RELATIONSHIPS BETWEEN THE PERFORMANCE OF TIME/FREQUENCY STANDARDS AND NAVIGATION/COMMUNICATION SYSTEMS

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ABSTRACT

Oscillators and clocks have moved beyond individual instrument applications and are now being used as critical elements of large scale electronic systems. The need for developing advanced time and frequency standards arises from increasingly more sophisticated DOD and civilian missions and functions in navigation, surveillance, identification and communication.

In these systems, time and frequency standards are employed to provide some desired performance or to be the central signal source for most systems functions. It is often not clear what frequency stability or accuracy is really needed. Often, a better clock or oscillator could simplify the system, or improve the performance of the system; in other cases, a different system design may lead to a reduction in the performance demands on the frequency or time standard.

This paper discusses the relationship between system performance and clock or oscillator performance. Our approach will be basic, pointing out some tradeoffs such as short term stability versus bandwidth requirements; frequency accuracy versus signal acquisition time; flicker of frequency and drift versus resynchronization time; frequency precision versus communications traffic volume; spectral purity versus bit error rate, and frequency standard stability versus frequency selection and adjustability. Our aim is to give the system designer and manager a better grasp of the benefits and tradeoffs of using precise frequency and time signals at various levels of precision and accuracy.

INTRODUCTION

During the last few decades, there has occurred a major revolution in the science and practice of time and frequency generation, dissemination and utilization. Frequency and time standards with very high performance characteristics have been developed, many of which are commercially available. Significant further progress in all important performance areas is possible. This includes improved short and long term frequency stability, spectral purity, size, weight, environmental insensitivity, cost, power demand and many more. In addition, there may be many cases where the application of a better clock could significantly relax other system parameters, and thereby reduce overall systems cost and complexity.

The question arises, what benefits can be derived from available or potentially available frequency standards and clocks? The PTTI Applications and Planning Meeting is the proper forum to address in a realistic manner this problem of long term technology planning. Our objective is to find a defensible rationale for long term investment strategy for time and frequency control device development. The usual approach to technology planning is to define system requirements and derive technology needs, which is followed by a program to achieve stated objectives. We have difficulties with this approach. Long term operational requirements are usually defined in very general terms, and it is very difficult to extract time and frequency generation and dissemination needs from stated goals.

We would like to suggest a possible alternate methodology. First, one should establish, for a particular application, the specific function performed by the device in the system and the elementary relationship between the time/frequency device and system performance. In addition, one should also determine the critical performance and operational time/frequency device parameters which limit system performance. After having established the quantitative relationship between the device and the system, the key question to consider is the system impact of improved time/frequency devices. How would an improved device parameter improve the system? It is hoped that by utilizing this approach, a systematic review of current and anticipated applications may point to a limited number of device parameters wich critically influence system performance. The optimum R&D investment strategy then is a program to improve these high system impact device parameters.

One possible methodology is to consider a matrix of (a) military or commercial functions and (b) evaluate the time/frequency device selection criteria. The functions consist of: navigation, positioning, and targeting; communications for command and control; surveillance and reconnaissance; intelligence; and identification. The selection criteria include: performance--stability, spectral purity, accuracy; system limitations--size, weight, power; cost--initial and/or life cycle; and

operational requirements. The operational factors consider: environment--space, nuclear, atmosphere; "ilities--reliability, durability, maintainability, interoperability; shock, acceleration, and vibration; warm up; and, finally, ease of deployment or man/machine interfaces. This paper is an initial attempt to define the qualitative relationship between clock performance and systems, and gives information which may be useful in deciding (a) how would better performing clocks improve system performance, or (b) what tradeoffs can be made between system performance requirements, the use of a better or worse frequency standard or clock, and other system design parameters. These questions are addressed from a purely technical viewpoint. It is beyond the scope of this paper as well as the competence of the authors to analyze system's tradeoffs and possible savings in system complexity and cost.

