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The Impact of Precise Time in Our Lives: A Historical and Futuristic Perspective Surrounding GPS

by

David W. Allan
Allan's TIME
UT 84632-0066

ABSTRACT

Precise timing has grown from a highly specialized discipline to where today it is integral to civilized societal needs. The list is long for the current users of precise timing, which timing impacts our lives much more than most realize. In the last two decades GPS has had a profound impact on navigation and precise timing. These trends appear to be continuing.

In all of this scientific progress, it is extremely important to learn from history so that its mistakes are not repeated. Drawing from history and projecting where timing and navigation might be over the next few decades suggests some very exciting and surprising scenarios. These projections come not just from looking at our own narrow discipline, but by drawing upon relevant Truths from other areas.

INTRODUCTION

The improvement in precise timing over the last two and a half centuries has been truly astounding -- nearly a factor of a billion. Now, the measurement of the "second" is the most accurate measurement known to man. Since I. I. Rabi conceived of an atomic clock in the early 1940s, the accuracy of this kind of clock has improved an order of magnitude about every seven years. Because of the ease with which the frequency of a clock can be both generated and used, it has become the basis of much of life's processes. Precise timing is now used in all communications systems; in most navigation systems; in computer systems and their networks; in accounting and banking systems; in traffic control systems; in much of scientific research; in fault detection and efficiency monitoring of power grids; in most military systems; in space research and exploration; in earth-quake detection and global plate tectonics; in environmental sensing; in ocean level and ocean current measurements; in air traffic control, collision avoidance and precision landing; and in truck fleet tracking and auto route mapping. More than two billion quartz resonators are made per year; and the number of atomic clocks in use is about a hundred thousand.

The "second" has been defined in terms of an atomic resonance since 1967. The most accurate clock in the world at this writing is the cesium-beam frequency standard in Boulder, Colorado, NIST-7, with an accuracy of fourteen significant digits. This is about plus-or-minus a nanosecond (a nanosecond (ns) is a billionth of a second) per day, or in laymen's terms a second in three million years.

As we look to the future, we see this trend continuing with astounding opportunities. The physics has essentially been done on a single mercury-ion frequency standard which has a potential accuracy of eighteen significant digits. Anticipating what the timing area of metrology may bring over the next fifty years is truly mind boggling. Einstein picked up a special pebble of truth on the beech of timing; the future holds buckets of golden nuggets. We will discuss some important and significant potentialities.

A FEW HISTORIC NUGGETS IN TIMING AND NAVIGATION

Galileo's hand-ground broken lens may be seen in the famous Museum of History of Science in Florence, Italy. With this lens he discovered three of Jupiter's moons. A unique instrument was developed which described the positions of these moons. This 17th century instrument, called a Giovilabio, was a sort of analogue computer providing a clock in the sky. Like a single Global Positioning System (GPS) satellite can be used to determine course position, so could the Giovilabio -- though much more course and not globally.

Galileo's work was impeded when he accidentally dropped and broke his lens, but not nearly so much as when he was imprisoned by the church because his very careful measurements had led him to believe and teach that the earth was not the center of the universe and that there were bodies in the heavens orbiting something other than the earth. This is a classic historic example where false traditions led the governing minds to err in judgement. We have learned much from scenarios such as this.

As early as 1450 astronomers had suggested longitude could be determined by the angle of the fixed stars to the moon; but the star tables were inadequate. In 1675 King Charles II had the Greenwich Observatory built, and the Greenwich meridian was established. It took 100 years to prepare the first Nautical Almanac. At this time in history, commerce to the new world was extremely important.

The critical importance of determining longitude was tragically brought to focus in 1707 when a fleet commanded by Admiral Sir Cloudsley Shovel ran into the Scilly Islands -- loosing four ships and 2,000 men including Sir Cloudsley. The British Crown responded by offering L20,000 (about $2M in today's money) for a chronometer good enough to determine longitude with an accuracy of 30 miles.

