DMA PRECISE TIME AND TIME INTERVAL REQUIREMENTS

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ABSTRACT

The Defense Mapping Agency, as well as its predecessors, has been a user of time for a number of years as part of the geodetic astronomy and satellite geodesy programs.

John Harrison's clock opened the door to the field use of time required in the determination of astronomic longitude. While current astronomic observing methods employ the same basic principles that were utilized 200 years ago, instrumentation used in the determination of astronomic positions has been greatly improved and epoch times are printed out rather than read from a clock face or interpolated from recorded clock ticks. The accuracy and particularly the stability of portable timing equipment used in the field for astronomic positioning has been greatly improved during the last 10 years.

Positioning by satellites using portable Geoceiver equipment has facilitated the rapid determination of geodetic positions on a uniform world system and has replaced positioning by astronomic methods in remote areas of the world. The high velocity of satellites being used for precise positioning has led to the requirement for more accurate time. Clock epochs to about 50 microseconds are now routine at satellite tracking stations with the goal being at least 10 microseconds. Although these accuracies are still less precise than the state of the art, they must be met with operational equipment and frequently under unusual field conditions. Crystal oscillators in the Geoceivers are stable in frequency to 8 parts in 10^{12} (short term) and 5 parts in 10^{10} (long term), and are among the better crystal standards.

Another geodetic system, the Very Long Base-Line Interferometer (VLBI) requires the synchronization of clocks at two or more observing stations to extremely high accuracy. The accuracy of the system depends largely on the accuracy of the synchronization. The use of Rubidium standards to replace the crystal standards will be tested in the near future at fixed satellite tracking stations for the purpose of improving satellite orbits. New satellite systems, such as those proposed in the Defense Positioning Program (DPP) will be able to use more precise timing for providing observational data required for the accomplishment of geodetic missions. Defense Mapping Agency timing requirements range from milliseconds to tenths of nanoseconds. These requirements will be discussed in detail.

INTRODUCTION

The Defense Mapping Agency was established in July 1972 by the Secretary of Defense. We are charged with providing the Unified and Specified Commands and Services with maps, charts, precise positions, gravity field data and other geodetic products. While DMA is a new agency, it is made up of elements of the former Army Topographic Command, the Naval Oceanographic Office and the Air Force Aeronautical Chart and Information Center, which have existed for some time. These are now known as our Topographic, Hydrographic and Aerospace Centers. Our small Headquarters is located on the Naval Observatory grounds.

One of man's earliest requirements for precise time was for navigation and positioning. The addition of the astronomical section of the Depot of Charts and Instruments in 1837 was a step in the direction of more precise time for greater accuracy for nagivation and charting. Although the U.S. Naval Observatory and the U. S. Hydrographic Office became separate entities in 1866, when the Depot of Charts and Instruments was reorganized, the need for time has made us more and more dependent upon the Naval Observatory throughout the years. This depedence shows up mainly in two areas of our work; time required for geodetic astronomy, and time required for satellite tracking.

GEODETIC ASTRONOMY

Since there is a direct relationship between longitude and time, determination of the local time at a specific point with respect to the time at the meridian of Greenwich will establish the longitude of the point. Present day time signals which are broadcast by several major observatories throughout the world have been synchronized and provide an excellent means of obtaining time with reference to the meridian of Greenwich. Time at the measurement point is determined by observing the meridian transit of stars using optical instruments and precise timing equipment.

The UTC (Universal Time Coordinated) time signal used to compute longitude must be corrected to UT1 (Universal Time Corrected For Polar Motion); in other words, the UT1-UTC corrections must be applied. This means that the local sidereal time of the observatory monitoring the radio signal which is received at the field station has been referenced to the identical pole or axis of rotation as the field station.

UT0 (Uncorrected Universal Time) as determined by stellar observations includes errors in the apparent positions of the stars observed, unknown refraction effects, observational errors, and a systematic error caused by the conventional longitude of the observatory not being exact, relative to the prime meridian. One millisecond of time represents approximately one half meter on the ground at the equator. Through the Bureau of International de L'Heure (BIH), the conventional longitudes of the time service stations are revised to minimize the errors introduced by inconsistent longitudes.