APPLICATIONS OF TIME/FREQUENCY STANDARDS

Overview

Application areas which most closely interact with frequency standards and clocks fall into the general categories of navigation and communication. Navigation has been linked for many centuries to clocks. Modern navigation ranges from the determination of the position of stationary objects on the surface of the Earth, to position finding of ships, aircraft and spacecraft, to some aspects of very long baseline interferometry. Navigation is characterized mostly by requirements on the long term stability, i.e., time keeping ability of clocks. Communication, which typically emphasizes the short term stability or spectral purity of frequency standards, ranges from exploitation of the electromagnetic spectrum to computer data links. Nevertheless, some forms of navigation, such as Doppler ranging, require also short term stability and spectral purity and some forms of communication, such as synchronous communication channels, may benefit from good phase or time stability of clocks. In addition, in a systems approach it may be beneficial to base systems which have both navigation and communication aspects on a common high performing time/frequency source.

Before we enter a more detailed discussion of any of these areas another important fact has to be noted. This is the ever present tendency to base specifications and systems performance requirements on the characteristics of a glamourous system component, in our case, on the frequency standard or clock. At the same time, there is often a lack of analysis whether the clock or other system parameters actually limit systems performance. In other words, a better clock may instantly lead to an improved system performance if other minor system limitations are removed, and/or serious system limitations would suggest the use of an inferior clock at no sacrifice in ultimate system performance. Similarly, procedural changes in system operations may be traded against

clock performance requirements resulting in benefits in system performance, complexity, reliability and operator dependence.

Tunability

Very frequently, the system designer is confronted with a need to provide for frequency or time (phase) adjustability. In the past, more often than not it appeared easiest to the system designer to specify an adjustable frequency standard or clock. Crystal devices can be made tunable by adding a capacitor in parallel or in series to the quartz crystal resonator. Tunability is then achieved by varying the value of this capacitor mechanically or electrically (varactor). Atomic frequency standards can be adjusted by changing the magnetic field which is applied to the interogation region of the atom (so called C-field region). The atomic resonance frequency has a second order dependence on the magnetic field in cesium, rubidium and hydrogen devices. This dependence is of the order of 10^{-4}/tesla (1 tesla = 10^4 gauss),[1] and rather large frequency changes can be affected.

A second method of providing frequency tunability is to use an adjustable frequency synthesizer in the electronic loop which is employed to servo the crystal oscillator (found in all atomic standards) to the atomic resonance. Since a certain frequency is needed to interrogate the atomic resonance frequency (here we assume a constant magnetic field), this variable synthesizer allows the generation of this fixed interogating frequency from a whole range of crystal oscillator frequencies, and thus provides tunability.

In most cases, however, it is overlooked that the addition of tunability affects the basic operation of the frequency standard or clock in a detrimental way. Frequency standards derive their high stability and accuracy from the fact that the essential control element, the quartz crystal resonator or the atomic resonator, has a high resonance Q, and that their resonance frequency is highly invariant with time or external parameter changes. The addition of a tuning capacitor, in the case of crystal oscillators, or the provision for magnetic field variability in the case of atomic resonators, virtually always degrades the performance by providing a direct coupling of the resonator to varying external influences. Similar arguments can be made for the variable synthesizer in atomic standards which affects the interogating microwave spectrum, and thereby again degrades the usable properties of the atomic resonance. The importance of this problem becomes clear if we consider high performance crystal or atomic resonators providing stabilities of the order of 10^{-13}. If the system designer requires tunability over a 10^{-7} region (often even larger is requested), this implies that we add an external influence capable of affecting the fundamental resonance phenomenon by 10^{-7} or more. If this approach is implemented, and at the same time the original 10^{-13} capability is expected, it means that the system designer expects all parameters operating on the tunability to be stable

to the 10^{-6} level. For example, if one volt at the varactor of a crystal oscillator provides the range of 10^{-7}, not only does the voltage have to be stable to one microvolt, but the capacitance versus voltage curve must be stable to the 10^{-6} level, and this stability has to hold, not only under idealized conditions, but also with respect to other parameters operating on these quantities, such as temperature, vibration, etc.

It is, therefore, useful to assert that large tunability and state-of-the-art performance in frequency standards and clocks are incompatible, and to the best of the authors' knowledge have never been satisfactorily combined. In other words, we have the axiom that tunability causes deterioration of clock and oscillator performance. Instead of requiring the clock manufacturer to supply a tunable, super-precision clock, system designers should consider implementing tunability by means external to the actual clock. To this end, frequency tunability can be achieved by adding an external direct synthesizer or a second tunable oscillator with a synthesizing loop. If phase or time adjustment is desired, external phase shifting by digital or analog means should be the method of choice.

