National and International Time and Frequency Comparisons

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Abstract

The advent of satellite time and frequency comparison techniques has provided the opportunity for measuring the time and frequency difference between remote clocks with greatly improved accuracies. The paper will give a brief review of various remote clock comparison techniques; in particular the Global Positioning System (GPS) will be highlighted.

The advent of GPS provides the opportunity for the first time for cost effective, high accuracy, operational (automatic), international time and frequency comparisons. It has been demonstrated that where the ephemerides of the satellites are known to within several meters, this translates to an error of only a few nanoseconds in measuring the time difference between remote clocks on the surface of the earth as long as the remote clocks receive the GPS time signal simultaneously. The time difference between the two remote clocks is obtained simply by subtracting the two readings taken at each site resulting from the common-view measurement minus a differential delay constant, which can either be calculated or measured at the outset. Other common-mode errors either cancel or are reduced using this simultaneous viewing approach; e.g., the GPS clock error, the ionosphere, etc. Because of the high inclination to the ecliptic of the GPS satellite orbits, simultaneous common-view is possible between essentially all principal sites in the Northern hemisphere, and principal sites in the Southern hemisphere have common-view with key timing centers in the North.

Some of the other techniques which will be reviewed and discussed will be the "two-way" satellite technique, LASSO, STIFT, the meteorological satellite system including GOES, and some other relevant techniques. The current status of these techniques will be discussed along with their functionality and essential characteristics. Some projections as to what the future holds will also be discussed.

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With the advent of atomic clocks we have seen a rapid improvement in the accuracy capabilities within the time and frequency community. Figure 1 is a plot of the accuracy of the primary standards at the National Bureau of Standards indicated by the circles. We are currently using NBS-6 with an accuracy of 8 x 10 ^{14}. We anticipate with optical state selection in cesium to obtain accuracies of a part in 10^{14}. The physics is essentially completed for a standard featuring laser cooling of mercury ions stored in an electromagnetic ion trap, which hopes to yield, within this decade, an accuracy of a part in 10^{15}. The sloping line drawn to fit the circles indicates one decade improvement every seven years.

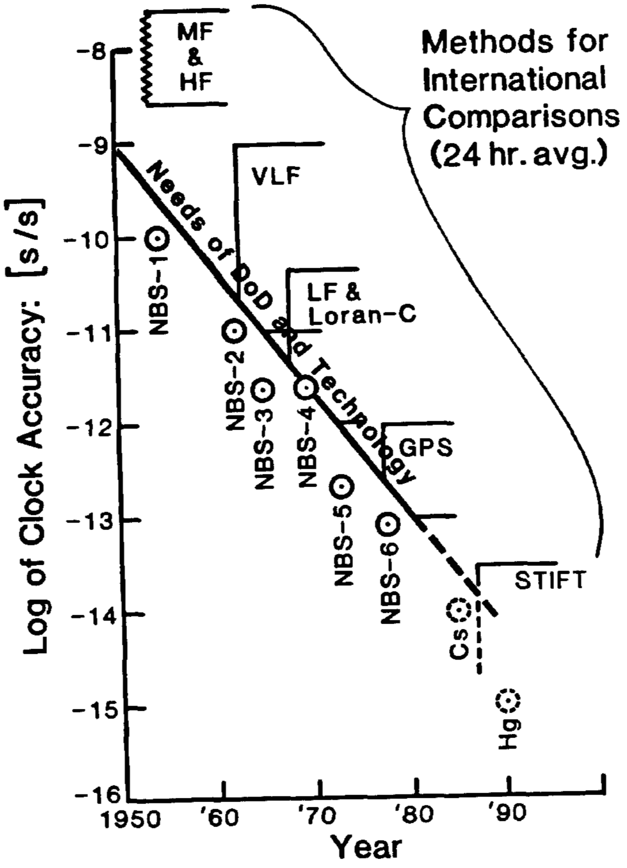


Figure 1. A plot of the accuracies of NBS primary frequency standards compared with some methods of comparing frequencies nationally and internationally.

Comparing standards between one laboratory and another at these accuracy levels is a significant metrology challenge. The comparison methods have usually been much less accurate than the primary standards and less stable than their associated time scales. It has only been of recent time with the advent of satellite techniques that one is able to compare with accuracies that are comparable to, and even better than, the current accuracies of primary standards.