John Harrison, then 21, from Yorkshire took the challenge and spent his life building chronometers of wood and metal. He made one with gears of wood that did not vary more than a second a month during a 14 year period. A voyage using his No. 4 chronometer sailed from Plymouth to Madeira -- giving a position accuracy of about 1 mile. The Astronomer Royal doubted the result. Another voyage was embarked on when John was 70 years old -- this time to Barbados. After five months at sea his No. 4 predicted the position of Barbados to within 10 miles. It took him another 10 years of painful pursuit to collect the reward money -- which he never did receive in full. Three years later, at 83, he died -- the same year as American patriot's signed the Declaration of Independence.

Though significant progress occurred with navigation chronometers after Harrison's work, the next major step did not occur until the 1920s. This decade brought the discovery and development of the quartz-crystal oscillator. With this discovery quartz clocks were developed which could detect the instabilities in earth-spin rate, UT1. These clocks moved all areas of chronometry a major step forward -- for navigation and otherwise.

Following the ideas of Rabi, the first atomic clock was built in 1948 by Lyons at NBS in Washington D.C., and presented to the world in '49. It was only accurate to about eight significant digits (1×10^{-8}, about the same as earth-spin), and was never used much as a clock. In the early 1950s Lyons's group developed a cesium-beam frequency standard based on Ramsey's double resonant cavity idea, and obtained two orders of magnitude improvement in accuracy (about 1×10^{-10}). Unfortunately, it was never used as a clock. They were more interested in physics than in serving society -- another lesson to be learned.

Atomic time keeping was introduced to the world by Essen and Perry in June 1955 at the National Physical Laboratory in Teddington, UK. They also employed a cesium-beam frequency standard as the "pendulum" for their clock, but this time they added the "gears" to keep a continuous count of the cycles from this cesium atomic resonance. Atomic time has been kept ever since.

With all the advancements and inventions above, precise timing devices were expensive, highly specialized and were not generally available. Over the last few decades, we have witnessed a change never before seen in all the history of the world in which precise timing has become inexpensive and generally available. Precise timing now has a major impact in the civilized world. Whether we pick up a phone, climb on an airplane, (in the next years) map an optimum route in our car, we do it via precise timing techniques; and the list goes on. Much of timing R&D is now devoted toward how society may be better served, whereas, in the past, it was toward how to build a better clock. We have witnessed, in recent times, enormous advancements in timing applications -- one of the principal beneficiaries, of course, is navigation.

TIMING IN THE GLOBAL POSITIONING SYSTEM

The heart of GPS is an atomic clock. Position is calculated by accurately determining the propagation delays of timing signals from a sub-set of satellites from the GPS global constellation. The constellation is configured so that four our more satellites may be viewed from any point on earth. Since each satellite broadcasts its time and position (ephemeridies), the receiver has the information to calculate x,y,z and t for its antenna's location. Because of the very accurate and stable atomic clocks on board each of the 24 GPS space vehicles (SV) and because of the careful work performed at the five synchronized globally distributed monitor stations, the SV timing errors are about 10 ns, and the ephemeridies errors are a few meters (m). Since the velocity of light is about c = 0.3 m/ns, these errors propagate through GPS to give a GPS receiver antenna location error of a few meters.

Because of the outstanding timing accuracies used in GPS, the employment of relativity has become the first engineering reality of Einstein's theory. The system would not work without it. The relativistic effects include the "red shift" from the gravitational potential, velocity effects on the clocks with respect to an earth centered non-rotating reference frame, and the Sagnac correction to deal with the rotating earth. The earth-moon system is in free-fall around the sun, and the relativistic effects can be calculated to an accuracy of a centimeter in reference to some known fiducial coordinate point and in proximity of the earth.

The GPS altitude (26.6 Mm) is about 4.2 earth radii. At this altitude and velocity, the "red-shift" (actually a blue-shift) and the second-order-Doppler amount to a positive frequency shift in an SV clock of about 4.45×10^{-10} (38.4 microseconds (μs) per day), which, of course, is very large compared to the timing accuracies designed into GPS. The Sagnac effect is $A_p \times 2\omega/c^2 = A_p \times 1.6227$ ns/Mm^2, where A_p is a projected area on the earth's equatorial plane. This projected area is determined by viewing from the north the projection of a triangle whose three corners are determined by the location of the SV, the location of the receiver antenna and the center of the earth. The Sagnac correction is positive when the propagation direction is eastward, since the earth is spinning to the east. The cross-sectional area of the earth is about 127.8 Mm^2 (207.4 ns). In other words, if a perfect portable clock were carried slowly eastward around the equator, it would have lost 207.4 ns upon its return with respect to a perfect reference left behind.