Frequency synthesis is not without troubles of its own. The large amount of signal processing within general purpose synthesizers results in elevated levels of phase instability compared to the input signal. Consequently, the use of a synthesizer as the output source may prevent the attainment of the needed level of short and long term stability. A better solution is usually to use a (crystal) oscillator which is offset from the precision clock by means of a frequency synthesizer. This arrangement potentially provides much improved spectral purity and long term stability than the direct use of a synthesizer as the output device; however, the frequency tunability is restricted in speed and range.

Warm-up and Environmental Sensitivity

From the point of view of the user, especially in military applications, some usually neglected properties of frequency standards may be the most important. These include the behavior in severe environments and the time required to achieve a specified accuracy and stability after a cold start. Such properties are usually not optimized by the design which yields the best long term stability or spectral purity.

Practical or engineering problems, including the need for ovens and vacuum pumps, limit the warm-up performance of both laboratory and commercial frequency standards. However, there is one device which was designed for fast warm-up, the passive ammonia frequency standard.[2] This device achieves its full accuracy of 10^{-9} shortly after turn-on from a cold start. Despite the unimpressive accuracy compared to com-

mercial cesium standards, the overall performance of such a device for short duration missions may be significantly better.

New schemes for temperature compensation of quartz crystals may also result in rapid achievement of 10^{-9} or better accuracy from a cold start. In addition, the application of "smart servos" may allow several oscillators to be combined in ways which improve the overall environmental insensitivity. Improvements may be made in the performance not only with regard to turn-on, but also in severe acceleration and radiation environments. Such servos would have both variable gain and time constants. This concept amounts to a systems approach to the frequency standard itself.

Synchronization

The effect of stability, accuracy and the ability to synchronize clocks on the performance of a complex system is well illustrated by the following sample problem: Find position with respect to a natural or artificial geographic grid, such as the surface of the Earth, or a network of orbiting satellites. An ideal system of this nature is global in coverage, three-dimensional, arbitrarily precise, providing instantaneous access and position fix, and able to accept users automatically and instantaneously. Another example for resynchronization requirements is a secure communications system with access and identification being provided via timing.

Of primary importance for the functioning of a time-ordered system of this nature, is time accuracy. Here accuracy is meant in the sense of time deviation of individual system clocks from system time, and user's knowledge of system time. In navigation, position information often is extracted from time information using the propagation speed of electromagnetic signals (speed of light); therefore, position accuracy of one meter requires a time accuracy of 3 ns.

In principle, system synchronism can be assured arbitrarily well via electromagnetic signals, providing time information to and between the components of the system. On the other hand, requirements of reliability, freedom from effects which deteriorate signal transmissions (natural and artificial interference, weather conditions) and autonomy of subsystems (ability to operate in case of partial system failure) would lead the designer to a system requirement of no reliance at all on electromagnetic signals. In other words, these latter requirements make ideal clocks desirable, having, once synchronized, no time deviation. Real systems, of course, fall in between those two extremes featuring finite resynchronization times. Nevertheless, the general statement can be made that a more stable clock would allow the relaxation of resynchronization requirements, and correspondingly increase reliability, autonomy and interference immunity.

For most clocks and oscillators one may write as a useful description of the time deviation [3]

$$x(t) = x_0 + y_0 t + 1/2 D t^2 + \varepsilon(t) \qquad (1)$$

The first three coefficients in this equation are model parameters: $t = 0$ signifies the instant of synchronization, x_0 is an estimate of the synchronization offset at $t=0$, y_0 is an estimate of the fractional frequency offset at $t=0$, and D is the estimate of the fractional frequency drift. The fourth term, $\varepsilon(t)$, represents the random frequency fluctuations of the oscillator which are characterized by the variance:

$$\sigma_y^2(\tau) = \left\langle \frac{(y_{i+1}-y_i)^2}{2} \right\rangle \qquad (2)$$

where y_i denotes the fractional frequency measurement of duration τ and $\langle\rangle$ denotes time average. All modern clocks and oscillators have been found to typically improve in stability with increased sampling times (region 1) until they reach their stability limit or flicker floor (region 2). For long sampling times τ, they finally deteriorate in stability (region 3). The errors in the model parameters and the frequency fluctuations all contribute to the time deviation error. Table 1 summarizes these three different regions and two model parameters and gives

Table I.