Since 1969 the international method of comparing time has been the Loran-C system. Loran-C has the problem that it is not stable enough to compare state-of-the-art clocks until time averages of a couple of months are taken, and also an annual term gives an additional instability in this technique. Figure 2 shows a bar graph comparison of some satellite techniques that have been studied -- compared with Loran-C. The Shuttle, TDRSS, and LASSO experiments have no near term experimental realization and though hardware has been built, there are some uncertainties as to whether they will be conducted.[1,2,3,4,5] The first row in

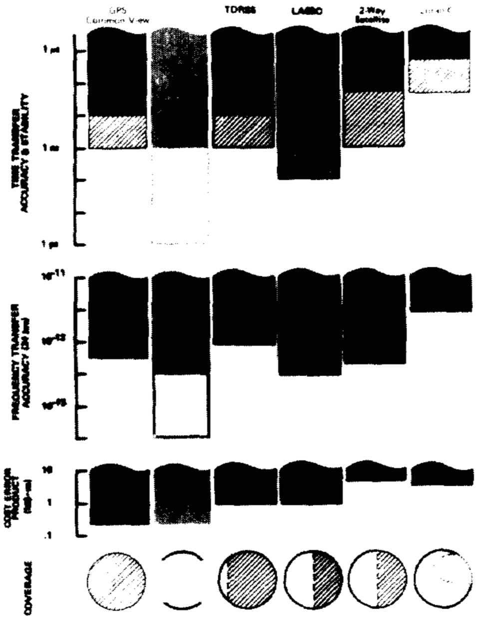


Figure 2. Time and Frequency Transfer Accuracy Comparison of some satellite techniques and Loran-C. The bottom of the bar indicates the accuracy or the stability as explained in the text.

this bar chart illustrates the time transfer accuracy and stability of these various techniques. The bottom of the dashed or shaded part of the curve is the time stability; the bottom of the solid part of the bar is the time transfer accuracy; i.e., the ability to measure the absolute time difference between two remote points. The second row is the frequency transfer accuracy averaged over a 24-hour period. There is a special case for the shuttle experiment (STIFT) which may allow frequency comparisons of a part in 10^{16} accuracy. This will be explained later. The third row is a cost-error product in megadollar-nanoseconds. The bottom of the bar is the economic-accuracy estimate. A lower number means less cost for more accuracy. The bottom row indicates the degree of global coverage.

Using two-way satellite technique [5] in a comparison between Boulder, Colorado, Ottawa, Canada, Washington, DC and Brittany (500 km from Paris, France) time stabilities of a few tenths of a nanosecond were realized and in a two-way double hop experiment between Brittany in Europe and Boulder via NRC in Ottawa a time stability of 6 nanoseconds was realized. The accuracy of this system, interestingly, is not limited by the reciprocity assumption for the nearly 80,000 km up and down signal path which is used, but by the non-reciprocity of the transmitter and receiver delays. The accuracy in the past, due to this problem, has been of the order of 50 nanoseconds.[6] With some recent work [7] the error due to this problem has been pushed down to the order of six nanoseconds.

The shuttle experiment called STIFT (shuttle time and frequency transfer) features three things [2]; first a laser for ranging to the shuttle from the ground with an accuracy of a few centimeters. Second is featured a three frequency microwave technique which accomplishes a Doppler cancellation and a cancellation of the ionospheric delay. Third, the Shuttle will carry an active hydrogen maser clock with frequency stabilities of the order of one part in 10^{14} and better for sample times

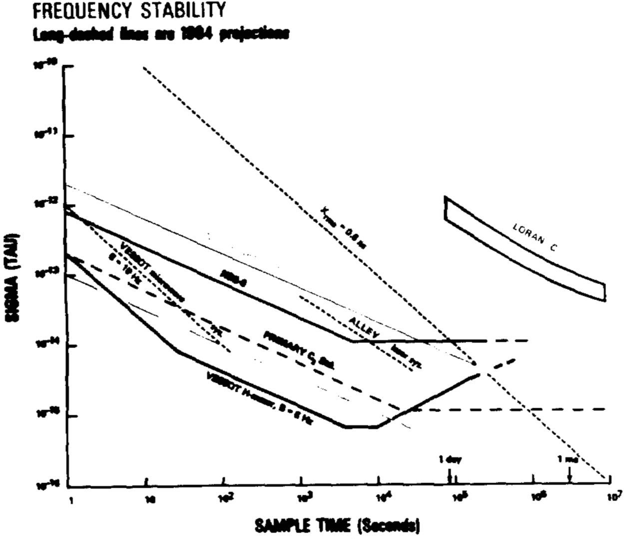


Figure 3. Frequency Stability of 3-frequency microwave (Vessot) Doppler cancellation system compared with other systems. It is denoted by the 1/τ dashed line marked "VESSOT microwave system" and "B = 10 Hz".

