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

---

*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

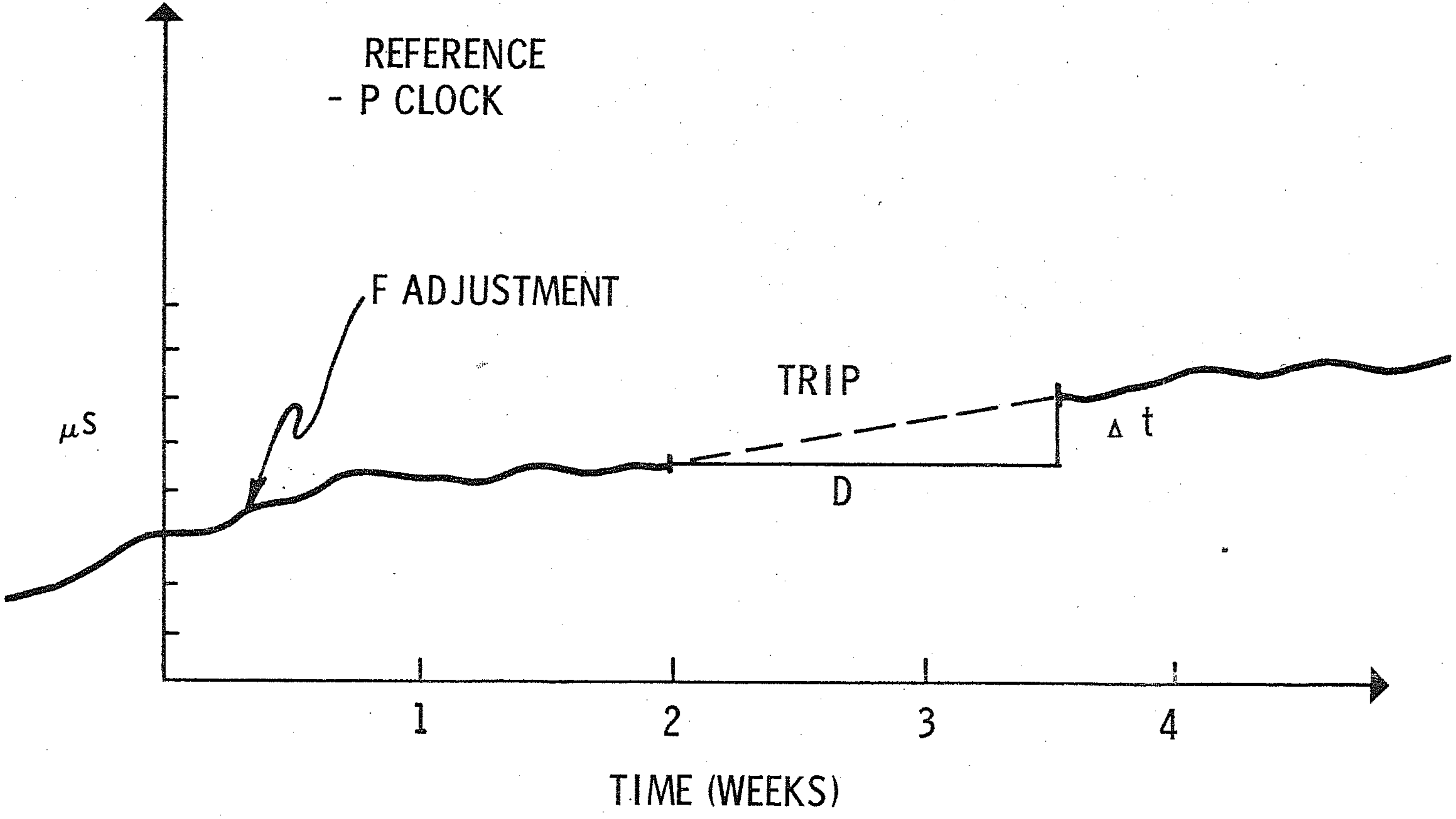

FIGURE 1

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 <u>Proceedings of the IEEE</u>, 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 $\sigma(2, \mathrm{tau}) = \frac{2 \times 10^{-13}}{\sqrt{\mathrm{tau}}_{\mathrm{days}}}$. 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**