	Frequency fluctuation	Time deviation x(t)
Region 1	$\sigma_y(\tau)=k_p\tau^{-1}$	$k_p/\sqrt{3}$
	or $\sigma_y(\tau)=k_f\tau^{-1/2}$	$k_f t^{+1/2}$
Region 2	$\sigma_y(\tau)=k_F\tau^{0}$	$\sqrt{\frac{1}{\ln 2}}\, k_F \cdot t$
Region 3	$\sigma_y(\tau)=k_w\tau^{+1/2}$	$k_w \cdot t^{+3/2}$
Offset	y_o	$y_o \cdot t$
Drift	D	$\frac{1}{2}Dt^2$

quantitatively the corresponding time deviation, x(t). It should be noted that the time deviation given in each of the five rows of table I assumes that the corresponding frequency fluctuation is the sole effect for all averaging times.[4] A more complete treatment of this behavior is given in reference 5. However, table I serves as an adequate quantitative guide because for any particular range of t the dominant effect can be easily identified by comparison of the relative values from regions 1, 2, 3. In such treatment the various coefficients k also become model parameters.

We should first examine table I. If we assume that we typically deal with relatively long times between resynchronization we can ignore the aspects of region 1. Region 2 and the frequency offset have in common that time deviation is proportional to elapsed time. Therefore, figure 1 depicts the conditions of frequency offset and/or flicker of frequency. Figure 2 depicts conditions where random walk of frequency (Region 3) dominates. In figure 3 the condition of a clock with frequency drift is shown. In the three figures, the fractional frequency offset or flicker floor (fig. 1), the frequency walk coefficient (fig. 2), and the frequency drift coefficient (fig. 3) are plotted versus the time between resynchronization; the desired or required timing accuracy (position accuracy) is the parameter.

Instantaneous access is the other system parameter which is related to clock performance. An example is best used to illustrate this. If one meter navigation accuracy is the system design goal, then a 3 ns capability must be available not only from the system but also from the user clock. The minimum requirement, therefore, on both clocks is x(t)=3 ns independent of time, or $\sigma_y(\tau) = k\tau^{-1}$ with k = 3 ns. This is a requirement which most clocks will fulfill for sampling times from less than a second to many seconds. If we want to require that the user has an instantaneous position fix entering the system or has no means to acquire system time then the user must have an a priori knowledge of system time to three nanoseconds. If the user had an initial, perfect knowledge of system time, then goes on a mission, (being cut off from direct access to system time), a clock with certain performance would allow him to have a mission duration of one hour while retaining a one meter positioning accuracy, whereas a clock with better performance in regions 1 and/or 2 would extend this to, for example, many days.

Another interesting aspect in this context is the tradeoff between signal-to-noise, (antenna design, signal strength) and clock performance. If, for example, system time can be acquired by rapid scanning on a second-by-second basis, across four satellites (the GPS system) then one nanosecond timing is required only for the duration of a few seconds; thus, a relatively inferior oscillator would be sufficient. If, however, more elaborate antennas and pointing are required and an acquisition time per satellite of, for example, several hundred seconds is needed, then one nanosecond needs to be maintained over one thousand or

more seconds requiring a very good oscillator performance on the users' side, as can be seen from figures 1-3. Related arguments can be made for geodetic application of very long baseline interferometry, or for the VLBI applications in deep space tracking.

An interesting example of the relationship between long term stability and recalibration interval comes from the area of communications. In order to increase the available spectrum, operating (carrier) frequencies are being increased while the channel width is held nearly constant, resulting in tighter specification on the long term stability of both transmitter and receiver frequency references. In the case of low cost mobile transmitters, the present specifications are just met by the crystals in use. In order to accomplish the next step higher in frequency it will be necessary to either improve crystal performance, ovenize the crystal, or use a transmitter/receiver design which calibrates itself using the received signal from a more accurate base station. If the last alternative is adopted, the mobile transmitter frequency standard may exceed specification limits between uses. This situation could be corrected by requiring that after the calibration interval such a mobile radio receives a transmission from a base station before transmitting itself.

