable
Portable Clock
VLF
Distribution Center
Crypto
Communications
Navigation
Other Users
CNI
Radar
Local Transfer
Microwave
Cable
Portable Clock
VLF Systems
HF Systems

FIGURE 3

FREQUENCY TIME/TRANSFER
1 x 10/11 .1 microsec.

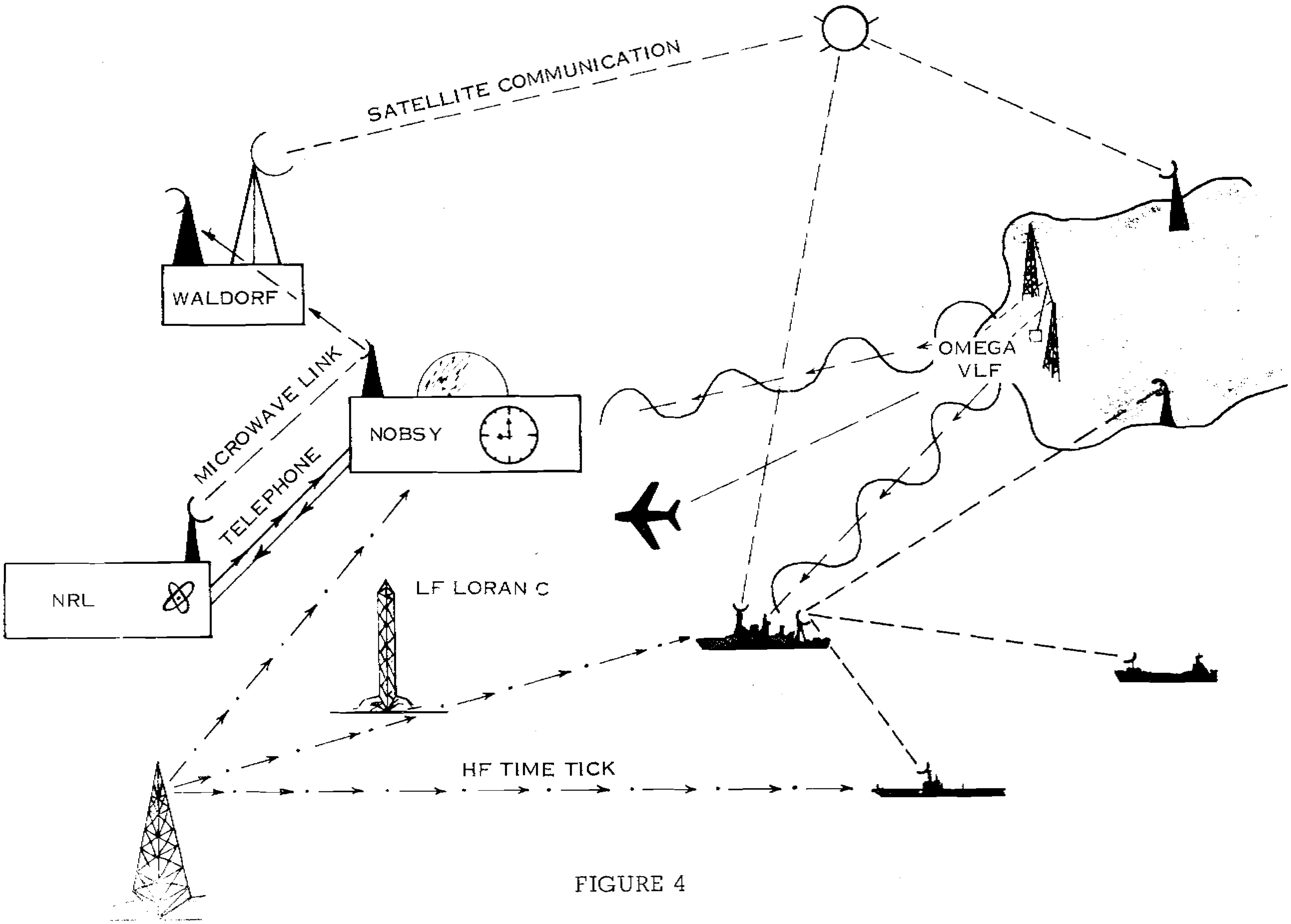
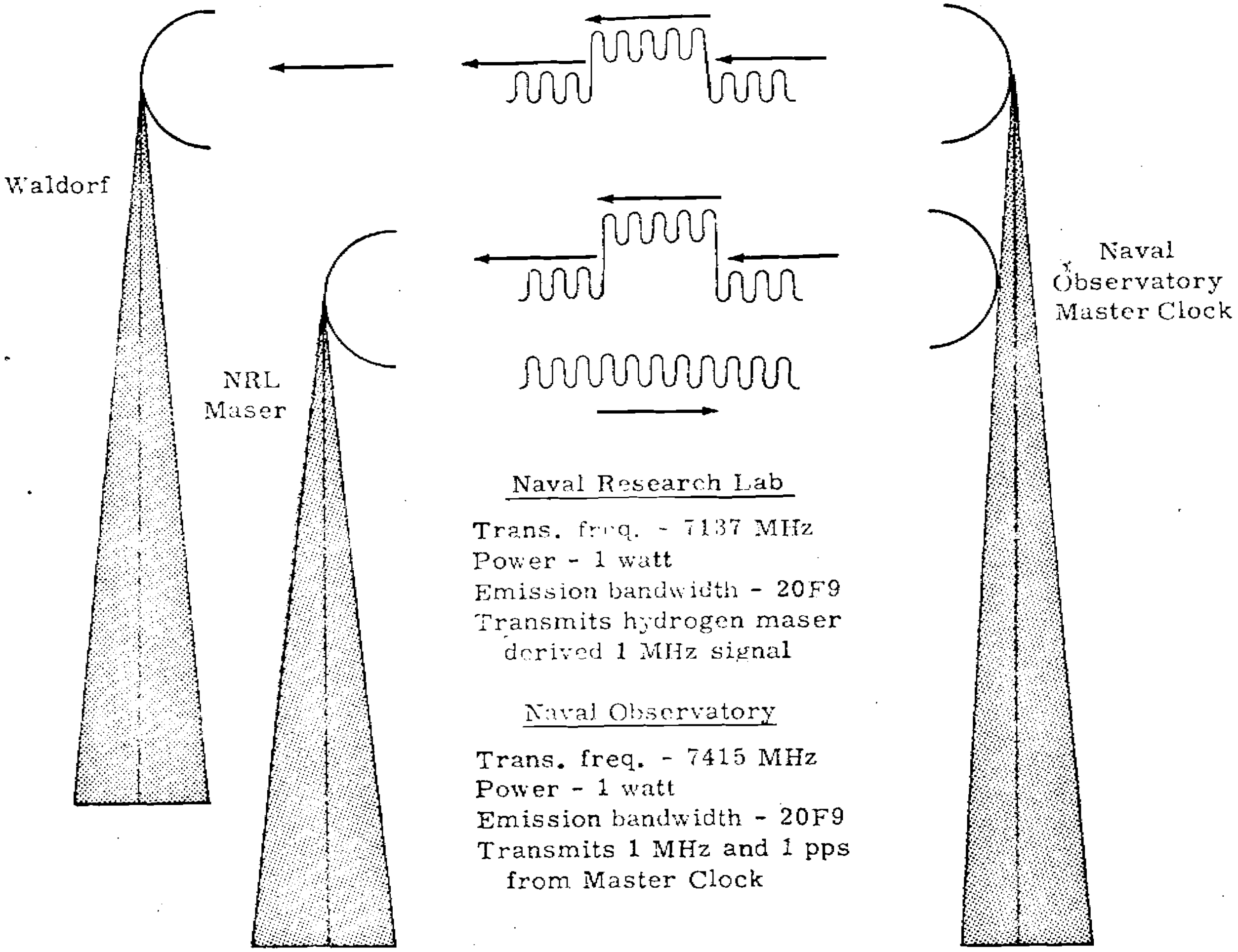


FIGURE 4

MICROWAVE LINK



Naval Research Lab

Trans. freq. - 7137 MHz
Power - 1 watt
Emission bandwidth - 20F9
Transmits hydrogen maser derived 1 MHz signal

Naval Observatory

Trans. freq. - 7415 MHz
Power - 1 watt
Emission bandwidth - 20F9
Transmits 1 MHz and 1 pps from Master Clock

Equipment: Raytheon Television Microwave Relay Model KTR-1000G

FIGURE 5

with the standards at the Naval Observatory via this link. Both a time tick and a 1-mc signal are transmitted. Accuracies of 10 msecs can easily be obtained. Although this link is devoted exclusively to the use of time frequency transfer, it is expected that comparable results will be obtained when the time transfer techniques are added to operational systems.