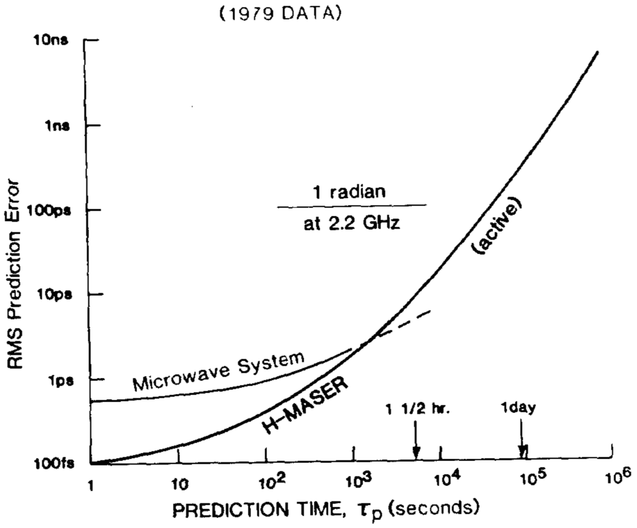


Figure 4. RMS time deviation error as a function of prediction interval for 3-frequency microwave Doppler cancellation system and for a hydrogen maser compared to 1 radian at 2.2 GHz.

convenient to the tracking and orbit times. In Figure 3 the stability of the microwave system is shown which translates to about one picosecond phase stability in the short term (during a single track) and about 10 ps over an orbit period. Figure 4 shows a rms time error analysis of the system. This figure shows that it may be possible to remove the cycle ambiguity of the 2.2 GHz carrier. In which case if this could be maintained over one day, this would translate to about one part in 10^{16} frequency transfer accuracy.

The GPS will feature an 18 satellite constellation. There are nominally four different techniques for using the GPS system as shown in Figure 5. One can also use a combination of the common-view and the viewing of several satellites and reduce the system measurement noise even more than using common-view alone. With this combination approach, a few parts in 10^{14} have been achieved for sample times of one day. Figure 6 gives some estimates, using the common-view technique, of the rms errors in comparing time between two remote sites, A and B, assuming a 25 nanosecond ephemeris error. The satellite is at an altitude of 4.2 earth radii. The common-view technique yields a large amount of common-mode error cancellation.[8] This technique has been studied between the Naval Observatory and NBS in Boulder, CO. Nine portable clock trips over the course of about one year agreed with the GPS in common-view to within an rms error of ten nanoseconds. Because of the high latitudes of most timing centers and because of the 63° inclination of the GPS satellite orbits, very good common-view is available between most sites as can be seen in Figure 6. The analysis illustrated in Figure 6 does not consider other important error sources, such as the ionosphere, troposphere and multipath distortion. Though the ionospheric model has been studied in a lot of detail over the years, the model elements used in the GPS are only about 50% accurate. Fortunately, in the common-view technique, some significant common-mode ionospheric error cancellation can be achieved -- to the order of a few nanoseconds. During nighttime viewing, the total delay for the nighttime sky at ±40° latitude is of the order of 5 nanoseconds so even for fairly large hour angles the differential delay may be stable to about a nanosecond. The tropospheric delay for high viewing angles is only a few nanoseconds at the GPS frequencies and can be estimated to the order of a nanosecond if desired. The errors due to multipath distortion can amount to a few nanoseconds, but can nicely be dealt with from a stability point of view by making the common-view measurement once per sidereal day i.e., the viewing geometry for the two sites to the satellite stay the same. Receivers are now being made by several different organizations. We have built some prototype units at the NBS. One can quite economically build a receiver with a long-term stability of about 1 ns with an antenna about the size of a man's thumb. Depending on the noise figure and configuration of the receiver's front end short-term stabilities may vary from 1 ns to nearly 30 ns. Their instabilities are typically characterized as a white noise phase modulation process hence the values are ameanable to averaging, and the confidence on the mean will improve as the square root of the number of values. The NBS prototype units are configured with a very powerful and friendly software system using a Z-80 microprocessor and a built-in 0.1 ns resolution time interval counter. All that is needed from the local site clock are 5 MHz and 1 pps signals. The receiver is RS-232 compatible and coupled to a modem and can automatically be dialed by a computer -- making computer