As a result of the longitude adjustments and the previous synchronization of the time services with the atomic frequency standards, conventional (high frequency) time signals and corrections thereof are based on the coordinated and synchronized system UTC (UT Coordinated). Published corrections are now available 30-60 days after the fact. It would, of course, be desirable to have these corrections available sooner, say, about 15 days. (Since the presentation we have been advised that the corrections are available in the desired time).

Until comparatively recent times, time for field astronomy was maintained with a mechanical chronometer which was compared about once an hour with a radio time signal. These comparisons were recorded in increments of two seconds on a chronograph along with the star transits over the observer's meridian and subsequently manually scaled (interpolated) and meaned. As the mechanical chronometers were replaced with crystal clocks, the times between radio clock comparisons were allowed to become less frequent. Finally, the increased accuracy, due to use of temperature controlled ovens, permitted longer periods between time comparisons.

Paper or magnetic tape recorders allowing direct input of star transit times into a computer have been considered for some time. This would eliminate the most time consuming (and I might add, the most monotonous) job in the determination of longitude; that is, the scaling of the time ticks from strip or oscillograph charts. As you know, field astronomic equipment must be portable. Very few sites, probably less than fifty percent, are "drive to" stations. Most stations are located on hill tops or in remote areas not accessible by road. The "backpacking" of generators or heavy batteries except for short distances is an extremely difficult task. We are still looking for a lightweight digital recorder system which can be used for direct entry into a computer.

Recently, DMA acquired several time position printer systems, Model SP-300, manufactured by Datametrics, a subsidiary of ITE Imperial Corporation of Wilmington, Massachusetts. One of these is shown with a Wild T-4 optical theodolite (Fig. 1). This system can be powered by disposable dry cell batteries. A sample of the "grocery tape" output of the system shows FK-4 star number, day of year, hours, minutes and seconds of observation (Fig. 2). About 60 astronomic stations have been observed to date with excellent results using this equipment.

