WHAT IS PTTI?

An Overview of Techniques and Applications of Precise Time and Time Interval

by

Gernot M. R. Winkler
U. S. Naval Observatory
Washington, DC 20390-5100

ABSTRACT

Precise Time and Time Interval (PTTI) is an electronic specialty which originated with the availability of high performance oscillators and clocks. The widespread application of PTTI in modern electronic systems is due to the close connection of time measurement with distance measurement, the possiblity of independent coordination of remote actions over extended periods of time, and better utilization of the time and spectrum domain. The great precision of modern clocks must be purchased, however, not only with dollars but also with greater sophistication of the necessary support.

Automation can overcome some, but not all of this extra cost. Moreover, if indeed we depend on our clocks more than before, then we also have to assure that system time can be kept with the greatest reliability. This also creates new and unusual requirements for a truly uninterrupted service. The basic concepts of PTTI are discussed.

BACKGROUND

Electronic time measurement found its first large scale application in conjunction with the development of RADAR and electronic navigation during World War II. Volume 20 (Electronic Time Measurements) of the MIT Radiation Laboratory Series gives an account of the techniques with which timing was implemented in a variety of systems. The quartz crystal was in wide use, albeit, mostly as a time base for short time measurements. The measurement of longer periods with great accuracy was still the undisputed domain of the astronomer and it remained so until industrially produced atomic clocks became available. The first modest steps in the application of these new devices for the solution of problems in the field started around 1958 with the introduction of atomic frequency control in experiments involving VLF and the, at that time experimental, Omega Navigation System (Reder et al. 1960). Ten years later, the transistor had completely replaced electronic tubes, and the atomic clocks had taken essentially the form which is still familiar to us. Most VLF transmitters and the LORAN transmitters were driven from Cesium frequency standards and Naval Research Laboratory (NRL) had plans to put atomic clocks into satellites. Many network television stations were procuring Rubidium frequency standards because of the reduced co- and cross-channel interference using atomic frequency control.

The next major step came with the merger of digital electronics with high-precision timing. Digital techniques are naturally suited for the full exploitation of the benefits which become available to the system designer with the application of precise timing and frequency control. Timing and/or frequency measurement is principally counting which is also the essence of the digital technique. But at this moment one cannot possibly foresee the full extent of the future massive use of PTTI throughout military and civilian applications. Indeed we can assume that no electronic system with extended spatial coverage will come into existence without the application of precision timing in one way or another. All of these developments find their documentation in the proceedings of the regular PTTI conferences as listed in Table 1.

What is PTTI?

(System Applications)

Precise Time and Time Interval (PTTI) in our usage stands simply for the application of precise timing and frequency control. Other designations for the various applications include the concept of "Time Ordered Systems" or simply T/F systems and technology. However, we must remember that there are really several different stages to be distinguished, all of which refer to the enhanced importance of precise time and frequency in the operation of the system, but with very different implications for their operational philosophy:

1. The subsystems require a tight relative frequency tolerance for the reference standards in use. There is no phase tolerance specified, or it is a very loose tolerance. The frequency tolerance is generally smaller than 1 x 10^{-9}. Precision quartz crystal oscillators are a necessary means for achieving such narrow tolerances and the system generally will allow some means of internal reference distribution such as pilot tones, etc. If the use of such references is continuously possible, or nearly so, then we should not really speak of a genuine PTTI system. Our television with its color subcarrier would fall into this category. The quartz crystal oscillators used in the receivers can be very inexpensive because they are re-calibrated during each frame.

2. The subsystems require highly accurate frequency generators. That would mean that in contrast to group one, the references must meet the specification a priori, i.e., without calibration after turn on. This requirement entails the use of atomic frequency standards, and very often, standards without long-term drift. (Rubidium clocks usually have such a small long-term drift).

3. Synchronized systems in the wide sense, i.e., they operate in relative synchronism but without accounting for propagation delays, or frame ambiguity resolution. A synchronization tolerance is specified together with a re-synchronization time interval. The better the clocks used, the longer can be this re-synchronization interval.