At present, NRL is investigating various operational systems which can be utilized for the short range transfer of time and it plans to develop techniques to extend the time hierarchy through these systems to the various DOD users.

PRESENTATIONS BY

Dr. G. M. R. Winkler

REQUIREMENTS AND PERFORMANCE FOR TODAY'S ATOMIC STANDARDS

by Dr. G. M. R. Winkler*

This paper addresses the requirements, specifications, and performance for atomic frequency standards in general. Requirements for universal time and certain general concepts of time-dissemination systems will be considered in later reports.

USER REQUIREMENTS

The first user requirement is the 100 msecs needed for celestial navigation. This contains a margin of safety, because most navigators are satisfied to know time to about 1 second. However, certain automatic systems under development or in use do need 100 msecs. From the total number of ephemerides, nautical tables, and almanacs used every year throughout the world, the total number of English-speaking users is estimated to be 100,000. It appears that their requirement of 100 msecs will not disappear in the near future. It has been pointed out that, once electronic navigation systems receive more widespread usage, the requirements may be relaxed; however, such relaxation is not expected within DOD; on the contrary, a need for immediate timing to 10 msecs (UT) has been indicated for some areas.

A more exacting requirement of 1 msec after the fact exists for universal time (UT_1) for geodetic purposes. Of course, this exceeds the state-of-the-art. It can be gotten only after about one or two months. The published International Bureau de l'Heure (BIH) values are precise to about 1 msec. (These are averages of about 50 observatories.) Anything more exacting

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*Director, Time Service Division, U. S. Naval Observatory, Washington, D.C., (202) 254-4546.

than the precision value of 1 msec can refer only to synchronization requirements. But synchronization requirements evidently can be satisfied at the same time or with the same systems, which also give this UT timing information. If the two are separated and only clock time is discussed, then the simultaneous existence of several timing systems is admitted--a most uneconomical and undesirable situation.

A stated requirement of 5 μsecs worldwide exists for the Air Force calibration system. Many purposes, related in one way or another to space tracking, have a less exacting requirement of about 100 μsecs. The observation and tracking of objects in space requires clock time synchronization to about that magnitude. However, a margin of safety is always desired, which explains many requirements that go down to a 10-μsec range or less.

A fourth area of requirement has been generated by the recent evolution of the time/frequency (T/F) technology, or time-ordered systems. This technology presents two general requirements. Systems that require the simultaneous emission of many, many signals on the same frequency need a very exacting ordering or assignment of time slots. This system is known as the time frequency collision-avoidance system proposal. Other requirements, then, come from the need to measure location to a very high degree of accuracy by measuring the times of arrivals of signals emitted from navigation transmitters. A range of 100 to 500 nsec is listed as a primary concern. This requirement covers most, if not all, of the systems currently being studied, under development, or in R&D. Some 100 users require that degree of precision at present. If, however, any of these systems is implemented during the next years, the number may easily increase to thousands. Some requirements have also been tentatively listed on the order of 10 nsecs for limited areas.

When the list of requirements for new distribution systems or high-precision clock performances is considered, it appears that 100-μsec or 200-μsec precision figures would leave a very large number of users unsatisfied. Therefore, effort should be concentrated on systems that have the capability of satisfying any of these requirements, i.e., systems that can give $\frac{1}{2}$ μsec or better.

SPECIFICATIONS

After this very short overview of existing synchronization requirements, the specifications for clocks or frequency standards to be used in these systems are discussed in the following paragraphs. There is, of course, a choice: (1) a continuously available synchronization can be assumed (e.g., the system described by Mr. Stone or any system that has continuous two-way communication, such systems are not considered to be typical time-frequency systems); or (2) systems that for months would require a maintenance of synchronization to microsecond precision, without any access to synchronization. In the first case, sophisticated oscillators would not be required, thus very cheap crystal oscillators could be used. But the tools required to maintain resynchronization reliability under all circumstances in the presence of noise, jamming, and spoofing would consume all your resources.

In the second alternative a significant advantage would be gained by being able to live for extended periods of time without any communication link; on the other hand, the selection of a clock that would offer precision, uniformity of operation, and the utmost reliability would prove a problem. It is somewhere between these two extremes that one has to select one's approach. In a comparison of the cost effectiveness of precision clocks, certain numbers were assigned to the initial cost, service requirements, stability and performance, and reliability of the clock; to production experience, and to sensitivity to environmental conditions, magnetic fields, altitude, high pressure, etc., and a simple formula was derived. In this comparison the quartz crystal oscillator came out far ahead of every other approach, not surprisingly, because the technology has been fully developed over the last 40 years. On the other hand, the most glamorized frequency standard--the hydrogen maser--did not look as good. (Such comparisons are useful only if one has all the freedom to develop a system. More often, the engineer must accept requirements blindly, is given no opportunity to point out certain pay-off possibilities, and has no choice but to look at what is available.)

At the present time, the Navy Electronic Systems Command is working on a specification for cesium-beam frequency standards, which is an extremely difficult task. On one hand, the largest number of requirements, including requirements projected for five years hence, must be satisfied. On the other hand, one cannot be exclusive. A good specification ideally would also encourage competition among capable contractors but exclude those with mediocre or poor performance records. But what kind of performance can one expect?

PERFORMANCE

As an example, the performances of cesium beam standards observed at the Naval Observatory are reviewed in the following paragraphs.

Before a portable clock is sent on its way, a frequency adjustment is made at least one or two weeks before departure to ensure that the clock's rate is as small as possible with respect to the Observatory Reference (see Figure 1). When the clock leaves, a time measurement is performed. When it comes back the same time difference should be expected, but, in effect, a small "closure error" is observed (Δt)--a sign convention that $+\Delta t$ means the clock has lost time. The most likely closure error of course will be zero. There is an equal probability for closure errors to be plus or minus if, for a moment, certain very small, predictable relativity effects are ignored. However, these are still not

PORTABLE CLOCKS

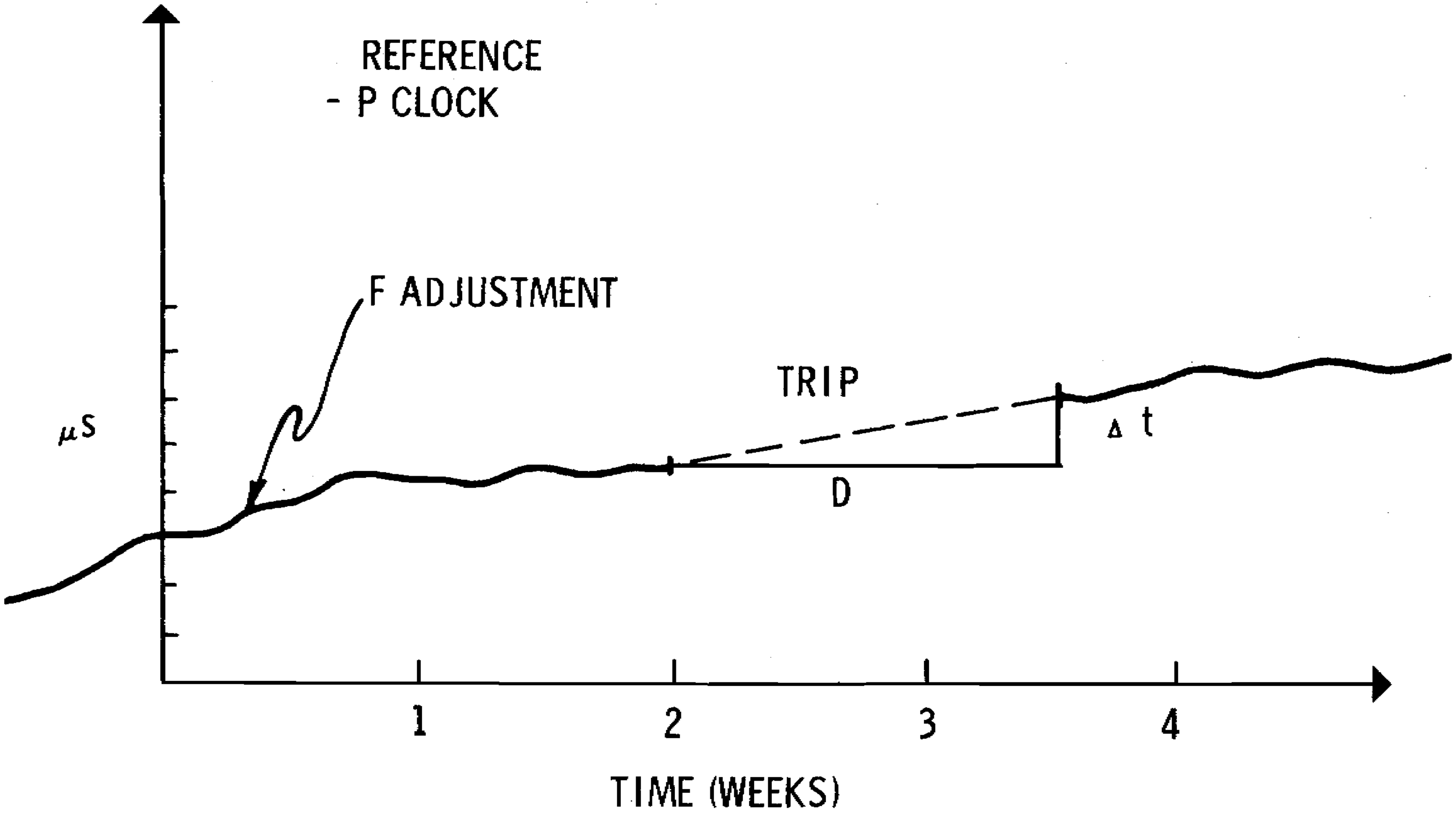

FIGURE 1

significant, so it is expected, on the average, to have a closure error of zero, and the performance of the clocks will be stated in the half bandwidth, so to speak, of that distribution.

