ON THE PROBLEMS OF SYSTEM TIME GENERATION FOR A FUTURE GNSS2

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Abstract

For any satellite navigation system clock synchronization to a system common time is a requirement of utmost importance. There are some features, being of particular interest, which are studied here. For clock comparisons one- and two-way methods can be applied. In the present conventional systems GPS & GLONASS systems, only the first method is actively in use. Improvements in several areas are expected in scenarios applying two-way and inter-satellite-links (ISL).

For generation of the system time scale (STS) with one or some chosen types of clocks the ensemble solution is the most stable and reliable. There are several and sometimes different constraints for the realization of a STS for navigation or timing users.

In this paper we discuss the impact of clock comparison measures and of STS generation peculiarities on the development of a 2^{nd} generation Global Navigation Satellite System (GNSS2). We give simulation results of a STS and induced navigation/timing user clock error in a possible GNSS2 scenario, defined by (Case 1) 15 Inclined Geosynchronous Satellites (IGSO) equipped with a RAFS (space Rb) each + 3 Geostationary Satellites (GEO) equipped with an H-Maser, and 4 ground stations operating with a Cs-frequency standard, where both inter-satellite and two-way links are adopted. It will be shown that for the navigation user the error contribution due to the clocks can reach a value of about 0.7 ns (1σ), with an update interval of 30 min in this particular scenario. Satellite constellations equipped with H-Maser give better results. For time dissemination purposes, the UTC steering policy will be addressed and an error

reaching 27 ns (1σ) is expected in the above scenario. Finally we also investigated a constellation using Ultra Stable Quartz Oscillators on-board the satellites (Case 2). We show that such a configuration could also satisfy the needs of navigation/timing users.

INTRODUCTION

For the designer of a new civil navigation system, i.e. GNSS2 the time keeping in such a complex system plays a major role. Much experience in this field was gained by the GPS developers over the past years. Only if the mutual clock synchronization between the satellite clocks is realized within a high level of precision can the navigation user solve for its own antenna position. This would enable also time dissemination to the scientific timing community or other commercial services. But to use such a feature to a high extent, some efforts have to be made to ensure the accuracy of the STS.
For navigation purposes only, a system as realized with the current GPS and GLONASS could almost live with its own free system time scale. But as written in the GPS-Interface Control Document, the timing user is a specified customer, and GPS-time & UTC dissemination is one of the system goals. This concerns GLONASS too, and a link to UTC had to be established in both systems.

For civil navigation purposes more or less relaxed requirements on the long-term stability of the STS could be specified if we consider the opportunity to have regularly and safe contacts to the satellites. This is also a cost factor. Now, for a future GNSS2 some decisions have to be made:

1. Do we need / wish to distribute a high accurate and stable time scale ?
2. In which terms this time scale has to be optimized, and what is the impact on the system design ?
3. How to find the most cost-effective solution ?

In order to answer such questions we identified some tasks which have to be studied very carefully:

- selection of the satellite clock type: Cs, Rubidium Atomic Freq. Standard (RAFS), H-Maser, Ultra Stable Oscillator (USO, quartz)
- clock synchronization method (one- & two-way)
- STS generation, ensemble technique preferred
- measurement rate & clock parameter update rate

For a GNSS2 in the present development phase also inter-satellite-ranging (ISR) is studied. Combined with a dedicated satellite constellation such a scenario can benefit from the opportunity to increase the measurement and update rate sufficiently. This could also help to decrease the requirements on the clock stability: much cheaper and more reliable clocks, i.e. USOs could be considered.

In a first step we investigated a clock scenario (Case 1) with 15 RAFS and 3 H-Maser clocks in orbit (European space-qualified versions each), and 4 Cs-clocks on ground. Both ISL and two-way links had been adopted. The User Equivalent Range Error (UERE, see below) clock requirement was 0.7 ns (1σ). We will show the results of this simulation and discuss possible system design constraints and simplifications. At the end we give another simulation result where USOs have been considered on-board the satellites (Case 2).

SYNCHRONIZATION METHOD AND SCENARIO

There are two different synchronization methods available which can be used for clock synchronization, namely one- and two-way methods. The advantage of the first is its simplicity in operation, but it is strongly correlated to the position error of the two participating stations. This can be avoided with two-way methods requiring active stations at both sites. A more detailed description can be found elsewhere. To meet a compromise between both methods the so–called two-way pseudo cross-link had been proposed. This mode works like a two-way cross-link: both stations send a signal wrt. the other station, but the transmission from one station is delayed by a certain interval τ_{wait}. Such an operation can be of highest interest in an ISL-scenario, where only one satellite transmits, others are listening. After a certain interval the transmit/receive configuration is changed and so on. The clock comparison between two satellites is depicted in **Fig. 1**.