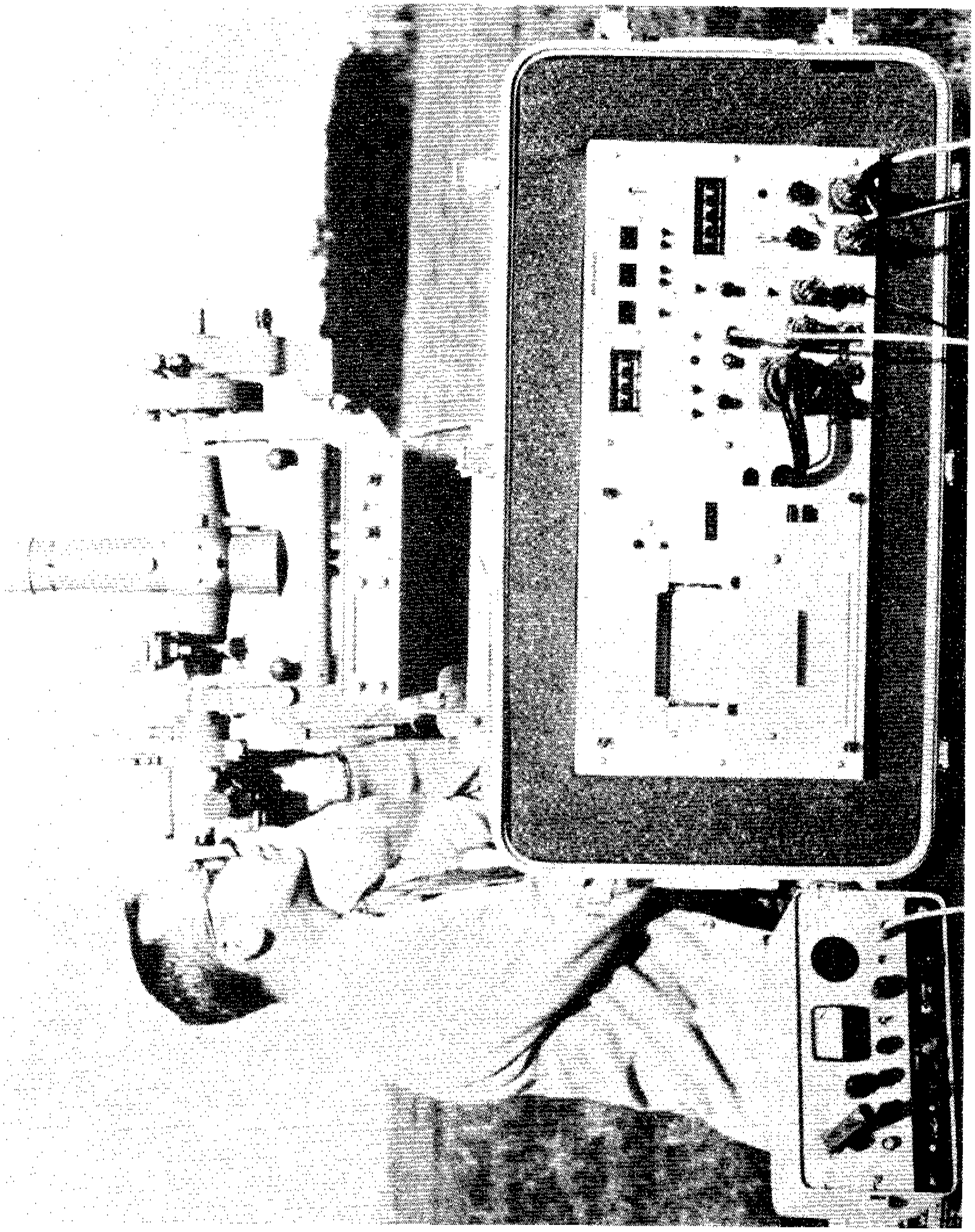

Figure 1

0-04
SETS 3, 4, 5, 6
30 JULY 73 PM
F-4 #87018
K.D. ZELLERS

FK4 Star No.	Date (Day of year)	Hours	Minutes	Seconds
3610	212	06	25	44 .347
3610	212	06	25	42 .713
3610	212	06	25	41 .207
3610	212	06	25	39 .739
3610	212	06	25	38 .103
3610	212	06	25	36 .900
3610	212	06	25	35 .372
3610	212	06	25	32 .059
3610	212	06	25	30 .523
3610	212	06	25	29 .897
3610	212	06	25	27 .417
3610	212	06	25	25 .276
3610	212	06	25	24 .322
3610	212	06	25	22 .017
3610	212	06	25	21 .253
3610	212	06	25	19 [illegible]
3610	212	06	25	16 .919
3610	212	06	25	15 .160
3610	212	06	25	13 .753
3610	212	06	25	12 .343
3610	212	06	25	10 .635
3610	212	06	25	09 .062
3610	212	06	25	07 .674
3610	212	06	25	06 .271
3610	212	06	25	04 .459
3610	212	06	25	01 .421
3610	212	06	24	59 .879
3610	212	06	24	58 .475
3610	212	06	24	56 .950
3610	212	06	24	55 .459
3610	212	06	24	54 .203

06 25 00

Figure 2

A major advantage of combining the DoD mapping, charting and geodesy functions under one single organization is that a larger base is available for the justification and development of new instrumentation. In an effort to reduce the possibility of error and to reduce the cost of astronomic positioning, an automated astronomic positioning system is being developed for DMA by the Control Data Corporation.

Electromagnetic distance measuring equipment used for trilateration or traversing measures the time required for a signal to make the round trip over the distance being measured. While the accuracy of measurements are limited by our knowledge of the speed of light, it is not the dominant error in these measurements.

SATELLITE GEODESY

DMA requires more precise time measurements for its satellite tracking programs. Satellites are tracked to determine an ephemeris which is used for positioning and in studies to improve our model of the earth's gravity field. Among other purposes, the model of the gravity field can be used to provide improved ephemerides. This bootstrap operation has been used primarily by the U. S. Navy, from whom the program was inherited, since 1960 and has resulted in the present gravity field model which includes harmonic terms through the twentieth order and degree, about 400 terms in all.

In addition to the Navy navigation satellites, other satellites, such as those launched by NASA, are used for gravity field improvements. The Timation III satellite, due to be launched next spring, will also be used. The GEOS-C satellite, scheduled to be launched next summer, will have an altimeter aboard which promises to provide deflections of the vertical over ocean areas and also an indication of the variation of the geoid. Other techniques, such as satellite-to-satellite tracking, are being examined to determine the least expensive system for improving the gravity field model and thus the shape of the geoid.