The Department of Defense (DoD), in an effort to give some advantage to DoD and its allies, has placed a synthesizer following the SV atomic clock. This synthesizer degrades the clock's signal (denoted as dither). In addition, the SV's ephemeridies can be degraded as broadcast (denoted as epsilon) so that a receiver lacking the information on how the signal has been degraded will have a degraded position and timing solution. This is called Selective Availability (SA). The DoD receivers are designed with the keys to undo the effects of SA -- giving such a receiver full accuracy. The peak-to-peak timing deviations due to SA are several hundreds of ns. In the interim, the civil sector has learned to live with SA.

For timing purposes, there are at least six different methods of using GPS: 1) direct access; 2) common-view; 3) enhanced; 4) clock fly-over; 5) as in VLBI; and 6) using the signal's carrier phase. These are discussed elsewhere [1], and only 2), 3) and 6) will be touched on in this paper.

The GPS common-view approach is back-bone in providing data to the Bureau International des Poids et Mesures (BIPM), which in turn generates Universal Coordinate Time (UTC) for the world standard reference. In this approach two locations (A and B) are in common-view of a single SV. The receivers at these locations are preprogrammed to measure the SV signal over identical concurrent intervals -- giving time differences A-G and B-G. These are subtracted after the fact to give A-B. The effects of SA are canceled at the ns level due to dither and partially canceled due to epsilon since the GA and GB vectors are nearly parallel. The world wide accuracy of this approach has been documented at the few ns level.

The third method, using enhanced GPS (EGPS), has the advantage that it provides a real-time output. Figure 1 shows a plot of the time-domain SA spectrum as compared with other time-transfer techniques. Once the SA spectrum was determined across the GPS constellation [2], and the characteristics of the receiver clock were known, then an optimum SA filter was designed and used along with some Smart-clock technology based on a NIST patent to generate a timing signal that effectively eliminates the degradation due to SA.

A test was conducted at USNO over nearly a month's worth of data compared to a DoD keyed receiver. The root-mean-square (rms) on the residuals between the two receivers was 1.5 ns, which is essentially as if SA were not present, from a timing point of view. [3] Different levels of stability are achieved depending on the reference clock used with the receiver, whether it is quartz, rubidium, cesium or hydrogen. The reference clock for the USNO experiment was a hydrogen-maser. Whereas the SA signal may have instabilities of hundreds of nanoseconds, the EGPS approach can yield 20 ns time stabilities and long-term frequency accuracies of 1×10^{-13}, even with a quartz reference. [4]

The sixth method is one of the most promising for accurate frequency comparisons. It takes advantage of the common-view technique but also utilizes some of the geodesy techniques by tracking the SV's carrier phase. If a common SV phase can be locked onto at two sites A and B, and all of the other effects are properly dealt with, then the resulting time-difference residual stability has been documented in one experiment at the 0.03 ns level. [5]. This is also illustrated in Figure 1. Averaging over one day yields frequency comparisons with uncertainties of better than 1×10^{-15}.

APPLICATIONS USING GPS TIMING TECHNIQUES

Aside from the BIPM's generation of UTC using GPS in the common-view mode as the time transfer method, there are several other users, and the number of users is increasing rapidly.

In 1982, Backer and Kulkarny at UC Berkeley discovered a rapidly spinning neutron star, millisecond pulsar PSR 1937+21, spinning at a rate of 642 Hz. The GPS common-view technique was used to tie the data taken at the 300 m Arecibo, Puerto Rico telescope to the atomic clock at NBS in Boulder, Colorado. From the data it was thence tied to the rest of the world's best clocks. The frequency stability is shown in Figure 2 as compared with other clocks. [6] Now more than thirty of these millisecond pulsars have been discovered and are being studied at several different observatories around the world.

These measurements have produced new information about our galaxy as well as about millisecond pulsars. One of the most exciting potential discoveries that may come out of millisecond pulsar metrology is the measurement and detection of gravitational waves. Time went to atomic in 1967, but when the long-term stability of PSR 1937+21 showed comparable performance to some of the best clocks in the world, questions arose as to whether time may go back to astronomy. It is the author's candid opinion that that will never happen given the rapid improvement in atomic clock metrology.