4. Synchronized systems in the narrow sense, i.e., with complete accounting for the delays and with "frame ambiguity" resolution. That means that the fundamental period in the system is very long, with the individual frames or repetition periods not being equivalent. But the system is on a purely arbitrary reference time.

5. Coordinated systems, i.e., synchronized systems in the narrow sense which, instead of being on an arbitrary epoch, are referenced to Coordinated Universal Time. Surprisingly, this does not necessarily mean that such systems operate from an external time reference. Their system time reference is only coordinated to public time but otherwise operates completely independently. This point is frequently misunderstood, which then develops into resistance to the idea of coordination. This mental block is then lastly the reason why so many designers do not admit that their system is really a timed system which can and should benefit from coordination because it costs so little.

Network synchronization involves usually #3. The step from #3 to #4 is expensive, whereas the last step is the easiest, least expensive and most beneficial. This is so because one always finds that there are interfaces with other systems, even if, as usual during the system design, one does not expect to have any. On the other hand, by becoming a member of a community of coordinated systems, the full synergistic benefits of redundancy, greater accuracy, and much greater operational reliability, can all be obtained at hardly any incremental cost.

The most important benefit comes about, therefore, from taking the step from #4 to #5 right from the beginning; an operational time and frequency discipline exists then as a matter of course and enters into all design questions, logistics and training matters as an integral part instead of having to be added at great cost only when one is inevitably forced into it. I say "inevitably" because I saw it happen to every system I remember which started to use precision clocks in one way or another. No, it can be demonstrated that once step #2 has been taken, the rest is only a question of time (in more than one sense!). The simple reason is that one cannot really measure or maintain a frequency reliably within 1×10^{-11} without making time measurements. Without accounting for accumulated time differences no accounting of short time frequency variations will be possible. Therefore, my recommendation is that, if one is really serious about a specification of frequency to that accuracy, that person should start taking time measurements into account also. And because one has then entered the domain of high precision, a host of unexpected additional points have to be considered also. It is better to have these questions brought into the open than to remain unaware of them until operational problems come up. Actually one can postpone most of that and delegate it to a "time manager", but such a responsibility must be established in every time-ordered system.

In navigation systems or systems which determine position, their role as a PTTI system is much more obvious from the beginning. The basis of operation is the simple fact that light or the electro-magnetic wave travels at a speed of 300m/us. This explains easily that the required precision of time measurement (and timekeeping if the clocks must be free running over some time) must be commensurate with the required accuracy of position determination. In earlier times this independent timekeeping was often circumvented by making relative measurements or by the use of the Doppler effect of moving beacons. But today the trend is generally to rely more on the clocks because of the great operational benefits. This has been the reason why, e.g., the LORAN stations have been equipped with cesium clocks as a replacement for the rubidium standards (which in turn had replaced the crystal standards in earlier times). Similarly, in the modern Global Postioning System (GPS), cesium clocks are used in the satellites vs. quartz crystal clocks in the earlier Transit system which relied on more extensive ground data processing and less on the satellite clocks for which no prior experience existed at the time.

To sum up: PTTI designates an electronic specialty concerned with the use of precise time (10ms tolerance or less) and/or precise time interval (within 1×10^{-9}) in electronic systems. The field includes basic PTTI policy questions; clock technology, including questions of reliability; time distribution, including the treatment of propagation delay; relativistic corrections for highest accuracy of time transfer; and clock "noise", i.e., statistics of clock performance.