Figure 2 shows two samples of actual measured performance. To arrive at these figures, for example, assume 27 trips for one time interval, and 26 trips for a second time interval. Of those, only the longer trips in excess of two and one-quarter days have been considered. The sample size is the same as well as the mean duration and the sigma duration. The average closure error is +0.1 μsec in the first case, and -0.5 μsec in the second sample. However, these numbers are not too meaningful, because of the sigma of about 1 or 1-1/2 μsecs. Figure 2 also lists the average of the absolute closure error, $|\Delta t|$ and the rms Δt; +2.4 μsec is the largest closure error in the first sample and -3.9 μsec is the largest closure error in the second sample. In addition, the first sample contained only 5060's and the second 5061's. The second sample has a somewhat poorer performance, which could be caused by a number of difficulties which was experienced with the 5061's shortly after they were introduced into the system. One component--the integration capacitor--caused us some problems initially; however, these numbers would not reflect a significant difference in the two standards on trips.

The question is how can one explain such a performance if one looks at performance measures taken in a laboratory.

Clocks are routinely measured at the Observatory in reference to the Observatory's average time scale. Such a clock average gives an extreme degree of redundancy and reliability of operation. The time scale which is used as reference is the average Observatory time scale.

If times for individual clocks and their frequency variations are plotted (see Figure 3), the variance is taken as was initially introduced by Dave Allan in the special issue of Proceedings of the IEEE, February 1967.

PERFORMANCE OF USNO PORTABLE CLOCKS

ALL TRIPS WITH D > 2-1/4 DAYS

PERIOD	NUMBER OF TRIPS	D MEAN DURATION	$\overline{\Delta t}$ + LOST	$\lvert\overline{\Delta t}\rvert$	rms Δt	LARGEST $\lvert\Delta t\rvert$	COMMENT
MAY 66 - FEB 68	27	15.5 d ± 8	+0.1 μ ±1.1 μs	0.82 μs	1.1 μs	+ 2.4	HP ALL 5060's
APR 69 - JULY 70	26	14.1 d ± 8	-0.5 ±1.5	1.15 ±1	1.55	-3.9	HP ALL 5061's

FIGURE 2

The variance is used as the standard notation and the frequency variations are essentially plotted as a function of integration time: 0.1 day, 1 day, 10 days, and 100 days. The individual cesium clocks fall into a general branch with a slope of minus one-half. That slope is exactly what one would expect if the variations in the disturbances are strictly random. It is the same law which governs any random statistical process, that over a larger number of samples the variations decrease as one over the square root of the number. And the same law, of course, can be expected here. It is remarkable that the clocks, which were selected as better-than-average performers out of a total sample of about 60, fall into a band which goes at that slope of about $\sigma(2, \text{tau}) = \frac{2 \times 10^{-13}}{\sqrt{\text{tau}_{\text{days}}}}$. The difference in quality between clocks is, however, noted by the point at which performance deviates from the heavy solid line and branches off horizontally. A relatively poor clock like #105B branches off at a point with an averaging time of less than one day. A very excellent clock, like #279, branches off at an averaging time of ten days; there is one best performer with a one-sigma frequency variation of three parts in 10^{14} for an averaging time of 40 days. It must be emphasized, however, that all of the performances shown in Figure 3 have been obtained under laboratory conditions. Clocks are separated in space, and they are individually operated, on individual power supplies, to assure that all variations are as random as possible.

Why do clocks branch off at various integration times? The major reason is that for such long intervals, the probability becomes so high that systematic, irreversible frequency changes occur. In a cesium beam, such an irreversible frequency change for instance, would be caused by a change in the control voltage of the Zener reference diode which controls the C-magnetic field. Or, furthermore, a systematic change can occur in the magnetic properties inside the transition region. Any one of a possible