Signal Aquisition

Systems which deal with very weak signals are sensitive to the spectral purity as well as the long term stability of the system oscillators. In this portion of our paper we illustrate the effects of stability, spectral purity and signal-to-noise ratio with examples from Doppler radar and Doppler navigation.

The simplest radars are CW Doppler devices which determine the radial velocity of a target by homodyne detection of the return signal with a transmitted signal. Phase noise in the vicinity of the frequency of the carrier occurs, of course, in the same small frequency range around the carrier as the Doppler shifted return signal from the target. Therefore, the relatively weak reflections of the phase noise from nearby objects with a very large cross section cannot be distinguished from the Doppler shifted signal of interest which, though initially strong, comes back at very small intensity from the distant target having small cross section. The level of phase noise, therefore, relates to signal contrast and a decrease in phase noise will extend the range and/or the contrast of this Doppler system.

Present day navigation systems for satellites and for deep space probe tracking utilize round trip coherent measurements. The signal is transmitted to the spacecraft where it is transponded for Doppler detection on the ground. The frequency instability of the oscillator during the round trip time of the signal to the spacecraft and back is proportional to the velocity error thereby establishing a requirement on the medium

term time stability of the frequency standard. Figures 1-3 can be used to determine the quantitative requirements. This two-way Doppler tracking has the disadvantage that the spacecraft must detect the transmitted signal with a very small antenna which requires large and accurate transmitting antennas with associated expenses. If an onboard frequency standard is included into the spacecraft the size and complexity of the Earth-bound antenna can be highly reduced. The spacecraft beacon is then measured and compared by two separated ground stations, in a way analogous to very long baseline interferometry. In both cases, position and velocity accuracy depend directly on the synchronization and syntonization of the clocks at the two ground stations. If 10 cm range error and .05 rad angular error are tolerable, then subnanosecond timing must be realized at the two groundstations.

A receiver for coherent communications must reconstruct the frequency and phase of the unmodulated transmitter carrier. This is normally accomplished by phase-locking a voltage controlled oscillator (VCO) to the received signal. The speed and accuracy with which this is done depend on the stability and accuracy of the signal as transmitted, the stability and accuracy of the VCO, and the signal-to-noise ratio of the received signal.

If the frequency offset, Δf, between the transmitted signal and the VCO lies within the phase-lock loop (PLL) bandwidth, B_L, then lock is acquired within one rf cycle. However, the PLL bandwidth is limited by the requirement that within this bandwidth the weak received signal must have signal-to-noise ratio greater than one. Thus, the usual situation is one where Δf greatly exceeds B_L. For a critically damped, high gain, second order PLL, the pull-in time is approximately[6]

$$T_p = \frac{4}{B_L}\left(\frac{\Delta f}{B_L}\right)^2 \tag{3}$$

In the case, for example, of a loop with Δf = 100 Hz and B_L = 1 Hz, the pull-in time would be more than 10 hours.

The result of this situation is that acquisition is generally achieved by sweeping the VCO. The maximum rate is limited by the bandwidth of the loop. Consequently, the pull-in time is approximately

$$T_p = \frac{4}{B_L} \cdot \frac{\Delta f}{B_L} \tag{4}$$

which would be only 0.1 hours for the above example. There are, of course, other more complex PLL and PLL/frequency lock loops, some with variable sweep characteristics, which can reduce the pull-in time for large initial offsets.

Once lock is acquired, the VCO phase reflects the transmitted carrier phase to a degree determined by the transmitted carrier phase noise, the VCO noise and the noise of the receiver. The residual noise results in errors in transmitted data and limits the data rate.

Thus, improvements in the a priori knowledge (accuracy) of the VCO would correspondingly reduce the PLL acquisition time via reducing the pull-in delay and/or the needed sweep/search amplitude or time. In addition, lower phase noise of the VCO allows faster data rates and/or lowers the error incidence.