Clocks and Their Performance

An overview of the main types of precision clocks is given in Table 2. Two main points must be considered:

a) In general one gets what one pays for. However, this also means one should not specify more than needed because of the excess cost of purchase. And even more important, and more costly in the long run, is the additional complexity and delicacy of clocks which are selected solely on the basis of their stability because one wanted to obtain "the best". The simpler a device, the more reliable it will be and the less support it will require.

b) Performance is not a one parameter quantity. Clocks differ in respect to their stability over short intervals (which affects spectrum purity, jitter, etc.) vs. long time stability (important for time keeping). In addition, their sensitivity to the environment must be kept in mind. Shock and vibration are bad for all clocks, but static acceleration is especially hard to overcome for quartz crystal clocks. Magnetic fields are a problem for all presently available atomic clocks. Temperature variations are also not conducive to precision measurements of any kind. We must remember that clocks are very high-technology items and require some kind of consideration even though militarized and space-qualified clocks have been designed to withstand quite a bit of environmental stress.

System Tolerances

Requirements for time or precision frequency are usually given in a rather simplistic manner, such as "must stay within 1 microsecond (us)". This is insufficient because the duration during which this performance must be available is as important as is the timing tolerance. Moreover, this number, whatever it is, is not to be confused with the necessary measurement resolution. To assure, e.g., that a clock stay within 1 us over 100 days, one will have to set its rate, or calibrate it initially, to better than 10 ns per day. If my measurement resolution is only 10 ns then this will take me a whole day to accomplish. As a general rule, this measurement resolution must be as high as feasible. Any attempt at saving on this item is very costly in the long run.

Clock Sets

For uninterrupted operation it is indispensable to have spare clocks. A single spare clock at a station can, however, create a small problem: which one is right? This is exactly the point where the great advantage of operating in a coordinated system becomes obvious. All the operator has to do is to make a time comparison with any other coordinated system to resolve his doubts, because with three clocks one can usually determine which one shows the irregularity. With more clocks available one may also want to use them for more than just as a reserve. This raises then the question of algorithms for the computation of a "best" time scale. In the simplest but also most effective case one can simply plot all time differences. This will allow the recognition of rate changes of individual clocks, provided that these changes do not all occur at the same time (Hafele and Keating 1970).

Reliability

CCIR Report 898, Performance and Reliability of Reference Clocks, gives an up-to-date and very comprehensive discussion of the presently available reliability data on atomic clocks. Briefly stated, the failure rate function follows the usual bathtub shape. After a pronounced infant mortality, the failure rate stays low up to about 3 years when end-of-life phenomena seem to begin. A practical aspect is the difficulty of measuring mean time between failure (MTBF) for devices which are, after all, and our complaints notwithstanding, very reliable. For an exact measure one would have to wait until all of the test clocks in a given set have failed. A more practical statistic, in such cases, is the mean life which is known after one-half of the clocks have failed. The full story, however, is only given by the failure rate as a function of operating time. Lastly, we really have not had consistent samples available in the past. Every change in a production or a supplier produces entirely different results. A major reason for the difficulty is the incredibly high demand which is placed on the electronics of an atomic clock. For the achievement of a stability of 1×10^{-13} per day, which is typical for an industrially manufactured cesium clock, the electronics is called upon to stabilize the driving quartz crystal oscillator to within 2×10^{-6} of the microwave bandwidth of the atomic beam tube. Phase lock loops at 5MHz must be stabilized to within fractions of milliradians and phase detector balances must remain within 1 mV over years to prevent long-time drift of the oscillator. Considering these requirements it becomes clear that most of the modules in such a device including the power supplies must be designed for the specific application and cannot be taken ready made and tested from a vendor. In one word, atomic clocks until now have not been mass produced but have remained typical high-technology items, manufactured in short individual runs. If anything changes in the manufacturing set-up, then we must expect also a change in the samples produced.

Clock Statistics (Clock Noise)

The concept of the atomic clock consists of an atomic package, functioning as a microwave discriminator, the output of which is used to control the driving crystal oscillator. The discriminator is used here as a passive device which has an unavoidable amount of noise in the output (Hydrogen Masers are a notable exception because here the atomic package itself produces a signal coming from the hydrogen atoms). This noise now modulates the frequency of the oscillator with random, white (uncorrelated) noise. Figure 1 shows the time error of such a clock. It is a random walk coming from the integration of the servo noise. This is the best possible case because any persistence of disturbances over some time (i.e., if the noise is correlated) will produce much larger time errors than this random walk. Now the causes for such persistent disturbances are systematic variations in the operating conditions, coming partly from relaxation effects in the structure, the magnetic materials, or the electronics, and partly they are environmentally induced. Older systems could be expected to have substantially relaxed and should, therefore, show a better stability than new systems. However, the signal-to-noise ratio will generally be poorer and this seems to cause the generally poorer overall stability of old clocks.