$\delta \frac{\Delta f}{f}(2,\tau)$ PLOTS FOR VARIOUS CESIUM BEAM CLOCKS

$\delta \frac{\Delta f}{f}$ MODEL, $\delta \Delta t$ MODEL

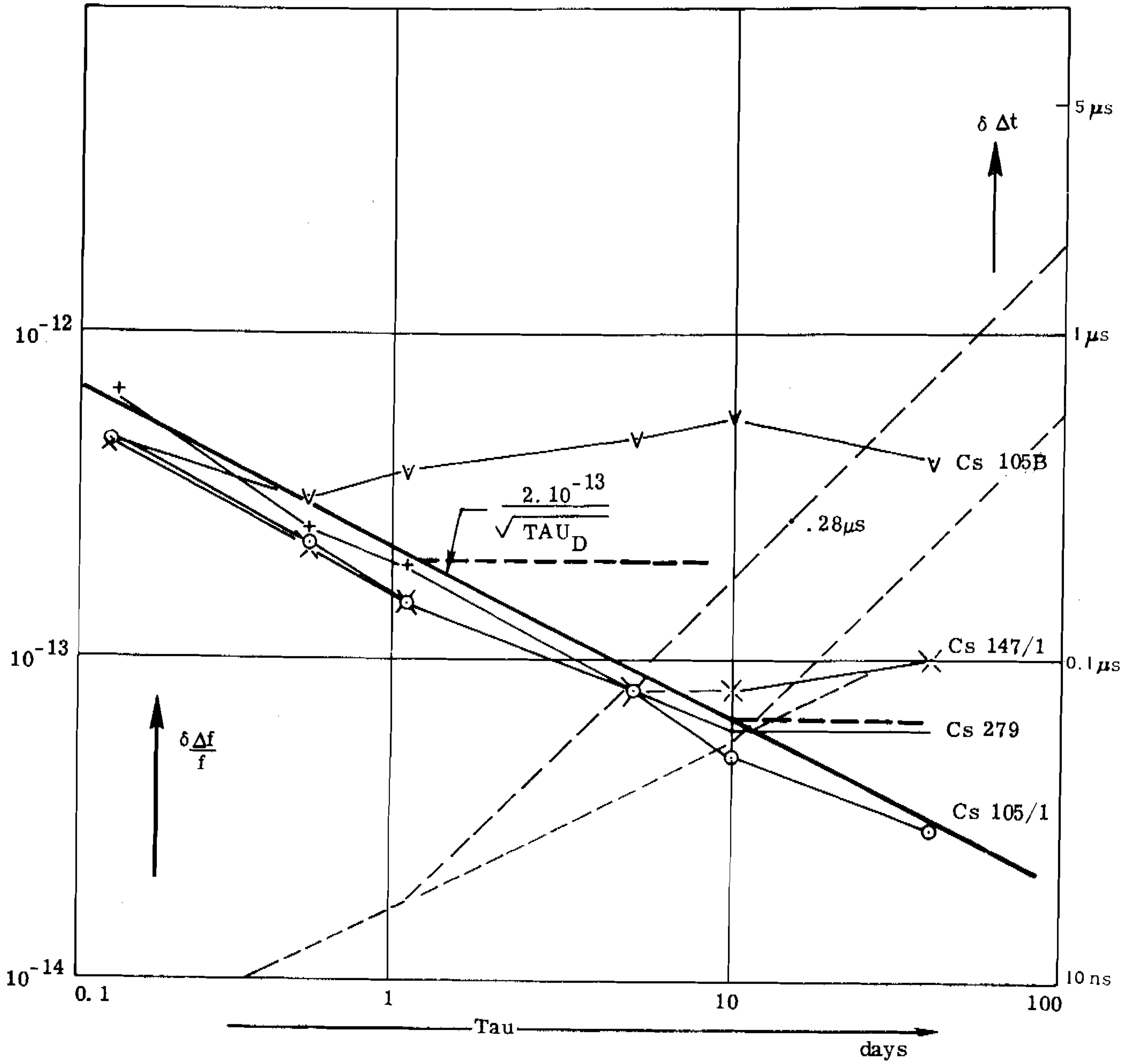

FIGURE 3

10 or 15 critical parameters which influence the frequency stability are subject to systematic change eventually. The longer a clock is observed, the greater the probability that such systematic changes start to predominate, and they will cause an upward swing to a "random walk" frequency modulation performance. For planning purposes, a typical performance has been assumed; this is shown as the heavy solid line in Figure 3. For the best available cesium clocks, that formula has been used as a model. One has to use two branches: one for the random frequency noise behavior (white FM), and the second to state the point at which the clock will "branch off." Variations in frequency can also be expressed in variations of time. Time deviations (dashed line) are then represented by a straight line with slope +1/2 as long as the model (heavy solid line) follows down the slope -1/2 and then will branch off at a slope of +1 from the point where the systematic distrubances begin to predominate. Now, assume that a selected portable clock, if left completely undisturbed, would perform as well as one of our best clocks. Suppose that clock is exposed to the troubles of a journey or moved around; suppose it is turned around in the earth's magnetic field; or exposed to vibration, or to shock. Suppose it is moved in an airplane to make a trip; it is moved into another laboratory; it is left there for one day. Suppose all of these things and then it may be reasonable to assume that something is done to this clock which can affect its systematic behavior on the average of about once a day. A performance along this model for a trip of 14 days is expected with a variation in time of roughly 0.3 μsecs. The actual performance is about three times poorer, but it is very much in the same ballpark. Therefore, similar considerations can be applied to many timing applications.

If less exacting requirements are stipulated so that a time base is necessary without any recourse to external synchronization for periods no longer than one day, then one can be satisfied with a standard which will branch off or go up into the random walk at that time interval as a rubidium standard does. A rubidium standard has a better performance, in general, up to about one day, than a cesium clock; however, it deteriorates in its performance rather soon.

There are a few hydrogen masers which we have seen or which we use repeatedly: two at the Naval Research Laboratory, which are accessible to us via the microwave link, and one at the Observatory which is available directly within our Laboratory. The performance of these hydrogen masers for short periods of time (such as fractions of a day) is absolutely outstanding; they are unquestionably, the best clocks in existence. When integration times of ten days or longer are reviewed, they become disappointing, because they tend to be poorer than the best cesium standards and, of course, poorer than the average of all cesium standards. Consequently, the best use of the hydrogen maser seems to remain in applications which require the utmost in spectrum purity or the utmost in suppression of phase noise for integration times shorter than a few days.

For many applications, engineers who have an understandable urge for a sufficient margin of safety and available precision, tend to select a high precision standard. If there is any question, they select the better, or what they feel is a better standard. This can be a very dangerous tendency. For instance, assume it is necessary to have a frequency stability for a timing requirement of a fraction of a microsecond for a couple of days. That would be a requirement typical for navigation-timing applications, or for systems such as OMEGA or LORAN-C. Further, assume that one would follow this tendency and specify something more elaborate than a commercial cesium beam standard. It would be a great mistake, because the available measurement precision also enters. If phase differences cannot be measured with a precision greater than about one-tenth of a microsecond, then it takes a very long time to make full use of even a cesium standard. It is this phase noise which places an ultimate limitation on the usefulness of a precision frequency standard. It appears, therefore, that future requirements will not go towards an increase in short-term stability over what has been accomplished with hydrogen masers, but instead will go towards a more reliable exclusion of systematic changes in frequency standards for longer periods of time because of these benefits for T/F systems use. Clocks can be left alone for longer periods of time and that means clocks can be selected which perform better in this area.

DISCUSSION

Dr. Reder

What is currently being done to improve cesium standards; does anyone have a contract?

Dr. Winkler

Does anyone want to express himself directly on this question? No response to the question. What is being done to improve cesium standards at the moment? Apparently "no response" indicates only an absense of Government sponsored R&D. We know that there is continuing commercial development.

Cdr. Potts

I would like to take a couple of minutes to explain our experience with the commercial standards we have. We own all Hewlett-Packard standards--a couple of 5060's, and mostly 5061's on the order of 80 cesium standards so, for the last year and one-half, we have undertaken complete maintenance of these standards. We ran into some problems on the commercial standards. Initially they were quality controlled. There were some bugs which were not removed, such as the integrator capacitor. There have been some failures which have occurred several times, and it has been a learning curve for us as well as for Hewlett-Packard. I prefer not to single them out, but they happen to be the only successful manufacturer of cesium standards and they are the only standards we have. We have had a direct link back to them in an effort to improve succeeding models of cesium standards. It has been a continuing program with us to document all problems and to inform Hewlett-Packard of them then, in turn when we receive standards from them, check to see if those problems still remain. I would solicit a comment from Lt. Dave Clements of our

Laboratory, who runs the time frequency laboratory and our cesium maintenance, and perhaps he can give you a little better idea of the real numbers.

Lt. Clements

We have shown recently, in the last eight or ten months, a mean-time-between-failure of all the units pushing 20,000 hours for the cesium standards, and the cooperation we got from Hewlett-Packard has been quite good. They have done some design changes within the unit on their most recent models concerning their operational amplifier, and they have also done some work on their synthesizer assembler. Recently, we received a batch of new units and we ran into a quality control problem inasmuch as 11 of the 23 units we received had something wrong with them. So, other than the quality control, the design work on the cesium seems to be gradually improving.

Dr. Winkler

I would like to make a further comment here. Mr. Acrivos at the Naval Observatory has organized very crucial and difficult environmental tests. Such tests have also been performed by Dr. Hafner in Ft. Monmouth. A recent report summarizing the results of Dr. Hafner's tests was issued by Sperry Gyroscope and is available upon request. One of the results of these tests, and one that has been overlooked in our testing up to now, is the very great sensitivity of these standards to AC magnetic fields. Some standards reacted extremely poor to an exposure. Both companies which produce cesiums, are making special efforts to improve and to reduce the the sensitivity to the AC fields. The sensitivity is not all centered in the beam tube alone; it is also in the synthesizer and frequency multiplier, where problems apparently exist.

Mr. Acrivos (USNO):

Hewlett-Packard is making modifications, both in their tube and in their magnetic shielding by installing new metal shielding around their synthesizer and multipliers. The first unit will be delivered for testing under NAVELEX sponsorship on December 15, 1970, and I believe, when you order the tubes from now on, the new tubes will all be equipped with additional shielding.

Dr. Winkler:

There is a second development which I would like to mention. Probably many of you have become aware of the nine-inch beam tube and the small portable standard or small airborne cesium beam standard engineering model which was shown by Hewlett-Packard. There is, at the present time, no intent so far as I understand on the part of the Hewlett-Packard company to offer that engineering model as a production unit. However, we have explored it, and there is a willingness on the part of the company, if a sufficient number of units should be ordered, to start a hand-made production series. The estimate which we have received has been $35,000 for the first unit. If we order more, presumably that price would go down. It appears that the performance to be expected from a very small cesium standard of this size would be still much better than rubidium standards that are available up to now. It could be carried in an airplane under the seat. It would have power for 10 hours, so it would not have to be connected to the aircraft's supply. There is a tentative specification for that instrument here, and it is available for anyone who has not seen it yet. It is certainly a most desirable unit to try out, and I wonder whether many agencies, even outside DOD, would be interested in such a unit, and whether or not we should pool our resources into one order for a number of these. The Observatory is interested in ordering one.

Beck (NRL):

Is there any thought on the physical size constraints of the device? There is a new device coming out with a long depth, and I think that there might be better physical constraints.

Dr. Winkler:

Yes, let me read the size quoted: 4-7/8" x 7-5/8" x 19-9/16", 40 pounds weight, 28 watts, DC 22 to 35 volts or 115 volts, 50 to 400 cycle. Its long-term stability is quoted to be better than one part in 10^{11}, and it includes any combination of environmental effects. It will withstand certain environmental conditions operating -54°C to $+71^{\circ}$C; storage -62°C to $+85^{\circ}$C; altitude 0 to 30,000 feet; vibration a quarter G 2000 Hz; shock MIL-E 5400 L, 30 G, 11 msecs; magnetic field 0 to 2 gauss. These are the specifications by Hewlett-Packard. So, my proposition is to invite an expression of interest to join in a procurement for a few units to be used in some of our portable operations and I am sure that would drastically reduce the cost of portable operations for everyone.

Mr. Chi:

If I may make one more remark on this, we heard previously some really hair-raising requirements or would-be requirements, and I think that the time is now to invest some money in improving these clocks. Because if you wait too long, then you have to start all over again, and it will cost dearly.

Dr. Winkler:

Thank you for your comment. I think the existence of a number of competitors will inevitably bring down the price and improve the performance. The existence of one competitor who very vigorously entered the market has already accomplished something in that respect.