NASA JPL's Deep Space Network (DSN) uses GPS in the common-view mode to synchronize and syntonize the three DSN sites in Australia, Spain and California. A navigation fete associated with Voyager 2's encounter with Uranus is that the location accuracy was equivalent to a golfer making a 2,000 mile putt!

The rapidity with which the enhanced GPS (EGPS), and variations thereof, are catching on in the telecommunications industry is impressive. GPS has truly become a world utility. "Plug it in" and you've got the time! Data flow, media techniques and communications efficiencies will be enhanced dramatically over the next few years because of the inexpensive, highly-accurate availability of EGPS. The power industry is also beginning to use EGPS for timing their grids and power flow economics.

LOOKING TO THE FUTURE OF GPS

The next two generations of GPS satellites, Block 2R and Block 2F, offer significant logical advantages. The othogonality provided by the cross-link ranging system has the potential to significantly improve the navigation accuracy over that now provided by Block 2A satellites. The system accuracy could reach the one meter level. How it plays out is yet to be seen. This will depend on the quality of the clocks deployed and on how the system is managed.

Since rubidium will be the principal clock in Block 2R, the propagation of timing errors due to the uncertainty in the estimation of frequency drift becomes a concern. If, for example, a rubidium clock were drifting 5×10^{-14} per day, and that could be estimated to within 10%, this uncertainty would propagate in 180 days to a timing error equivalent to 1 km. This is because the time dispersion goes as $\frac{1}{2} \delta t^2$. where δ is the uncertainty in the drift estimate. This timing error also has built into it the optimistic assumption that these errors will be random and uncorrelated across the 24 SVs; hence, a single clock's error was divided by $\sqrt{24}$ to get the above timing error.

How this effects the navigation error is different, because additional information is available as part of the cross-link measurement set up. Properly modeling how these errors effect the navigation solution is very important in the Block 2R simulations. Otherwise, when the next generation of SVs are launched, there may be some surprises. From a time dispersion point of view alone, the cesium clock would be a much better choice as the principal clock since the frequency drift is negligible in a well designed cesium-beam frequency standard. For autonomous operating periods of the order of months as is anticipated for Block 2R and Block 2F, the timing errors in a cesium clock would be orders of magnitude smaller than for rubidium.

THE FUTURE: BEYOND RELATIVITY AND TIME -- A PERSPECTIVE AND CONCLUSIONS

In what follows, I am building a philosophical basis for some very important points to be made at the end of this section and as a conclusion to the paper. In developing this basis, the points made are consistent with the scientific method. These points taken in context with the rest of the paper allow some important conclusions to be drawn.

As a scientist, I have chosen not to be restricted to the five senses. Using the scientific method, I have pragmatically learned over my scientific career that there is a sixth sense. The ultimate quest is for "Truth" with a capital T -- those absolutes we can always count on. Where do we obtain such Truth?

Up until the last three centuries, the religionist (loosely defined) played a paramount role in being the source and disseminator of "truth." Some of the darkest oppressions of scientific endeavor were a result of religious subjectivity and suppression during this period. Some argue (such as Bertrand Russell, for example) against religion, as the atrocities performed in the name of religion have been perpetrated. The Dark Age era prospered little in terms of scientific advancement. The learned of this period, such as Tertullian, Jerome, and Augustine used rhetoric and cleverness to convince the mind of man. Appropriate is the quatrain of Omar Khayyam:

Myself when young did eagerly frequent
Doctor and Saint and heard great argument
About it and about: but evermore
Came out by the same door where in I went.

To conclude from the above that all religion is bad would be a serious error of generalizing from the specific.

Though everyone is grateful that Galileo, Bacon, etc. developed the scientific method and broke the shackles of subjectivism, we need to ask the question, "Has the pendulum swung too far?" As spin-off in this modern era, we find ourselves worshipping objectivism, relativism, the mind of man and mother earth. Have we slid into the situation where we believe God, absolutes (including intrinsic values), and the sixth sense (our conscience and spiritual sensitivities) are not important to guide our lives? The break-down of our social fabric is the most obvious manifestation of this course.