OUTLOOK

The above discussion shows that navigation and communication systems can benefit if better frequency standards and clocks become available. "Better" means not only a further increase in fundamental stability and accuracy, but, even more importantly, availability of adequate stability and accuracy at attractive cost, size, power demands, as well as environmental insensitivity. For example, many applications would become commonplace as well as economical if a user-oriented frequency standard which provides 1 ns timing capability from less than one second out to several thousand seconds, and which performs under severe environmental conditions would become available. Such a standard still does not exist. Therefore, development has to focus on both the area of subnanosecond timing out to many days in a practical, rugged, environmentally insensitive device at reasonable cost, as well as on the area of user-oriented standards. In addition, oscillators of low phase noise which are practical and environmentally stable are needed.[7]

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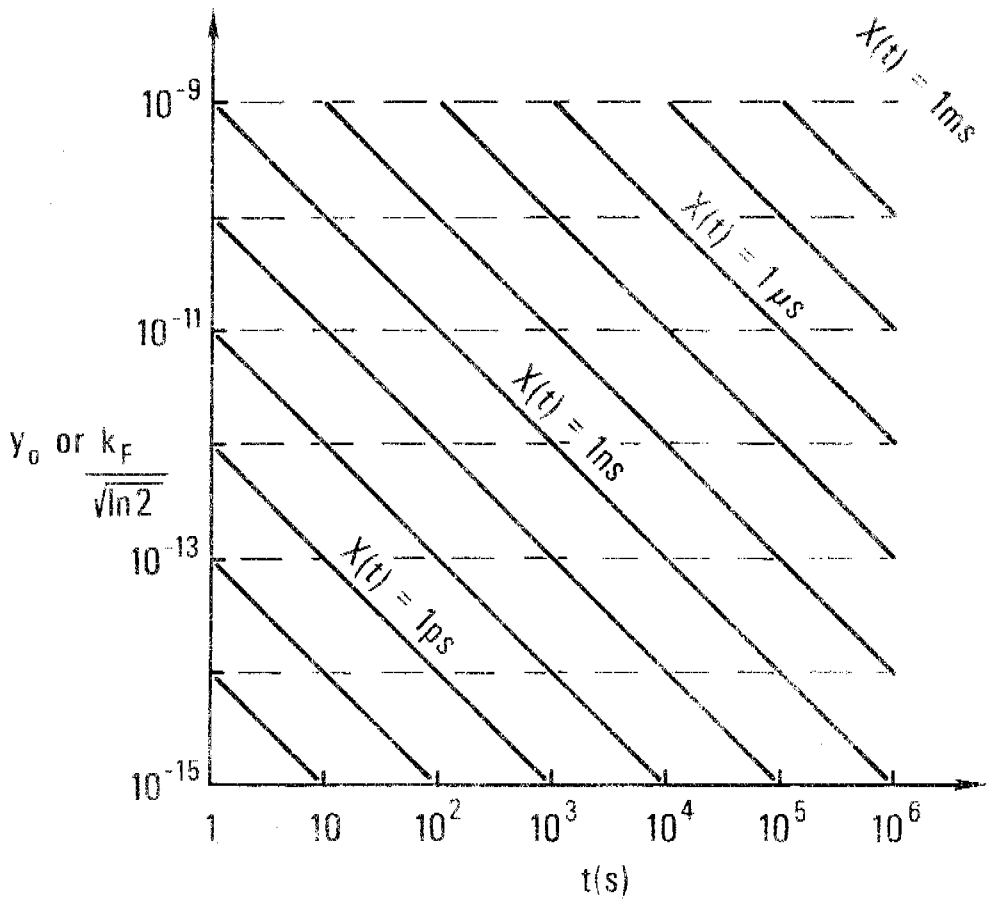

Figure 1. Largest allowable frequency offset, y_0, and flicker of frequency floor, k_F, as a function of time, t, after perfect synchronization. The achievable time accuracy, X(t), is the parameter.