Mr. Chi:

The specification for the new Hewlett-Packard short-beam tube is designed for general-purpose type, and that is why it takes 40 watts. I wonder if you want to follow the company specifications to develop such a unit, since there is very little difference in terms of power requirements. The advantage of that unit is that it is small, and it should also consume less power (which the beam tube indeed does, it consumes much less power). There is no reason to add on to it so much electronics, which may not be neccessary for the intended use.

Dr. Winkler:

It is my understanding that the electronics proposed are a bare minimum requirement and even the one pulse-per-second output would not be available except as option. There would be no clock movement; you would just have the one pulse-per-second output and get your seconds and minutes from good old WWV.

Mr. Chi:

Well, I understand that the beam tube takes less than 10 watts total power. So with the technology of electronics and possibly a simpler power supply where most power is wasted, one probably can reduce the power by a factor of two.

Dr. Winkler:

But after all, there is only one way to find out, and that is to purchase a few of these units and test them. I think that this is perhaps a more economical approach for us than to start a separate R&D project.

Mr. Chi:

I think without making any commitment, if you paid the first $35,000, we will be willing to buy the second if they come down in price.

Dr. Winkler:

Yes, but I believe that price is available only if you buy all of them at once.

Mr. Lieberman (NAVELEX):

We glossed over rubidium, though, and I understand that many of these systems that are coming out are going over to rubidium. I wonder if you could discuss comparative differences between rubidium and cesium and your crystal oscillators.

Dr. Winkler:

Let me emphasize that in the Observatory we have not had nearly the same experience in respect to rubidium standards in comparison with cesiums. We have had some of them in the Observatory for extended periods of time, both the Tracor unit and the Hewlett-Packard unit. We have slso received reports, particularly from Mr. Easton's group at NRL, who for some time made differential phase measurements against our signals. We have evaluated about five to seven. I would like to have Mr. Easton give us some additional comments. But to answer your question with regard to the rubidium standard in comparison to the cesium, I believe it is a fine standard-- the same performance you would expect from an extremely fine crystal standard. It holds its frequency during short-time stability for periods shorter than one day, better than cesium; but when it comes to longer periods, which may be of no interest to many systems, then you are forced to make continuous adjustments of the C-field or, if the adjustments become very large, change one digit in the synthesizer, in order to keep on the same specified system frequency. If you have continuous resynchronization capability in a system, and if you are willing to put up with that need to make adjustments, then the rubidium standard may be an excellent choice. On the other hand, if the system is designed properly from the beginning, these adjustments will not be difficult because you can do it by way of adjustments inherent to the needs of the system. For instance, in LORAN-C, you could perhaps make adjustments by means of very small phase steps. Or, in the OMEGA system, as I understand it, there are regular phase adjustments performed to bring the rates of all standards to the same nominal value. You can incorporate the adjustments due to the drift of the rubidium into these adjustments which are already necessary. So it depends upon the system's configuration, I would say, to decide that question, and I completely agree with your thesis that one should not overlook it. It is a standard which is half as expensive and certainly about as complex, and presumably, it will have better lifetime characteristics of its primary frequency controlling elements than a beam tube, which is rather good already, in the case of cesium. One should not overlook the rubidium standard, I perfectly agree with that. I would like to ask for more comments.

Mr. Ed Rickey (Aerospace Guidance and Metrology Center):

I would like to comment on the rubidium standard. Just as you were saying, continuous synchronization is a must if you are going to consider instituting a rubidium standard. If you are going to be at a remote location where you have a requirement to maintain no worse than 500 msecs in six months for example, you are wasting your money to buy a rubidium, even though microseconds is not a very stringent requirement today. Nevertheless, you cannot guarantee yourself 500 msecs in six months if you have a rubidium with no resynchronization capabilities. As a consequence, I just want everyone who may be thinking of buying a rubidium standard to keep this in mind, and if they are not going to have the resynchronization capability where they are going to install the system, then it is a waste, completely.

Dr. Winkler:

The Coast Guard, I think is in an excellant position to comment on this question, would you, Cdr. Potts?

Cdr. Potts:

Yes, we have used the rubidium standards for a number of years. We do not have a large family of them, but one of the major problems we found in rubidium standards, no matter who makes them, is their reliability. I tend to live in the real world. We have a system, or systems, to operate. That means we have standards scattered all over the world. We must keep them operating-- not just one in a laboratory somewhere or in some nice environment, but, quite frankly, the rubidium standards have not cut the mustard! I would like to point out also that if you are considering a single standard, or even several, which are going to be within the range of some quality electromagnetic emission, you can purchase a good quality crystal phase-lock it to the received carrier from whatever source you want, and enjoy the best of two worlds from the good short-term stability of the crystal oscillator and the excellent long-term stability of the received carrier. So you can see that you do not need to spend a lot of money, if you have something available in the atmosphere.

Mr. Lieberman:

Along these same lines, and since I did mention that new systems are coming in which use the rubidium, do we now have any capability of calibrating them, as to their full capacity?

Dr. Winkler:

It appears to me that we have touched upon an issue where strong beliefs are at stake and we will cover these points later.

Mr. Chi:

I would like to discuss the rubidium gas cell. Number one is to put it in its proper perspective. As far as frequency stability is concerned, the short-term frequency stability is better than the cesium. However, when the long-term stability exceeds one day or so, it is a factor of almost 100 better than crystals, although it may be a factor of 10 poorer than cesium. Reliability of the rubidium gas cell has not been proven worse than that of cesium, although there might be some problems which we have been investigating for the last year or so by ourselves and with the Goddard Space Flight Center, and also we have given small support to Dr. Vanier at Laval University in Quebec, Canada. The problem involved in the rubidium gas cell is that there is long-term drift, the cause of which no one exactly knows. The most likely sources will be the exciter in the light source, the filter, and the absorption cell. The approach at the moment for instance is to solve the light intensity problem. One method is to use a gallium arsenide type of laser. Also, we have another approach which I will leave for future discussion. For the gas cell part, we are using a new material, namely ruby, and we try to evaporate ruby on the wall. Hopefully, that will tend to reduce the systematic frequency drift. However, I do not have any results to report, since this is not my work. This would generally indicate that there is a certain amount of effort in reducing the systematic drift. So, if you can stand, in my opinion that is, with the crystals for whatever operation you may be doing, then the gas cell probably would be at least a factor of 10 or 100 better than the crystal in the long-term drift. This means that you will not have to correct quite as much; the power consumption we should be able to bring down. This is one reason why, in the short cesium beam tube, if it is properly designed, there is no reason for the electronics and power supply to consume 30 watts of power. It should come down by at least a factor of 3 or so to 10 watts. These are some of the things which

I think we should look into very carefully. The next area of comment is the hydrogen maser. So far as the hydrogen maser experience is concerned from our measurement, the stability exceeding one day is a little bit better than what was indicated, although it may not be beyond ten days. If you recall, Harry Peters did show a curve that showed that he obtained the desired result.

Dr. Winkler:

I did not want to say that the hydrogen maser is "no good." As a matter of fact, this is the best clock anywhere for short integration time, even for the next five years, unless we have a major breakthrough in another principle. My comments were solely directed to the experience which we had using the Varian (manufactured later by Hewlett-Packard) design and modern electronics. But, as has been pointed out by Mr. Phillips (NRL), one part in 10^{13} is an excellent stability, and by no means anything to be sneezed at.

Dr. Reder:

We have had ten rubidium standards since 1965. Just to answer your question, Mr. Lieberman, out of this ten, only one holds the frequency to approximately 10 μsecs a month. The other nine standards have a bigger drift. This is point number one. Point number two is one which some people may overlook on the rubidium: you must reset the crystal from time to time because crystal drifting--despite the high servo-gain--would cause an appreciable frequency change over a period of six months. The last point I want to make is with respect to reliability. Rubidium standards were considered more reliable than cesium standards about five years ago: however, I doubt if that is still true. Because according to the ten we have, I would say that the reliability with respect to the rubidium gas cell and the excitation lamp, is probably about the same as that of the cesium beam tube.

Dr. Winkler:

These questions are of great importance, and I would very greatly appreciate receiving more information. In the meantime, Mr. Easton is here and I wonder if he has any comments to make on his experience concerning rubidium standards.

Mr. Easton:

I am afraid our experience has not been as great as testing eight or so. We only tested two, and those two did test out very well for integration times of one day, as compared to cesium standards.

Dr. Winkler:

It appears that we are approaching the end of questions or comments. Before I move to a different subject, let me mention that NBS has just published a Technical Note 394 by Dr. Barnes, Mr. Chi, Dr. Cutler, and others. It is actually a group that is working in support of efforts to come up with proposals for an IEEE standard for specifying frequency stability. According to my copy here, it is for sale by the Superintendent of Documents for 60¢, and you may get some of them free from the Bureau. It is NBS Technical Note 394, "Characterization of Frequency Stability."