The internal relaxations are to a large degree foreseen by the designer who tried to compensate for such effects. Similarly, external effects such as power line fluctuations are effectively regulated out at the expense, however, of secondary effects (changes in the internal temperature distribution) that will show up delayed, which in turn will induce compensatory processes. For all these reasons the clock system does not really have a stable equilibrium and that produces what is known as "flicker noise" in the output frequency for long-time intervals. This is, however, still a simplification because there are different noise types depending on the time interval considered. These details become really important for the prediction of the clock errors to be expected.

The "bottom line" here is that the clock operator must do his/her best to protect the clocks from all disturbances as much as humanly possible, and it means also that people should be kept as far away as possible!

Time Access (Time Distribution)

Table 3 gives an overall picture of the main PTTI access tools. If the present trend continues then the situation will become about as follows:

In its area of coverage LORAN C will remain a most reliable and simple precision source for PTTI.

For very high-precision requirements and for true global access, the Global Positioning System (GPS) is the choice. For non-qualified users there will likely be a degradation of precision in the future, but it remains to be seen how much it will actually affect a user who can afford averaging his readings over a day. At this time a relatively simple, single frequency receiver can provide a smoothed daily precision of better than ±10 ns anywhere. With the "common view" technique even better results have been reported. The potential for qualified users of the full system will be at least as good.

For highest requirements, point-to-point satellite links allow timing with uncertainties of less than one ns, albeit at high cost.

For modest requirements (50 us) in the Americas, the GOES satellites allow inexpensive, fully automatic timing.

For modest requirements anywhere, with very high reliability, the Transit satellite system is an excellent choice. (More expensive than the GOES satellite).

For lowest cost, least precision but widest coverage, the standard HF time signals and even the telephone are available.

In all cases where uncertainties of less than a few hundred nanoseconds are required, relativity theory must also be consulted for the computation of corrections to the actual measurements of distant clocks. This is a fact of life today and not, as it used to be, an abstruse question of only theoretical concern. Time is, in principle, a local ordering parameter. For distant measurements the concept of simultaneity must be refined which leads to the corrections just mentioned.

CONCLUSIONS

There are a number of general principles which should guide the confused mind in this jungle of possible choices. One can recommend the CCIR Study Group VII documentation (particularly Reports 363-5, 580-1 and 364-4) as a guide. The only disadvantage is the high price of the "green book" which is sold by the International Telecommunications Union (ITU) in Geneva (3). Less expensive and closer to home are these PTTI conferences which have the additional advantage that personal contact with experienced colleagues can be utilized to the fullest extent. Nothing beats experience! Table 4 suggests the use of a continuing service which is available for the operational PTTI user. The new DoD Directive 5160 of June 14, 1985 specifically directs the Observatory to establish a "Repository" of PTTI information for which this service is to be the core. We will appreciate receiving your requirements and suggestions.

References:

1. Reder, F. H. et al. (1960) World Wide Clock Synchronization. IRE Transactions Mil. Electronics 4(2/3) 366-376.

2. Hefele, J. C., and Keating, R. E. (1972) Around-the-World Atomic Clocks. Science 177, p166-170 (14 July).

3. Recommendations and Reports of the CCIR. (last issue 1982) Vol. VII CCIR, ITU, Geneva

PTTI CONFERENCES

SYMPOSIUM ON FREQUENCY CONTROL

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TABLE 1

CLOCK TYPES AND THEIR PERFORMANCE:

CLOCK	STABILITY			LIFE	COST	NOTES
	10 MIN	1 DAY	10 DAYS			
QUARTZ CRYSTAL	E-11 E-6	E-11 E-6	E-10 E-5	10 YEARS	8K$ 1$	SENSITIVE TO STATIC ACCEL., TEMPERATURE
RUBIDIUM CELL	E-13	E-12	E-11	5 YEARS	10K$	BAROMETRIC PRESSURE MAGNETIC FIELD SENS.
CESIUM BEAM	E-12	E-13	E-13	5 YEARS	35-45K$	MAGNETIC FIELD SENS.
HYDROGEN MASER	E-15	E-14	E-13	2 YEARS	400K$	LABORATORY INSTRUMENT
MERCURY ION	E-13	E-15	E-14	1/2 YEAR	110K$	PROTOTYPE ONLY.

TABLE 2

COMPARISON OF TIME TRANSFER METHODS
Status as of 1985

SYSTEM/METHOD	COVERAGE	EQUIPMENT COST	PERFORMANCE	NOTES
VLF/OMEGA	WORLDWIDE	5k$-25k$	2μs/day	Frequency Reference
LF	REGIONAL	3k$	1μs	Automatic, Time Code
LORAN-C	NORTH HEMISPHERE	1k$	100ns-2μs *	Manual
		10k$	100ns *	Automatic
HF-TIME SIGNAL	WORLDWIDE	200$	1ms	Operator Training
GOES	AMERICA	4k	50μs	Automatic, Code
TRANSIT	WORLDWIDE	14k$	10-25μs	Automatic, Code
GPS	WORLDWIDE	25k$	10ns	Automatic, Code
COMMUNICATION SATELLITE	POINT-POINT	100k$	1ns	Two way, Transmit

* Excluding skywave and over land paths.

(FROM CCIR REPORT 7/113-E (REPORT 363-5)

TABLE 3

AUTOMATIC DATA SERVICE FOR PTTI USERS:

1. TELEPHONE 300, 1200 AND 2400 BAUD

EVEN PARITY, FULL DUPLEX

BELL COMPATIBLE 300/1200 BAUD 202-653-1079

CCITT V.21 300 BAUD 202-653-1095

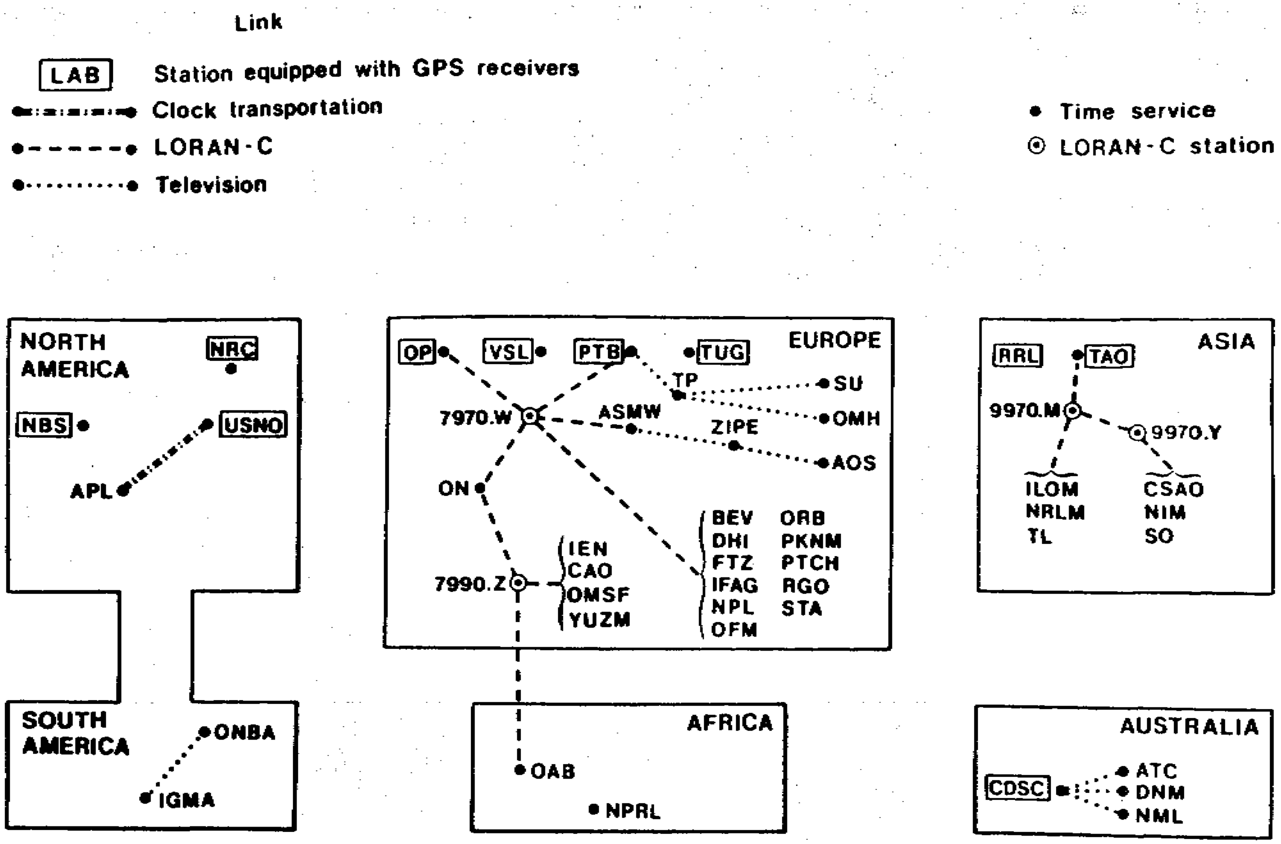
CCITT V.22 AND V.22 bis (1200/2400 Baud) 202-653-1783

2. General Electric MARK III Information System Catalog RC28 FOR TIMING DATA EXCHANGE WORLDWIDE.

CONTACT Neville F. Withington, Code TS, U.S. Naval Observatory Washington, DC. 20390

Telephone 202- 653-1527 or -1529

TABLE 4



INTERNATIONAL COORDINATION: MAJOR LINKS AND CONTRIBUTORS TO TAI 1985

(FROM BIH)

TABLE 5

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THE FOLLOWING IS A TEST COMPUIATION FOR AN IDEAL CLOCK WITH PURE WHITE
FREQUENCY NOISE OF EXACTLY I part in 10 to the 13th FROM HOUR TO HOUR.
THE AVERAGE FREQUENCY IS ASSUMED TO BE EXACT.

DATA REDUCED AT (UT): 11:21 AM  WED.,  6  NOV., 1985

START DATE AND VALUE     0.00           0.0
              AVERAGE VALUE:            3
END   DATE AND VALUE  166.71           -.7