The DMA TRANET tracking network is managed by our Topographic Center and consists of 15 semi-permanent stations deployed worldwide and six stations available for mobile deployment. These ground stations track doppler satellites by recording the time of day when a preset number of doppler cycles have been received since the last data point. The measurements are dependent on a local clock synchronized with UTC from the Naval Observatory. The master tracking and control station at the Applied Physics Laboratory of The Johns Hopkins University is equipped with a cesium clock, which is tied to the Observatory by VLF, Loran, TV and portable clock transfers. When tracking the Navy navigation satellites, containing clocks maintained close to UTC, the time to receipt of the satellite's timing marks provides a means of calibrating the satellite clock against the Observatory's clock. The time signals from the same satellite, when received at the other stations, provide a means of calibrating the clocks at those stations. Redundancy is provided by tracking VLF time signals. At the present time, epoch is maintained at the tracking stations to an accuracy of about 50 microseconds. At the altitude of the NAVSATS, satellites move at the rate of seven meters per millisecond. The 50 microseconds, therefore, equates to 35 centimeters of satellite motion. Although this is well within the current observational accuracy, improvements are desired which will require timing accuracies of about 10 microseconds. Rubidium oscillators have been ordered for six of the semi-permanent stations, as a first step in achieving increased timing accuracy. Other changes are being considered at the same time to improve the overall observational accuracy. These include modification of a digitization technique, study of the third order ionospheric correction, and improving the phase lock loop. Quartz crystal oscillators are currently being used at the stations to drive the clocks as well as to measure the doppler shift. These oscillators have a stability of about one part in 10^{11} per day and slightly better than that over the period of a satellite pass.

As with astronomic observations, satellite observations must be corrected for the latitude shift due to the motion of the pole. A satellite making a dozen or so revolutions about the earth each day becomes a powerful tool for determing the position of the pole. The Naval Weapons Laboratory, Dahlgren, Virginia, reduces the data collected at the TRANET stations every other day to generate an ephemeris. These ephemerides can only be accurate if the polar motion is taken into account. Knowing the positions of the tracking stations, the position of the pole becomes a bias in the adjustment of the data, and must be applied as a correction. Comparison of the NWL polar motion values with the BIH and the IPMS (International Polar Motion Service) values shows as good agreement as between the BIH and the IPMS values themselves.

Although we are supplying the polar motion coordinates derived from doppler data to the Naval Observatory, the corrections applied to astronomic positions are derived by the BIH. Most astronomers are not ready to replace the traditional star observations with corrections derived from satellite data.

Positioning by satellite is also accomplished by using a geoceiver (Fig. 3) with the antenna unit located over the mark to be positioned. The geoceiver (geodetic receiver) is a miniaturized doppler tracking station weighing only about 45 kilograms. Designed by the Applied Physics Laboratory and Magnavox, geoceivers are operated by DMA Centers, as well as NAVOCEANO and others. The geoceiver clock is driven by a quartz crystal oscillator similar to the ones used at larger tracking stations. The clock is started from and synchronized with the NAVSAT time signals. The frequency of the oscillator and the clock drift can be