Mr. Lieberman:

We are writing the specification for cesium. We are just in the process of the final draft, and I would like any comments you might have so that we can include them if there are any special parameters needed. We think we are trying to get a cesium standard to satisfy everybody, but at this time we do not know.

EXPLANATION AND REQUIREMENTS FOR UNIVERSAL TIME

by Dr. G.M.R. Winkler*

This subject strongly depends on feedback and is one of extreme importance for the Observatory, which asks for your patience, all of you who are not directly concerned with the subject, the last Time Service Announcement, Series 14, on plans for an improved system of universal clock time dissemination. A copy of this information is available if you have not received one. The changes, very briefly, have a high probability in excess of 95 percent to change the system of dissemination of UT. Presently this is being done by the "offset" clock time system, UTC. In the future it will operate without offset on the standard frequency.

As you recall, standard frequency in the so-called Systeme Internationale (S.I.), is defined by the length of one second expressed in so many cycles of the cesium frequency. The Observatory does not at this time correct its clocks or operate its clocks at this rate, but instead operates at a slightly different rate called "offset." Under that system, it has been able, with very few adjustments, to stay within 100 msecs of UT. The list, which has been shown before, indicates that a very large number of users require that kind of precision, and that has been the reason for the system of UTC as it has been operated until now.

The yearly frequency adjustment has not always been sufficient to retain the rate within the tolerance, and the Observatory has had to make additional 100-msec adjustments. However, they were very infrequent.

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*Director, Time Service Division, U.S. Naval Observatory, Washington, D. C. (202) 254-4546.

That system was an excellent one; in fact, it was the perfect one 15 years, 10 years, or 5 years ago. But approximately 1,000 atomic frequency standards are now owned and operated by the U. S. government or by contractors; and many, many oscillators are working continuously in the field. The Observatory has been lucky during the last four years not to be forced to make any such frequency adjustments. However, that luck cannot be depended upon to prevail, and in the future such adjustments may be required every year or every second year. It has become quite evident that the great increase, or expected increase, in time-frequency technology users will force upon us a revision of these methods. Once you agree that the frequency offset is a bad thing and that it is very hard to change frequencies, for instance, of a TRANSIT satellite, of a TIMATION satellite, or of a listening station in Antarctica; and once you agree that one cannot continue to make frequency adjustments, then you must provide UTI by way of information in the form of a time code which will give you the small differences (which may become as large as .6 or .7 seconds) directly on the time signal. The code, which the Observatory intends to use on the Naval time signals (which are presently emitted on about 35 frequencies every couple of hours) will be in this form, which will indicate the digit in question by emphasizing or marking the respective second tick.

There are two questions with which as many potential users as possible should certainly be acquainted. If you have any opinions on them, let the Observatory staff hear them. The two questions are these: (1) Is there any need to have that correction immediately available at the moment of use, (with the time signal) with a precision exceeding 100 msecs; say 10 msecs? Some users have indicated that there may be such a requirement. If there is such a requirement, the Observatory wants to know about it. (2) Would the proposed time code be acceptable, and do you envision any difficulties? There is one which came to light after the announcement was published, that it would be impossible to mark the zero digit. That point can be modified to the extent that if the correction is going to be zero, the mark will be second 30 or - 0, instead of + 0. UT is defined as a correction to be applied to UTC in order to give UT1 directly an additional change since the users are not interested in UT2. It is an artificial concept which is excellent for the timekeeping and timemeasuring people, but not for the user. The user needs UT1, and the correction, therefore, will refer directly to UT1. At any rate, if you plot that correction, you will have adjustments of exactly 1 second. When the adjustment begins to exceed $-\frac{1}{2}$ second, then it will jump to $+\frac{1}{2}$ second. The correction will go slowly from + to -, and a step will be made about every year or so. That adjustment, therefore, will be exceedingly simple for all precision clocks. All that is necessary is to press the button at the right moment and you have dropped one second. It is the dropping of the second which will, in all likelihood, be a necessary adjustment--not the introduction of an additional second. However, the system makes provisions for both, because the performance of the earth's rotation cannot be predicted far enough into the future. So, that is the way the difference will go, and the advantage will definitely be that it is a better compromise which necessarily has to be selected. It is a compromise weighted more in favor of electronic timekeeping, of applications in physics and technology, and less in favor of the users of astronomical time.

The Observatory must move to that system because of almost insurmountable difficulties which otherwise would have occurred. However, as stated in the proposal, it will really have minimum impact on the users. It is only an adjustment which you will have to make on your clock, showing minutes and hours and days of the week, but not on your electronic systems for LORAN-C, for instance, nothing needs to be adjusted. All the Observatory will do is issue new times of coincidence tables (TOC) to become effective at the moment a step is going to be made, which will be known three or for months in advance, and you will just remove the old table, throw it away, and use the new one. You need not make any adjustment except on your wall clock, The adjustment also will not disturb OMEGA. None of these systems needs to be adjusted. All that has to be done is to receive a new reference table to give you the fundamental epoch of the system. The same could be true, of course, for a collision avoidance system. Simply do not start on seconds 3,6,9 and so on, if your basic period is 3 seconds, but instead start on 1,4,7 and so on.

Everybody should now be aware of these plans and there does not seem to be any major difficulty from the correspondence which has been received in response to this announcement. A feeling of relief is evident from some people who said, "that is very fine; we didn't like the offset frequency and that is a step in the right direction."

CONCEPT AND ADVANTAGES FOR PTTI INTEGRATION OF TIME ORDERED SYSTEMS

by Dr. G.M.R. Winkler*

The question: To what degree is the Naval Observatory concerned with distribution of precise time to the lowest level of each individual user? This is really a question of policy and of basic decisions. It brings up, of course, the problem of fundamental distribution philosophy which will be answered in as much detail as possible.

The Observatory is in a period of transition. What it does now, of course, is not perfect. It sends traveling clocks to individual centers of activities--for example, to Oahu, where the Naval Astronautics Group operates a time reference station, Detachment Charlie (see Figure 1). This station also furnishes data for adjustments of more local time services. In other words, a concept of "trunk-line" timing is used.

This, of course, can only be considered an interim solution and it may even be considered an economical solution as long as there are only a few users, but it should not be the final one. One, therefore, has to ask what the concepts should be for the organization of PTTI distribution (see Figure 2).

First is the concept of <u>economy.</u> It appears unnecessary to have one specific system for the distribution of time, as long as so many systems are available which are capable of distributing time as a piggyback operation. This makes PTTI available on navigational or communication

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*Director, Time Service Division, U.S. Naval Observatory, Washington, D.C. (202) 254-4546.