 166 DAYS OF DATA. BEGIN MJD     0.       166 END MJD
     ALL VALUES IN E-15

TWO SAMPLE SIGMA FOR   1 HOURS IS  100.4   WITH  4000 DATA POINTS AVAILABLE
TWO SAMPLE SIGMA FOR   2 HOURS IS   69.7   WITH  2000 DATA POINTS AVAILABLE
TWO SAMPLE SIGMA FOR   4 HOURS IS   49.6   WITH   999 DATA POINTS AVAILABLE
TWO SAMPLE SIGMA FOR   8 HOURS IS   35.2   WITH   499 DATA POINTS AVAILABLE
TWO SAMPLE SIGMA FOR  16 HOURS IS   24.6   WITH   249 DATA POINTS AVAILABLE
TWO SAMPLE SIGMA FOR  32 HOURS IS   19.2   WITH   124 DATA POINTS AVAILABLE
TWO SAMPLE SIGMA FOR  64 HOURS IS   13.4   WITH    61 DATA POINTS AVAILABLE
TWO SAMPLE SIGMA FOR 128 HOURS IS    6.9   WITH    30 DATA POINTS AVAILABLE
TWO SAMPLE SIGMA FOR 256 HOURS IS    6.1   WITH    14 DATA POINTS AVAILABLE
TWO SAMPLE SIGMA FOR 512 HOURS IS    3.2   WITH     6 DATA POINTS AVAILABLE
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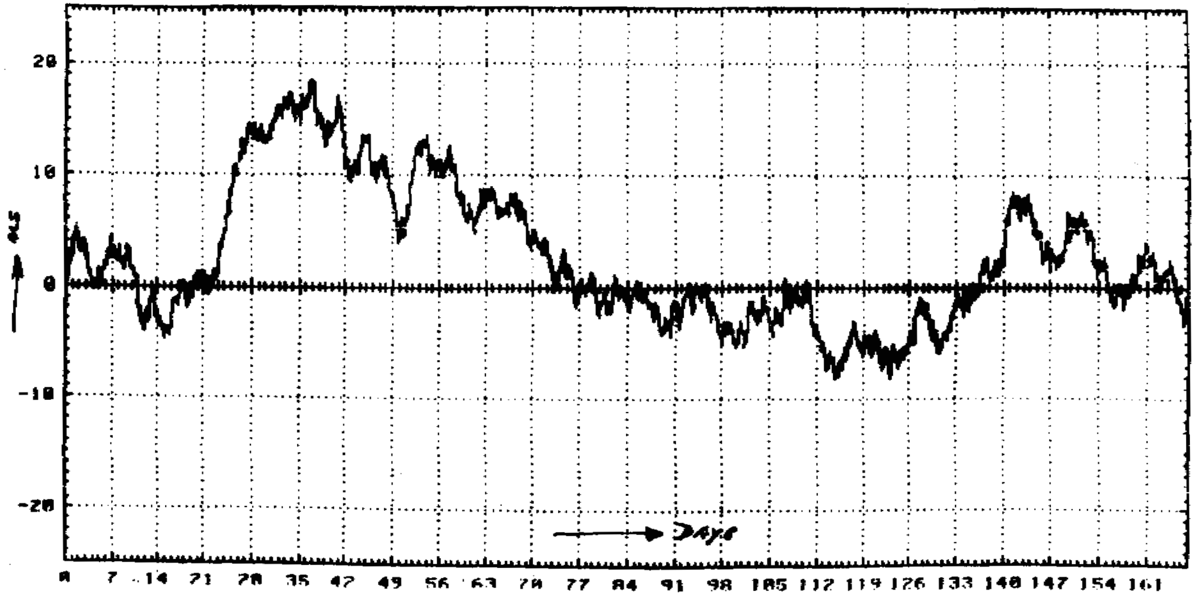

FIGURE 1. IDEAL CLOCK

QUESTIONS AND ANSWERS

RONALD BEARD, U.S. NAVY RESEARCH LABORATORY:
We periodically hear that we have reached the penultimate in precise timing and in systems that require precise timing. Do you think that this trend will continue in the future?

MR. WINKLER:
One has to consider two things: number one, we are evidently very close to fundamental limits in propagation delay. I question that systems will not be able to maintain global synchronization to, lets say, ten picoseconds or one picosecond. There are certain limits. Just the noise due to the signal going through the atmosphere, for instance, the troposphere consists of bubbles on the order of a few centimeters, as these bubbles of different density move, they generate noise. The propagation delay will fluctuate. Therefore, there are limits. Where, however, the need for better clocks continues is that the better our clocks are, the more independence we will have in our stations. If we can have clocks which are reliably stable to within apart in ten to the fifteen, as comparison with present operation at a part in ten to the thirteen, that will mean that we can extend independence that much farther out into the future, or reduce the frequency of calibration. So there is a great benefit in the continuing development of clocks, but most of the emphasis here will have to do with reliability, with long term performance, with freedom from systematic changes, and I repeat reliability. That has been the major problem in system applications.