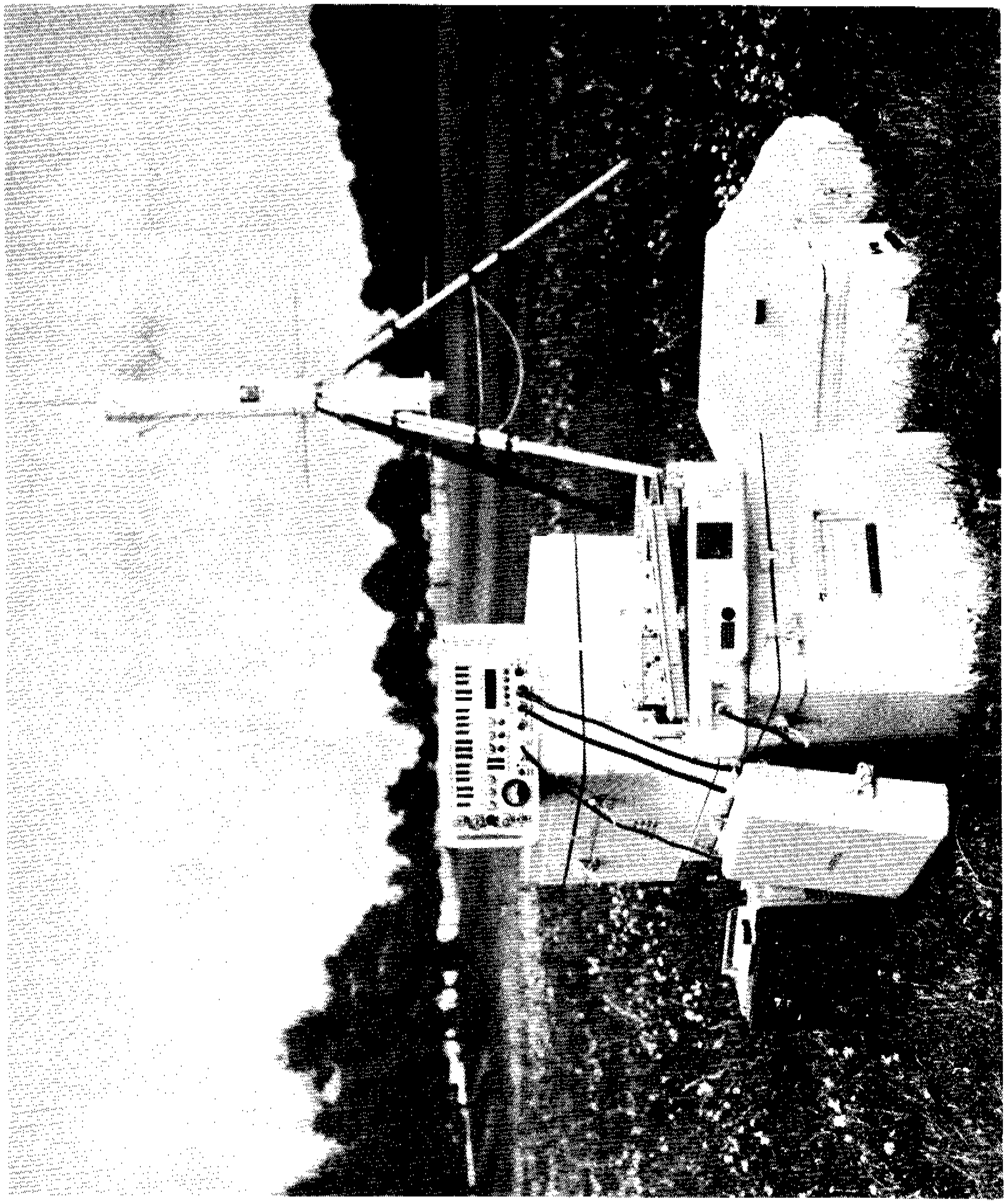

Figure 3

determined on site by hand calculations or as a part of the data reduction program. The stability of these oscillators is five parts in 10^{10} per day and eight parts in 10^{12} per minute. The time at the end of one doppler counting period and the start of the next is read out with a resolution of four microseconds. Positioning by geoceiver, when using the precise orbits computed by the Naval Weapons Laboratory is better than two meters in each coordinate axis. Approximately 35 usable passes are required to achieve this accuracy.

CONCLUSION

The knowledge of time epoch and the measurement of time interval have traditionally played an important role in the field of mapping, charting and geodesy. Current methods of astronomic positioning and satellite tracking will be replaced by new systems coming over the horizon. The present navigation satellites will be replaced with a new system of satellites, possibly those proposed under the NAVSTAR program (also referred to as the Defense Navigation Satellite System). We will be ready to make use of that system when it is available. Epoch accuracy will need to be about the same as the present accuracy. In the meantime, an order of magnitude improvement in the epoch accuracy of our tracking stations is anticipated which should approach the accuracy of the new system in the along track direction.

Much of the DMA survey work, particularly point positioning, depends upon time for its accomplishment. Nanosecond accuracy is not yet required, but the equipment for providing time and measuring time interval which is required, must operate under difficult field conditions. Cost, reliability and portability are of utmost importance. DMA is a production organization and must depend on the developers to provide the hardware needed to do the job with the accuracy and low cost demanded in these days of tight operating budgets.