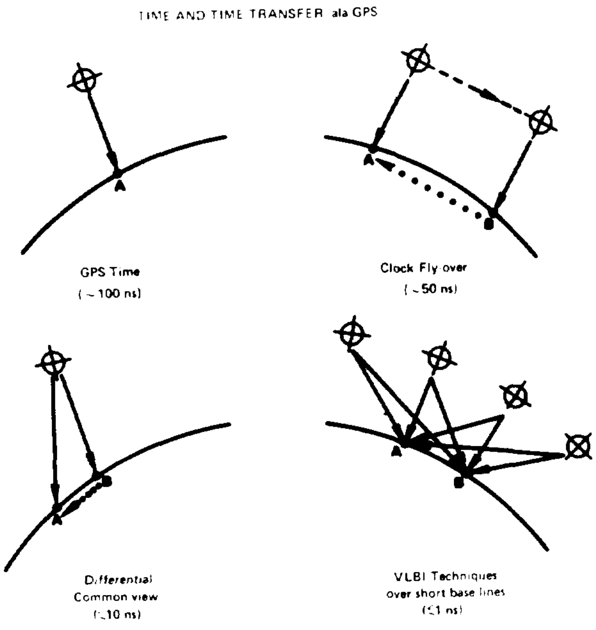
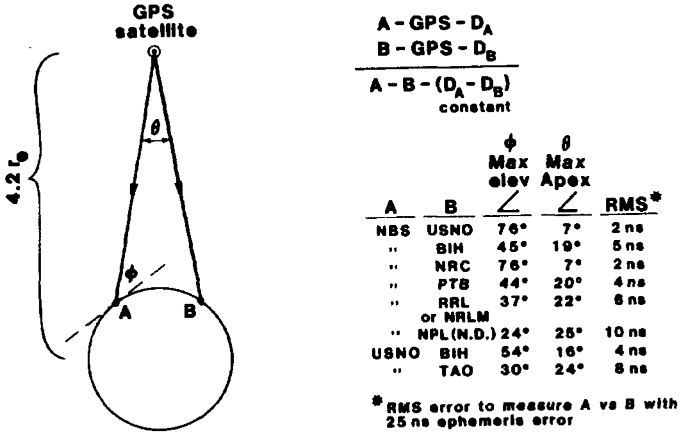


Figure 5. Four different methods of doing time transfer using GPS.



A	B	φ Max elev ∠	θ Max Apex ∠	RMS*
NBS	USNO	76°	7°	2 ns
"	BIH	45°	19°	5 ns
"	NRC	76°	7°	2 ns
"	PTB	44°	20°	4 ns
"	RRL or NRLM	37°	22°	6 ns
"	NPL(N.D.)	24°	25°	10 ns
USNO	BIH	54°	16°	4 ns
"	TAO	30°	24°	8 ns

*RMS error to measure A vs B with 25 ns ephemeris error

Figure 6. RMS error estimates to do time transfer between two sites A and B with an RMS GPS satellite ephemeris error of 25 ns -- showing the advantage of using GPS in common-view. The locations are: NBS (Boulder, CO); USNO(Washington, DC); BIH(Paris, France); PTB(Braunschweig, W. Germany); RRL, TAO, and NRLM are near Tokyo, Japan; and NPL(New Delhi, India).

analysis very straight forward. Internationally, the Mark III computer system is being used for comparing GPS common-view data.

The frequency stability measured between the U.S. Naval Observatory clock ensemble and the NBS clock ensemble is shown in Figure 7. The stability of the difference between these two ensembles was measured at the one or two in 10^{14} level at sample times of the order of a week and longer. An assessment was made of the GPS in common-view measurement limit and it appears to be about 1 part in 10^{13} at one day and going down on a Mod. $\sigma_y(\tau)$ plot as white noise phase modulation ($\tau^{-3/2}$). In fact we have a data point at 3.5×10^{15} at $\tau = 10$ days. This stability value was verified over several months of data. The NBS receiver stability at $\tau = 1$ day is 8 parts in 10^{15} -- making the receiver noise negligible for almost all clocks for $\tau > 1$ day.