PRECISE TIME SYNCHRONIZATION SERVICE (PTSS)
WORLD DISSEMINATION

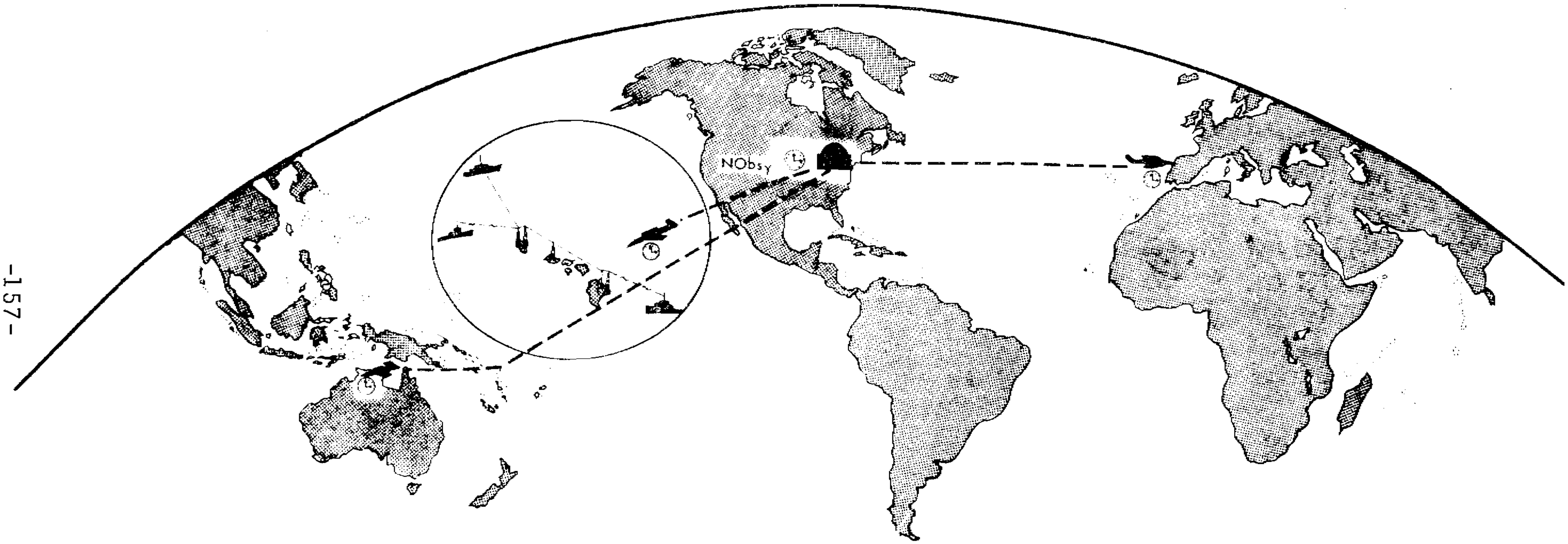


FIGURE 1

DISTRIBUTION

CONCEPTS

1.	ECONOMY:	SUPERPOSITION OF PTTI ON NAV & COMM. SYSTEMS
2.	REDUNDANCY:	USE DIFFERENT SYSTEMS, IF ECONOMICAL
3.	ORGANIZATION:	HIERARCHY — ONE SOURCE - "TRUNK LINE" TIMING TO PTRS

SPECIFICATION OF NEEDS

1. PRECISION OF SYNCRONIZATION
2. FREQUENCY OF ACCESS TO SYNCRONIZATION
3. QUALITY OF CLOCKS USED (RELIABILITY X PERFORMANCE)

WITHIN SERVICES:	ARMY-NAVY-AF CALIBRATION SYSTEM
BY AREA:	GLOBAL-INTERMEDIATE-LOCAL SERVICES
BY SYSTEM:	PROPAGATION PTTI WITHIN EACH SYSTEM, INTERFACE WITH OTHERS AS BACK-UP
EXAMPLES	OMEGA USES INTERNAL SYNCH. AND USES LOR-C AS EXTERNAL BACK-UP
	MANY LOR-C CHAINS CAN BE LINKED DIRECTLY, BUT MUST USE SATELLITES AND PORT. CLOCKS FOR CHECKING

FIGURE 2

systems. That principle is far superior to the design or implementation of a specific time distribution system, because it offers as a second benefit, the necessary redundancy. Different systems should be used simultaneously, since only incremental costs have to be spent to provide that additional service.

PTTI incremental cost is sometimes exceedingly small. To put time signals on the VLF high-powered transmitters requires an expenditure only for the clocks--an expenditure of approximately \$30,000 or \$40,000 per station, with some redundancy, compared to the millions of dollars of investment for the station itself. Redundancy will become more important in the future, since there are several time frequency systems under development, and these may require more reliable access to synchronization sources.

As to organization, Figure 2 in Mr. Stone's presentation (page 123) exploits the principle of hierarchy. There is one source--trunk-line timing to Precise Time Reference Stations (PTRS)--which provides the nodal points for regional distribution of time. For the specification of needs, precision of synchronization is only one parameter, and frequency of access is another very necessary parameter. The payoff to be decided is where to put the money, either in the quality of clocks or in the frequency of access to synchronization.

The overall principle of organization would be very simple if it were not for other complicating factors. There are calibration services within the Army, Navy, and very extensively in the Air Force. Evidently, needs for certification exist here which are in direct conflict to such an organization. In addition, there are geographical facts; there are systems which provide global synchronization or intermediate range or local services; and there is synchronization within each system. It would be a grave mistake for any system designer who proposes to use time frequency technology not to provide for some synchronization capability within the system. In addition, however, it is necessary to provide for an interface to satisfy the requirements of redundancy and invulnerability against jamming or spoofing. Such an interface must be provided, therefore, with other systems as a backup. That appears to be the real crux of the whole concept of PTTI. There is no justification for going to more expensive clocks and less frequent access, if these considerations do not make a system less vulnerable and more reliable. (That is a point of greatest importance, not only for military systems, but also for any kind of civilian time frequency system.)

Figure 3 shows the capabilities of the standard transmitting stations. The high-frequency time signals are of continuing necessity. There are approximately 50 reliable time signal standard transmission stations distributed over the earth which are synchronized to about 1 msec. They all cooperate in the BIH system of coordinated time which has, at the present time, a tolerance of 1 msec. Within the United States or in the Eastern Pacific, one will listen to WWV, WWVH, and in addition, on the East Coast, the excellent Canadian time signal, CHU. From these stations, time is transmitted very reliably and very simply to 1 msec precision, or greater. The day-to-day variations of the WWV signals which we observed in Washington, D.C. are on the order of 0.2 msec, if the precaution is taken to make the same measurement, on the same frequency, at the same time every day. Any PTTI user should have access to a $50.00 communication receiver, and one must compare that kind of timing capability with other concepts which have previously been discussed.

The CIRR has consistently neglected to consider possible improvements in the high-frequency time signal emissions. These improvements cannot be incorporated because of the limitations to 5-kc bandwidth. If time signals were radiated in a bandwidth of 20 kc and the number of stations was reduced in favor of bandwidths, there would be a distribution

DISTRIBUTION

1. HF RADIO TIME SIGNALS: 1 ms GLOBAL
2. PORTABLE CLOCK: ½ μs GLOBAL
3. VLF-OMEGA: 1-3 μs PHASE TRACK (RELATIVE)
4. LORAN-C: ½ μs NORTHERN HEMISPHERE EXCEPT WESTERN U.S.
5. SATELLITES:
   - A) DSCS: 0.1 μs "TRUNK LINE"
   - B) TACSAT: 0.5 μs "INTERMEDIATE"

     2 WAY
   - C) TRANSIT: 10 μs GLOBAL
   - D) DNSS: 0.1 μs GLOBAL

     SILENT (ONE WAY)
6. EXOTICS: R & D (VLBI, POWER LINES ETC)

   TV FOR LOCAL SERVICE

   UHF BEACONS: ——————"——————

   μ WAVE: LOCAL LINKS

FIGURE 3

system in which each mode of atmospheric propagation could be clearly distinguished by time of arrival. There would also be a stability of these modes either the same or nearly the same, as the skywave propagation of LORAN-C; namely, better than 50 μsecs. The stations could be reduced in number very easily, since some were built only for reasons of prestige. Some crowding may occur in the future when all the developing nations insist on a radio standard time system. To summarize, radio time signals will continue to be required by navigators as well as many others.

The exact opposite system with respect to numbers, costs, etc., is one which has already been mentioned--the portable clock. It is a system which has been called a counsel of despair, but it is one which can be implemented immediately. Inasmuch as there are only 100 to 200 users, it is still, by far, the most economical way to bring time to any location of the surface of the earth with better than one-half usec precision.

Many people propose $5 million or more for systems to satisfy five or ten users. Such expensive designs can no longer be considered. With regard to VLF or OMEGA, PTTI capability for a very small cost exists, and I am amazed that VLF seems to be completely out of fashion with many users.

Relative phase track can be performed today with great reliability without danger of loss of coherence, and it gives everyone located anywhere on earth a timing capability of a 5-μsec precision. The situation is different only by an order of magnitude from what there is in LORAN-C; the same thing will be true at OMEGA. The local setup must be calibrated to extract 1 μsec, because other effects enter. Antenna problems are not important for navigational applications, because differences are measured; however, for timing applications they are essential and may be a primary limitation. The LORAN-C is really the best existing operational distribution system with a capability exceeding 1 μsec. Unfortunately, it is not available everywhere.

With regard to satellites, the future situation may utilize the Defense Satellite Communication System and possibl TACSAT with a mutually compatible PTTI modem. This will yield a timing precision certainly in excess of 0.1 μsec, as referenced in the very conservative presentation by Mr. Stone and Mr. Murray. There was nothing in Mr. Murray's data to indicate that the present limit of performance is not entirely due to the limited resolution of the measurement equipment. The figure of 1 μsec is excellent for timing precision. The system will soon be in operation. The concept has been approved both by the Joint Chiefs and by DCA and efforts are well under way to provide an operational capability to the major centers of activity. Hawaii will, of course, be the first, with other stations to follow. The concept contains a link between the East Coast and the West Coast of the United States.

Of the next two systems--TRANSIT and TIMATION--the major advantage is the fact that they are "passive." TRANSIT is an existing capability which is not being exploited. There are five TRANSIT satellites in the air, and there are replacements scheduled in an operational way. It is a full-going system, and it will continue to operate for a long time. It is a pity that the TRANSIT capability has not been utilized for PTTI except by the French, who have demonstrated it very surprisingly.

There are "exotic" systems for PTTI which have been mentioned. But there are also at least 100 different navigational concepts for electronic navigation, and each one would be a useful concept for the dissemination of time.