In this connection a very fascinating and remarkable stipulation is imposed upon mathematics by the famous theorem of Kurt Godel. The "...formal systems with which Godel worked are sufficiently rich in syntax for the derivation of all of classical mathematics (and presumably of much of mathematics yet to be developed)". [7] In brief, Godel's theorem proves that for a system to be consistent it must contain "undecidable" propositions; i.e. the scientist has to have faith -- even the atheist! Faith in what? Most would say, "That which works well and brings about good among our fellowmen." Einstein said, "...the deeper that I delve into the sciences of the universe, the more firmly do I believe that one God, or force, or influence, has organized it for our discovery." [8]

In my opinion, one of the most devastating impositions on our education system is that we teach one another that we are evolved animals -- restricted in our appreciation of life to the five senses. I prefer the Genesis approach: that we are created in the image of Him who created all things. This places within us an enormous potential for good. In contrast, often our worst enemy is the constraints we place on ourselves -- lacking faith in who we really are and what we can accomplish as we seek the mind of the divine with our sixth sense. Many scientists practice the divine art of discovery and creation without acknowledging a divine hand in their serendipity which blesses their efforts. When appreciation is expressed to Divine Providence by the lives we live, this brings an additional richness to life -- even bringing out more of the divine in the recipient.

Goethe profoundly stated:

> Until one is committed, there is hesitancy, the chance to draw back, always ineffectiveness. Concerning all acts of initiative (and creation), there is one elementary truth, the ignorance of which kills countless ideas and splendid plans: that the moment one definitely commits oneself, then providence moves too.
>
> All sorts of things occur to help one that would never otherwise have occurred. A whole stream of events issues from the decision, raising in one's favor all manner of unforeseen incidents and meetings and material assistance, which no man could have dreamed would have come his way.
>
> Whatever you do, or dream you can, begin it. Boldness has genius, power and magic in it.
>
> Begin it now.

Einstein gave us the four dimensions of relativity. In 1961, Gustaf Stromberg proposed a fifth dimension based on some experiential information. He suggests that this fifth dimension, called the "eternity domain" gives to time elasticity while maintaining sequence. He further explains that this eternity domain can

> ...be described as an *Almighty, Wise and Living Person, the Creator* of all things, physical, mental, and spiritual. In our mind we have an "image" of this Person, and an idea of His existence and nature. We are created in His image,... We can also understand that this Person in His wisdom may select one or more souls to carry important messages and admonitions to other human souls,... Some of these messages we can also hear directly when we listen to the voice of the "Cosmic Conscience." They tell us unequivocally that the essence of Divine law can be expressed in the simple admonition: "Love ye one another!" [8]

In 1975, Dr. Raymond Moody added significantly to the data base that Stromberg was alluding to with numerous case histories carefully documented in his classic book, "Life after Life." These several experiences augment this fifth dimension, eternity domain thesis. One of the most moving of these experiences has been recorded in a separate book, "Return from Tomorrow" -- the story of Dr. George Ritchie.

In thinking about what life will be like for timing and navigation fifty years from now, I find the preceding information very relevant. This information would lead me to believe that there is a whole set of physics that we do not now understand, but which is quickly coming to be understood and proven and which could well describe these documented experiences in the eternity domain. In the next 50 years, we may no longer be constrained by gravity or the speed of light. Communication may be by spiritual thought waves, and the current navigation systems of which we can conceive, using the five restrictive senses, may become totally archaic.

The anticipated ideal society of that era will be based on unselfish service with no poor nor rich and with pure love as the prime mover and guiding principle. If we are to learn an extremely important lesson from history, it is that a purging process is necessary to waft society toward goodness and purity. We may yet see the worst world war and other incomprehensible tribulations before our world society is purged sufficiently. Societal purity can be measured by the thoughts we think and the things we do. We can look to God and live the full and abundant life, or we can serve selfish ends and have measured to us what we have measured to our fellowmen.

In his 1994 book, "The Physics of Immortality," Professor Frank J. Tippler says, "It is time scientists reconsider the God hypothesis... The time has come to absorb theology into physics, to make Heaven as real as an electron."