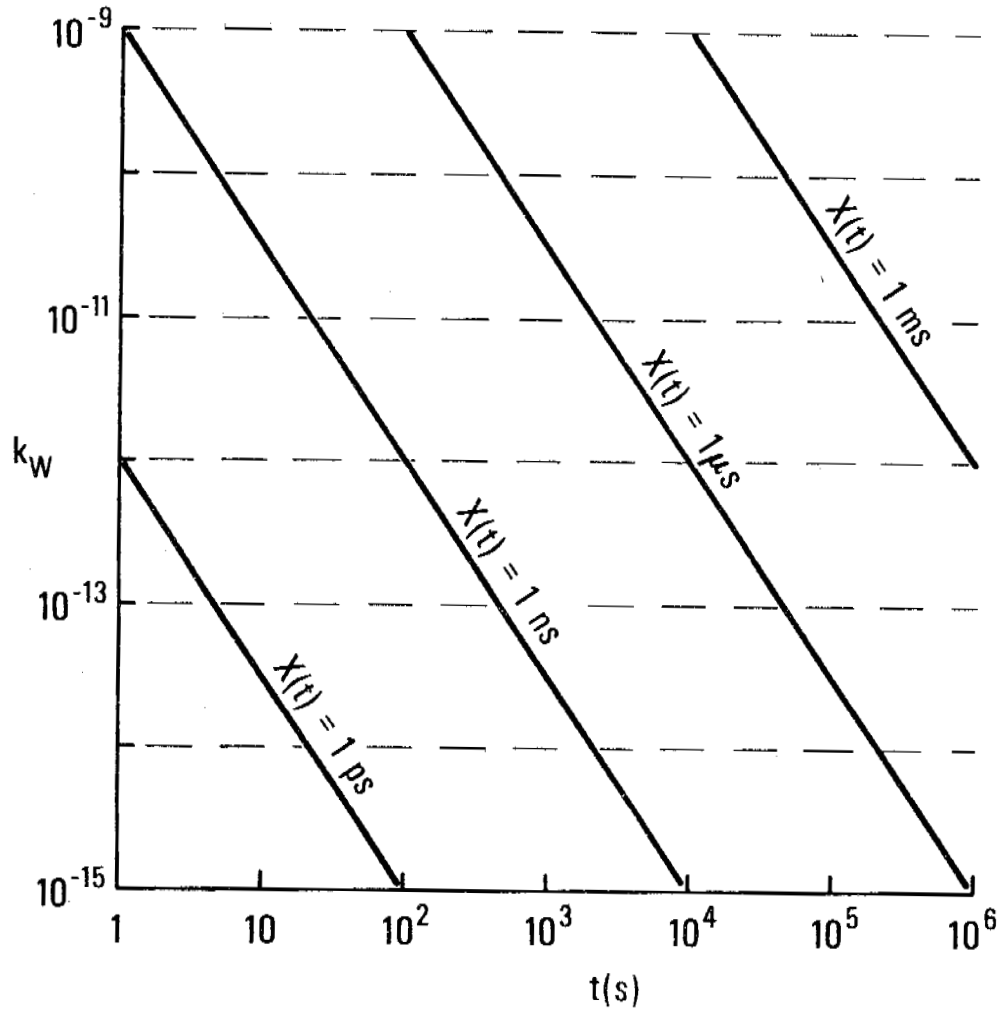

Figure 2. Largest allowable walk of frequency coefficient, k_W, as a function of time, t, after perfect synchronization. The achievable time accuracy, X(t), is the parameter.