The question appears to be not what <u>can</u> be done but what <u>should</u> be done. Where should the money be spent? Which compromise would be the best, both from the present point of view and for the foreseeable requirements? The use of television stations is of great importance wherever they are available for local dissemination of high-precision time.

Several concepts have been discussed in previous talks and should be reviewed briefly. The first one is the utilization of the television signals in a differential way. The differential system was first exercised and demonstrated by Tolman and has been used for a couple of years between major timing centers. It does not require any investment at all on the part of the television stations, not even a stabilized carrier emission. One just selects a pulse and makes differential measurements.

The second system, which is the present "line 16" system, or the one which was proposed and designed by Mr. Davis of the National Bureau of Standards, is one which would be of use for application as a local system for dissemination of time. With regard to the "network" dissemination, some essential additional comments are in order. Namely, that although it is true that microsecond stability from day to day over larger distances (almost continental distances) is available, it is also true that the service is continuously being interrupted. The same objection exists against the HF timing signal. That system should also be tested by the same standards and there may be an operational difficulty. More importantly, the propagation delay through the network from time to time changes violently.

There has been a proposal made by the Air Force, Newark, which has great merit, and which is outlined following this discussion. Briefly, they propose to use all three networks; however, people should not immediately jump into a sole reliance on this method because very serious difficulties could arise. At least, "caution" is a very good adjective here until more operational experience has been gained. The television system's great usefulness for local distribution would be of interest anywhere. Wherever there are centers of activity, there is a need for entertainment, and there will be entertainment stations not only in the

United States but in other areas as well. Such a system is very easy to set up and it offers terrific resolution at very little investment. The system has merit; however, the Observatory is faced with a dilemma, in view of some differences of attitude and interest between it and NBS, which evidently is interested in having a very wide general use of the system at a modest accuracy. The Observatory's interests are to use the system to the very highest possible precision in those areas of activity where there is the greatest demand.

This dilemma is posed because the Observatory still has to work out a design which would be compatible with both purposes, because otherwise, approval from the FCC will be difficult to obtain. The FCC, for very good reasons, has to move cautiously in its approval of any such system. Such compatible designs are possible and, such systems should be put into operation immediately. There is some danger that the common R&D syndrome to develop forever and to never become operational will prevail.

The Observatory is at the present time making an extensive effort to improve its own capabilities (see Figure 4). The improvements of the capabilities go on in every area--in the provision of a very stable, very reliable time base and in the determination of astronomical time where a small improvement by a factor of two to five can be squeezed out. Some of these capabilities will not be of use in PTTI, but in related areas like polar variation, etc.

The greatest problem at the moment is to provide funding for high-precision synchronization of all LORAN-C chains, which means that direct synchronization will obviate the need to use corrections, as mentioned by Cdr. Potts. The program has been approved by the Secretary of Defense and is now in the reliable hands of the fiscal people where it will be solved. The next great interest and effort is in making use of the DSCS

PLANS

1. IMPROVEMENT OF USNO CAPABILITIES
2. HI-PREC. SYNCH. OF ALL LORAN-C
3. USE OF DSCS OPERATIONALLY FOR TRUNK-LINE TIMING TO PTRS
4. UTILIZATION OF FSK SYNCH ON VLF
5. OMEGA SYSTEM
6. USE OF DNSS PROTOTYPES
7. LINK-UP OF MAJOR USERS BY TV, μ WAVE, ETC.

FIGURE 4

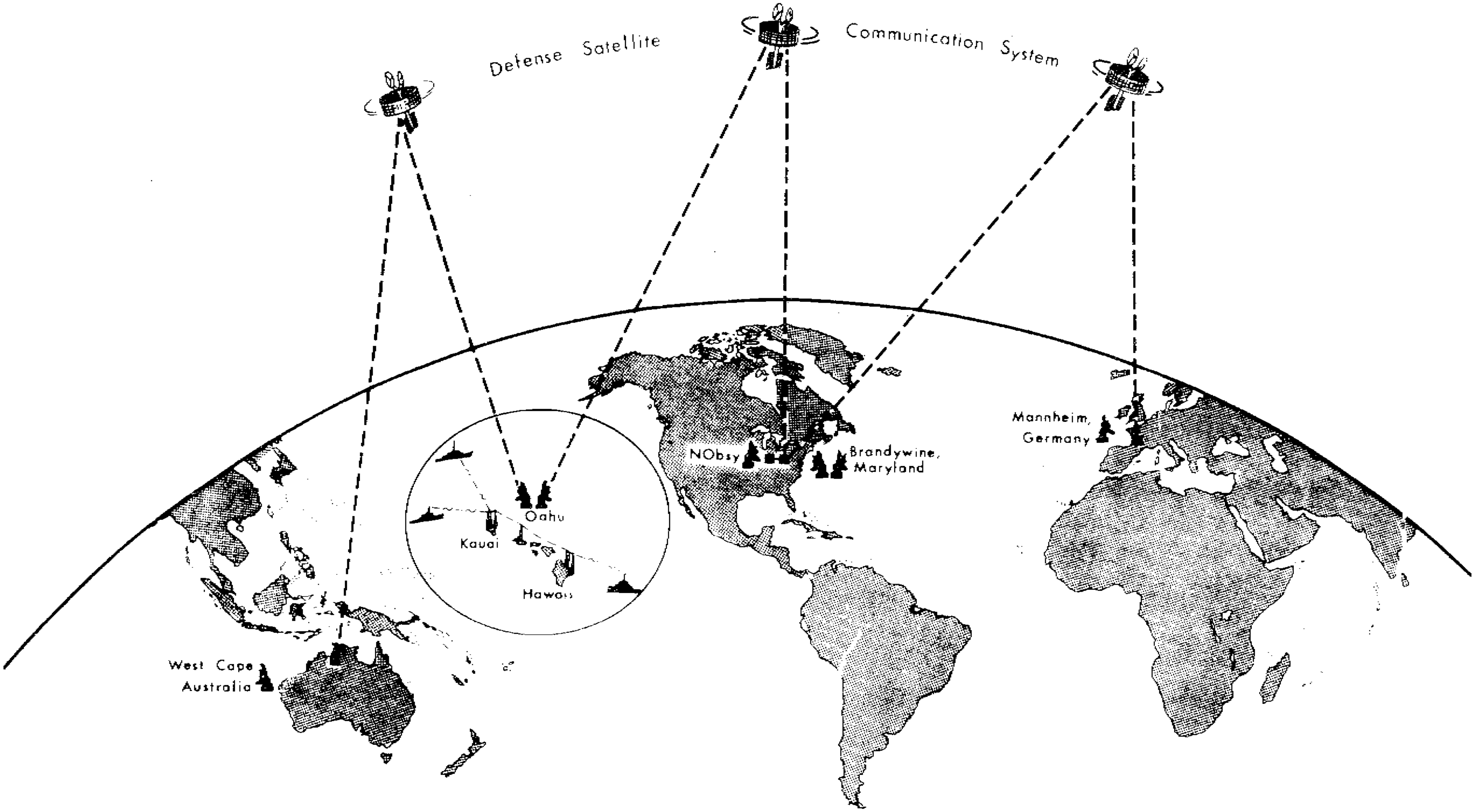
capabilities for trunk-line timing, not only with the precise time reference stations, but also with a number of additional stations--particularly in the Air Force where there is an interest to link-in with that system. It can be done, and there is general agreement that this is very desirable.

Another item of interest concerns the DNSS prototypes. TIMATION II can already be utilized for time purpose dissemination. The numbers which you have seen on the Alaskan LORAN chain frequencies are examples of what can be expected for operational use.

Finally, a point of concern is the link-up of major users by television or by microwave. If a hierarchical organization of time distribution is accepted as an overall strategy, there should be no serious objection for the reasons and the various principles which have been previously listed. But if that is accepted as a primary concept, then it is clear that access possibilities should be provided to regional or local sources of synchronization while more detailed requirements and their justifications should be left to the user or the user system. The Observatory does not have the capability to even consider organizational details; however, it should know about problems and such requirements.

Most people, and particularly those good system designers who have kept in mind the principle that each PTTI system must provide internal synchronization, evidently feel that this is what they need; they have provided for all of their needs and they see no benefit in interfacing with anyone else. That question points to an identity crisis within the PTTI community, because where and why does the need exist to single out this field of interest activities and coordination efforts? How far should we go, and what are the main benefits? They simply have to do with hardening operations of all systems and with economy of operation.

Figure 5 shows the new, high precision "trunk-line" distribution system. For the immediate future, the Observatory will replace a great number of portable clock trips to major centers by satellite links.



PRECISE TIME AND TIME INTERVAL (PTTI) – WORLD DISSEMINATION

FIGURE 5