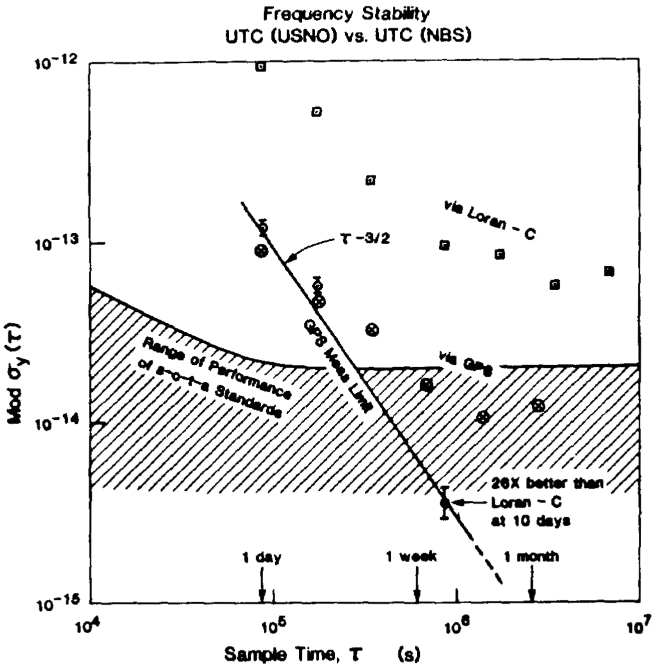


Figure 7. Frequency stability comparisons using Mod. $\sigma_y(\tau)$. The $\tau^{-3/2}$ line corresponds to white noise PM. The s-o-t-a are state-of-the-art frequency standards.

Consider now a combination of common-view comparisons employing three or more satellites. If the three satellites, denoted i, j, and k, are available to make independent common-view measurements between sites A and B, and the measurements are made within a few hours of each other so that the random time deviations between the clocks at A and B are small, then a variance analysis can be performed on the sidereal daily common-view values as follows: Let

$$\sigma^2_{AB'} = \sigma^2_A + \sigma^2_{sv_i} + \sigma^2_{B'} \qquad (1)$$

where $\sigma^2_{AB'}$ denotes the measurement variance from the common-view data time series, which is composed of the variance of each of the site clocks plus the variance of measurement fluctuations resulting from using GPS space vehicle in common-view. Also, assume on the basis of the satellites being independent that

$$\sigma^2_{sv_{ij}} = \sigma^2_{sv_i} + \sigma^2_{sv_j}, \qquad (2)$$

which can be measured by taking a variance of the difference between the i and j measurements, since the measurements are taken at nominally the same time. Performing this same analysis on the difference between the i and k and the j and k measurements allows the computation,

$$\sigma^2_{sv_i} = \tfrac{1}{2}[\sigma^2_{sv_{ij}} + \sigma^2_{sv_{ik}} - \sigma^2_{sv_{jk}}], \qquad (3)$$

which can be subtracted from equation (1) yielding an estimate of $\sigma^2_A + \sigma^2_B$ with the measurement contribution being only a few parts in 10^{14} at $\tau = 1$ day, and improving as $1/\tau$.

In the Hafele-Keating[9] experiment, performed some years ago with some clocks from the Naval Observatory, the clocks were flown in both directions around the globe and verified the Sagnac effect, since a disparity of about 200 nanoseconds was observed. One can do that same experiment now using either GPS or other satellite techniques using the photon as the portable clock. The size of the effect is proportional to a projected area on the equatorial plane -- the area being that made by the circumnavigating photons. The coefficient of proportionality is 1.6 ns/Mm². For GPS signals going around the globe the Sagnac effect will be about 200 to 300 nanoseconds depending on the particular geometry. We plan to do this experiment this summer and fall, as soon as we have around-the- globe capability. Tables 1 and 2 show the characteristics of major time and frequency dissemination systems. Table 1 shows the operational type of systems (VLF, LF and high frequency stations, etc). Table 2 shows estimates of the state-of-the-art satellite techniques giving the time stability and frequency stability and accuracy of each of these techniques. Figure 8 is the $\sigma_y(\tau)$ plot showing the fractional frequency stability of these various operational and state-of-the-art satellite techniques as a function of sample time. Clearly, satellite techniques for time and frequency metrology on a national and international basis have been and will be extremely important in keeping up with state-of-the-art time and frequency standards now and in the future.