As I look at the past and anticipate the future, with great expectation, I wonder if in contrast to the past that one of our current worst inhibitors are the limiting traditions that the five senses of science have placed upon us. Whereas oppressive religion appeared to be the main impedance during the dark ages, I believe enlightened religion and understanding the "eternity domain" will be our ultimate answer to the world's ills and will be a key factor into achieving the ideal society we seek. We need to open our hearts and minds to Truth with a capital T -- turn to God and live.

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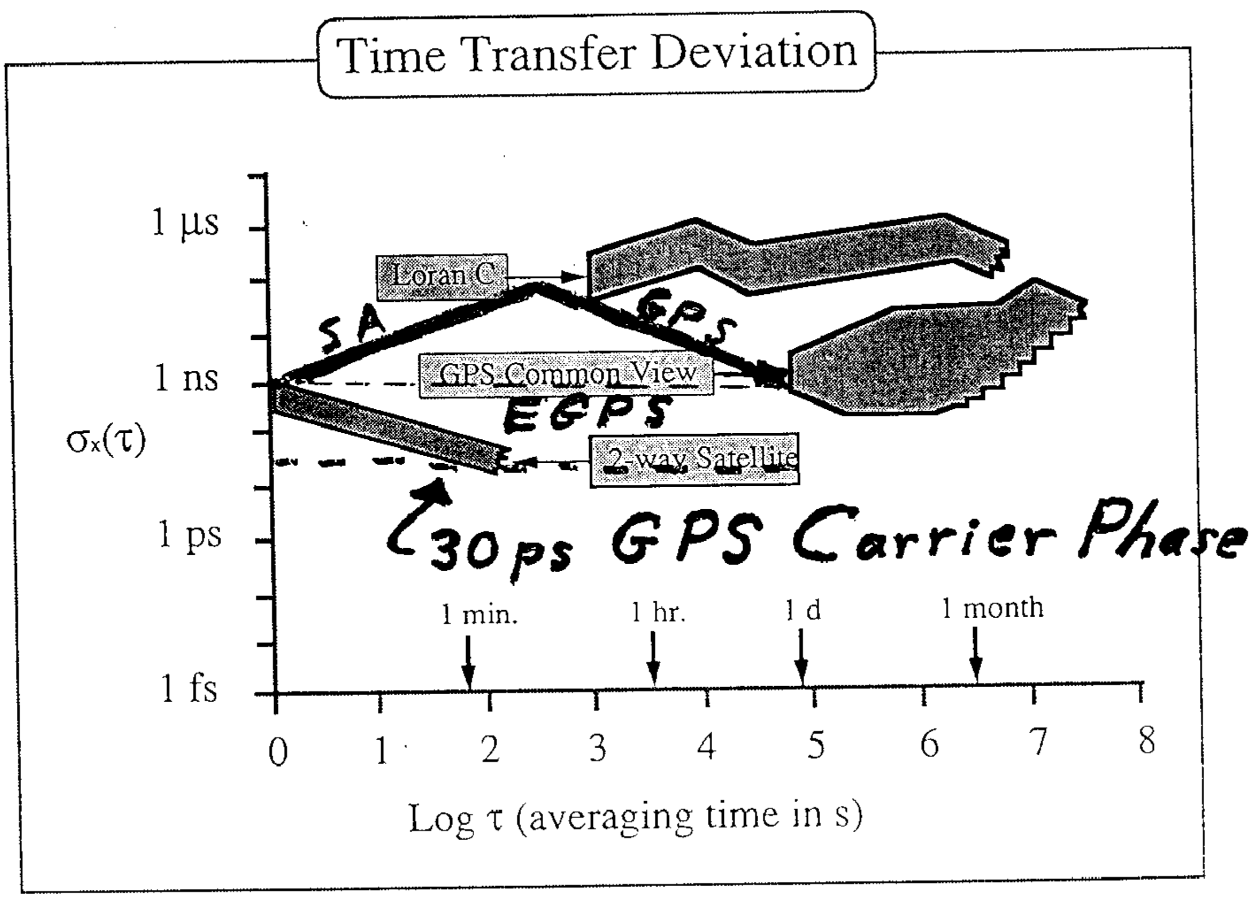
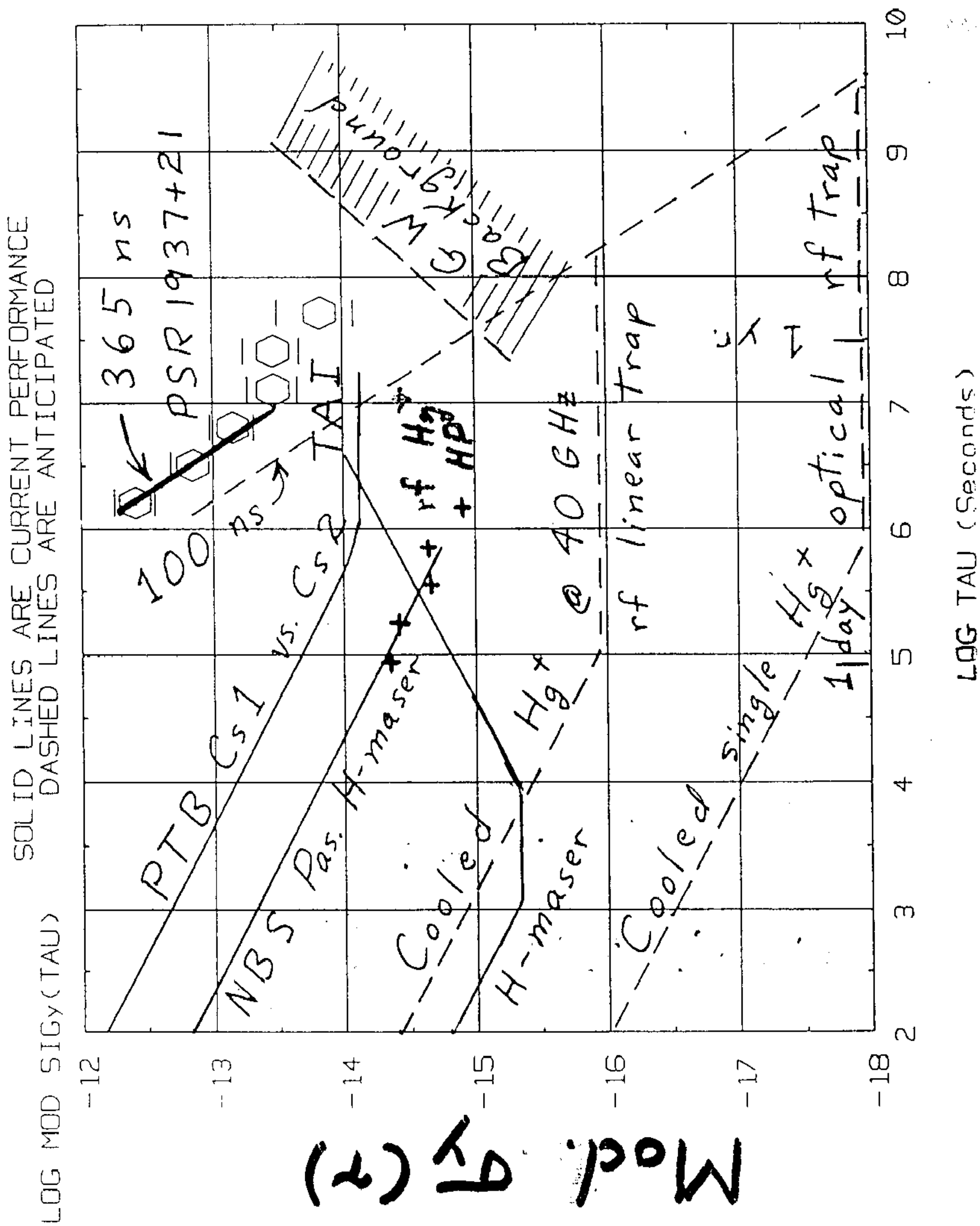


Figure 1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DASHED LINES ARE ANTICIPATED
LOG MOD SIGy(TAU)
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PTB Cs1 vs. Cs2
NBS Pas. H-maser
Cooled H-maser
Cooled Hg+
Cooled single Hg+
365 ns
PSR 1937+21
100 ns
TAI
rf Hg+
@ 40 GHz
rf linear trap
optical
rf Trap
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Figure 2