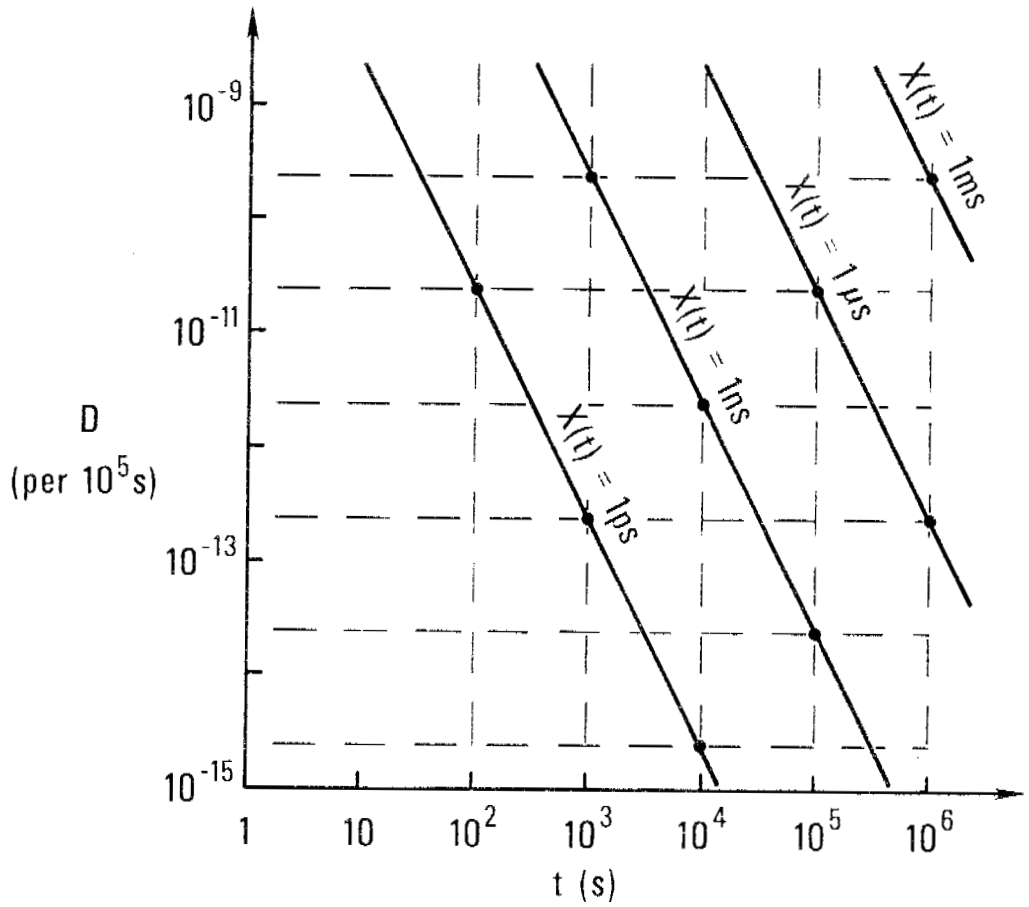

Figure 3. Largest allowable frequency drift coefficient, D, as a function of time, t, after perfect synchronization. The achievable time accuracy, X(t), is the parameter. D is used as a fractional frequency drift per 10^5 sec (approx. 1 day).

QUESTIONS AND ANSWERS

MR. HARRY PETERS, Sigma Tau:

I just wanted to comment on the tuneability equation relationship between range of tuneability and the stability of the oscillator. I think you will agree with me that there are now synthesizers which require on the order of half a watt, no phase lock loops, and give, for example, for the hydrogen maser, 10^{-16} or 10^{-17} range, digitally controlled, and where that relationship really wouldn't hold.

These are already developed and are operating in two laboratories at this time. They are very simple system-wise and, therefore, probably not a reliability problem.

DR. HELLWIG:

I totally agree with you, Harry. My answer to that is that it is sometimes difficult to draw the line between talking about the basic clock and talking about the system. In your case (in my philosophy, if you want) the line is drawn at the maser. And what you are saying, really, is what I am recommending: Put the tuneability outside of the basic clock concept. I fully agree with you.

MR. SAM WARD, Jet Propulsion Laboratory

I don't feel that enough emphasis has been put on reliability in these approaches because not even the reciprocal nature of time and frequency is effective if you can't keep the system going. And redundancy is not the answer, either, because that only complicates the problem.

DR. HELLWIG:

Do you mean reliability of the clocks themselves or reliability of the system and clocks?

MR. WARD:

Basically, the clocks themselves.

DR. HELLWIG:

I deliberately stayed away from that aspect and I think we will stay away from it in the printed paper. I think the only thing I can say

is to repeat what Dr. Winkler said already: If you plan to run operational systems, please put in clocks which have proven themselves.

DR. GERNOT M. R. WINKLER, U.S. Naval Observatory

And have redundancy. I will put in my five cents worth also, and offer a conjecture to Dr. Hellwig's very excellent observation that, unfortunately, the manufacturers have not been turned on by, let's say, the intermediate range because they know that only the best will be specified. But the situation is opposite for the OEM market for understandable reasons. Only the least you can get away with will be specified.

So I think the situation will change as the OEM market expands, and more and more of these intermediate performances will be required, for instance, in counters and other such things. These have been the major driving force for the development of very nice little crystal modules which are available today at relatively low cost.