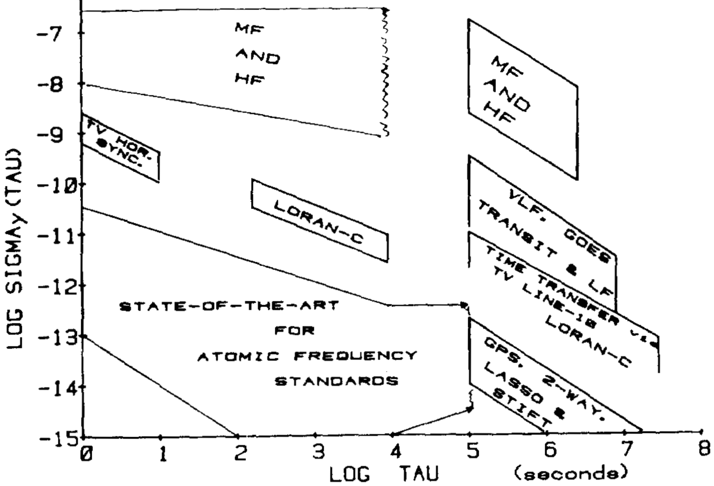


Figure 8. Frequency stability of different remote comparison techniques. The MF and HF notations are e.g., WWV, CHU, JJY; the LF stations are e.g., WWVB, MSF, DCF77.

TABLE 1. CHARACTERISTICS OF THE MAJOR T&F DISSEMINATION SYSTEMS

DISSEMINATION TECHNIQUES		24 HOUR SYNTONIZATION ACCURACY	SYNCHRONIZATION ACCURACY	AMBIGUITY	COVERAGE FOR STATED ACCURACY
VLF RADIO	GBR, NBA, OMEGA, ETC.	1 x 10-11	ENVELOPE 1 - 10 ms	1 CYCLE	NEARLY GLOBAL
LF RADIO	STANDARD FREQUENCY BROADCAST (e.g., WWVB)	1×10^{-11} PHASE 24h	ENVELOPE 1 - 10 ms	YEAR	USA - LIMITED (WWVB)
	LORAN-C	5×10^{-12}	1 μs (GND) 50 μs (SKY)	TOC 15 MIN PHASE 10 μs	SPECIAL AREAS
HF/MF RADIO	STANDARD FREQUENCY BROADCAST (e.g., WWV)	1×10^{-7}	1000 μs	CODE - YEAR VOICE - 1 DAY TICK - 1 s	HEMISPHERE
TELEVISION (VHF/SHF RADIO)	PASSIVE LINE-10	1×10^{-11}	1 μs (line of sight)	33 ms	NETWORK COVERAGE (Useful only in local areas in USA)
SATELLITE (UHF RADIO)	GOES	3×10^{-10}	50μs	1 YEAR	WESTERN HEMISPHERE
	TRANSIT	3×10^{-10}	30 μs	15 MINS	GLOBAL
PORTABLE CLOCKS	PHYSICAL TRANSFER	1×10^{-13}	10 ns to 100 ns	N/A	LIMITED BY TRANSPORTATION

TABLE 2. INTERNATIONAL TIME AND FREQUENCY COMPARISON (<< 1 μs)

	T/F Transfer Technique	Synchronization Accuracy	Time Stability	24 Hour Syntonization Accuracy	Coverage
(1)	[†]GPS (Common-view)	10 ns	a few ns	$\lesssim 10^{-13}$	Global
(2)	Shuttle (STIFT)	1 ns	0.001 ns	$\lesssim 10^{-14}$	To ± 57° Latitude
(3)	GOES (Trilateration)	10	a few ns	$< 10^{-13}$	All but near the poles
(4)	LASSO	1 ns	0.1 ns	$\sim 10^{-14}$	Depends on Implementation
(5)	[†]GPS	40 ns[*]	10 ns	$\sim 3 \times 10^{-13}$	Global
(6)	[†]2-Way (Communication Satellite)	<10 ns	$\lesssim$ 1 ns	$\sim 10^{-14}$	All but near the poles
(7)	[†]Portable Clock	10 ns to 100 ns	N/A	$\lesssim 10^{-12}$	Global (Best accuracy within reasonable driving vicinity of Air Ports)
(8)	[†]Loran-C	500 ns	$\lesssim$ 40 ns	$\lesssim 10^{-12}$	Excludes most of Asia and Southern Hemisphere

[*] This inaccuracy may increase if the GPS C/A code is deteriorated for strategic reasons.

[†] These techniques have been demonstrated.

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