In closing, I would like to acknowledge the fine assistance of Mr. Philip D. Kuldell of our Topographic Center in preparing this paper. I would also like to assure you as DMA's needs for increased precision and accuracy of time develop, we will appraise you of them.

QUESTION AND ANSWER PERIOD

DR. KLEPCZYNSKI:

Are there any questions from the audience? Yes.

MR. LIEBERMAN:

The new system that will replace the NAVSAT, will that be able to use geoceivers?

MR. WILLIAMS:

Yes.

MR. LIEBERMAN:

Is the new system GPS?

MR. WILLIAMS:

That is another name, yes. It is very hard to keep up with the bureaucratic name changes, I must admit.

DR. KLEPCZYNSKI:

I believe "GPS" stands for "Global Positioning System."

MR. WILLIAMS:

Right.

(Editor's Comment: Later during the week of the meeting, the System was renamed "NAV STAR".)

DR. KLEPCZYNSKI:

Are there any other questions?

(No response.)

DR. KLEPCZYNSKI:

Well, thank you very much. Maybe we can get a discussion going here for a few minutes with some audience participation.

Before the meeting started we were talking about writing requirements for PTTI system. This seems to be a very difficult thing to do. People require, or they say they need accurate time. Some people talk about accuracies of ten nanoseconds.

Apparently it becomes very hard to justify requirements in terms, which upper management finds easy to accept.

Now, I am wondering if anybody in the audience might be able to contribute some type of discussion as to some hard and proven techniques for justifying extreme accuracies in certain time systems?

Everybody knows all systems work better with more exact time, but it is difficult to formulate that in words which are easily understood, or can be proven. It sometimes gets to be a very difficult thing, and I don't know if anybody here has had experience with this.

Yes, Dr. Winkler.

DR. WINKLER:

Well, my experience is rather broad and general; there seems to be a subtheorem of the more general one that the more expensive a system is, the easier it would be approved. The subtheorem offered is: The fancier the clock, the better will be the system.

But I think, to be more on the serious side, in specifying requirements, and in justifying requirements, you have really two problems.

The first one is the acceptance of a common terminology; how do you specify a frequency, how do you specify time, or frequency and phase variations. In most specifications which you see there is a tremendous confusion. People like to talk in parts to the 10 to the something, when in fact they mean phase noise, and vice versa. We will later on have occasion to refer to some papers, some fundamental literature which exists regarding terminology, most notably, the IEEE Subcommittee work on Frequency Stability and its publication on characterization of frequency stability by Barns et al. I think this paper is one which may lead the way to a uniform specification of frequency stability.

Uniform specification language in time should be simpler. You simply state what your phase noise expressed in time is going to be.

But turning now to the second part of my concern, the credibility aspect, and to the justification which would be given in a language easily understood by the many levels of review and approval, I think you have again basically two aspects. One nanosecond propagation time of light corresponds to one foot; it is an extremely short interval of time. I will caution systems designers and systems proponents, to be very, very careful not to overstate the actual requirements, because it will be very expensive to implement timing systems with nanosecond time requirements.

In the discussion of a system, anyone, who talks about nanoseconds and so on, should better first study the various disturbances in the atmosphere, the various disturbances in signal propagation, through the electronic systems, etc., before specifications of requirements for clocks are firmed up.

Once you follow that common engineering syndrome of overspecifying, and of doing things more complicated than may actually be necessary, then you have already embarked on a path which leads to disaster, and you will end up with the typical problems of production, maintenance and cost. I remind you what an elephant is; an elephant is a "military specification" designed mouse.

(Laughter.)

And one should not use cesium clocks or hydrogen masers in a backpack unless absolutely required (if one can't get a time signal in time!).

(Applause.)

DR. KLEPCZYNSKI:

Do you have a comment over here?

MR. LIEBERMAN:

I think to turn the question around, rather than requirements, as Captain Fowler pointed out, perhaps we should look at what is available in precise time on existing systems, and try to make maximum use of what is available at comparatively reasonable costs.

We now have 1 microsecond around the world at the SATCOM stations. VLF, it was pointed out, could be used down to 10 microseconds and approximately 1 microsecond is available on some Loran C systems.

Try to build systems based upon this availability.

DR. KLEPCZYNSKI:

Very good. These are very interesting comments.

Are there any more?