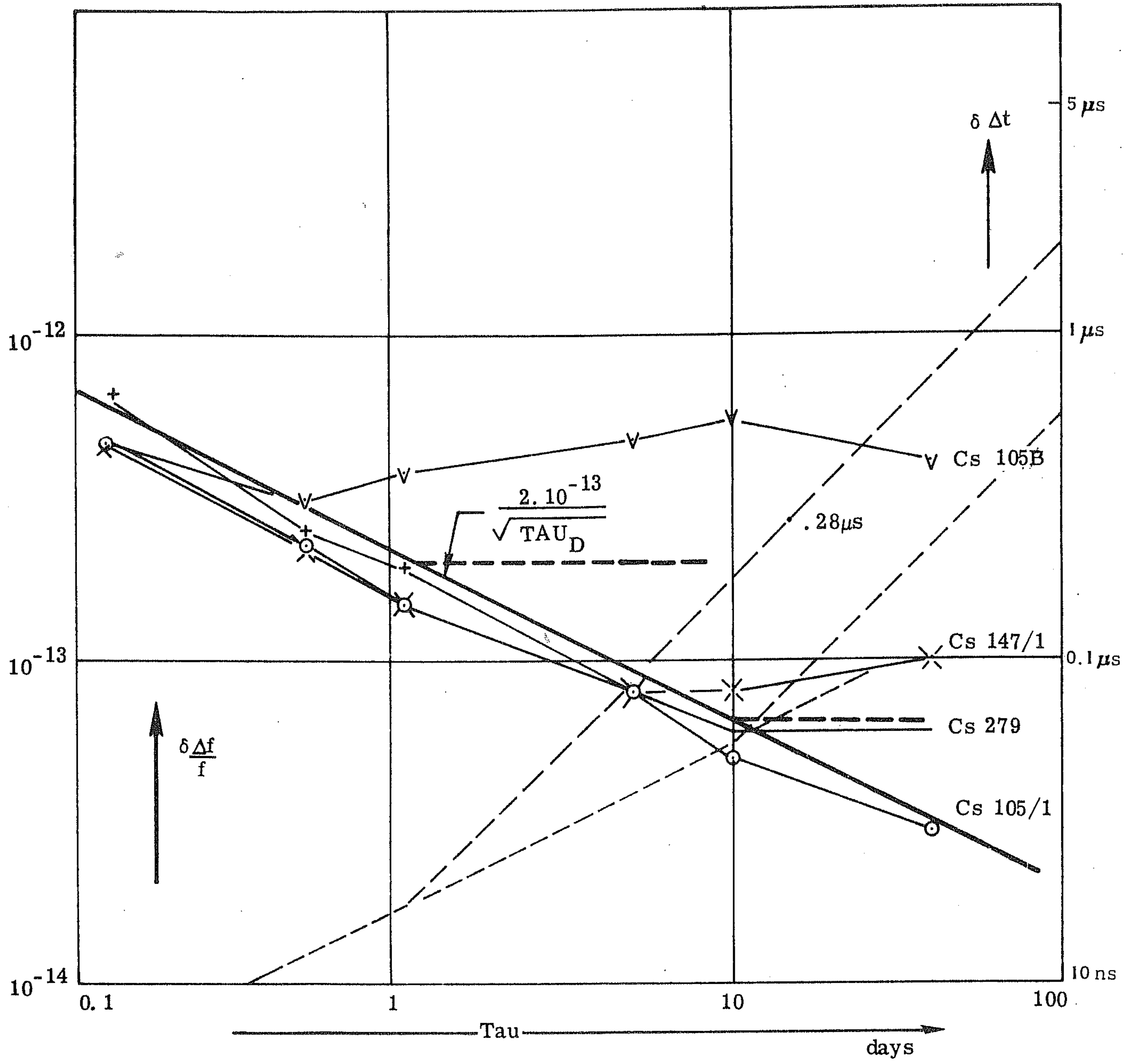

FIGURE 3

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°C; storage -62°C to +85°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.