Applying a pseudo cross-link the clock offset $T_{n,m}$ in [s] between two stations (satellites) can be determined in the same manner as with a cross-link by just subtracting the offset due to the clock rate during the interval τ_{wait}:

$$T_{n,m} = \frac{PR_m - PR_n}{2} - \frac{\Delta\tau_{n,m}}{2} - y \cdot \tau_{wait} - \tau_{rel\,n.m} \qquad \textbf{Eq. 1}$$

PR_m & PR_n being the time intervals between the transmitted and received signal (recorded as one-way pseudoranges in [s]) as measured at both m & n sites, $\Delta\tau_{n,m}$ is the asymmetric delay in [s], y is the rate between both clocks in [s/s], $\tau_{rel,n.m}$ relativistic delay in [s]. The waiting interval depends on the number of satellites involved in such a system. The accuracy will mainly depend on a decrease of the asymmetry term, which itself consists of the

- geometric
- atmospheric (iono- + troposphere).
- Sagnac effect
- instrumental (transmitter + receiver, receiver noise)

differential delays. Clearly it can be seen that there is a requirement for stable clocks at both stations at least over the whole waiting period (i.e. some seconds till 2 min.)

Using such measured clock offsets the STS is generated. This scenario applies essentially highly accurate two-way data. Additionally, clock offset solutions from the Kalman filter for ephemeris determination (pure one-way solution) can be used in a weighted combination to the more accurate two-way measured clock offsets. Getting such data the STS can be computed as an appendix to the orbital Kalman filter.

STS AND ITS GENERATION

For navigation, dating, and maybe time dissemination purposes, the existence of a system reference time scale is compulsory in a GNSS2. The clocks of each satellite shall then be synchronized to the common reference time scale. This is necessary in particular for:

- providing correct information on the clock status in the navigation message,
- having a common reference time for scheduled system operation activities,
- evaluating satellite ephemeris,
- disseminating a reference time scale to different users.

The system time reference can be an independent time scale with the unique request of being the common reference for all the GNSS2 (space, ground, and users segments). In the civil as well as military standards, the use of the UTC is recommended and, actually, UTC has a wide diffusion.

The solutions adopted to define a STS are usually twofold:

- The first is the *master clock* solution, where one of the system clocks is chosen to be the *master* and it defines the time scale for all the system. Such a solution seems to be preferred in GLONASS.
- On the other hand, the STS can be defined as an ensemble time scale obtained from a suitable average of *all the system clocks* either on ground or on-board. This second solution is adopted in GPS-time and it has evident advantages in reliability and stability.

As far as stability is concerned, it can be demonstrated that an ensemble time has better stability than any single clock participating to the ensemble, at least for some particular values of integration time τ.

STABILITY ?

The STS constitutes the reference time scale versus which the errors of all the single clocks are estimated. The better the reference time, the better are the estimations of the clock errors. Moreover, all the system clocks are synchronized to the STS and they have to locally reproduce, in real-time, the STS. The STS will in fact be available only in deferred time because a certain delay is introduced due to the need of gathering clock data and of computing the ensemble time. To this aim, a prediction of STS and of each single clock behavior is necessary. The more stable the STS, the more it is predictable and thus better reproduced, in real-time, by each single clock. In addition, if the system time is more stable than any single clock, it would be almost sure that any observed anomaly in the time offset between a satellite clock and STS can be ascribed to the satellite clock, and thus corrective actions can be taken.

ACCURACY ?

As far as the navigation is concerned, the STS accuracy defined as the degree of agreement versus UTC is not a compulsory demand. System clocks could be all very fast and delivering a time unit far from the SI-definition, but, if all the system clocks were coherent in such a system, navigation accuracy would not be damaged. Thus, the agreement with UTC seems not necessary in principle, but it results in some related benefits:

- The first is the **very long-term stability**. It was stated that the STS has to be stable, but clock stability depends on the integration time τ, so the integration time τ over which optimize stability has to be chosen. A different choice of the clock weights results in a different stability of the ensemble time. Due to the aim of the STS of being a measurement reference and also for practical reasons due to measurement availability, with the Case 1 a study was performed by choosing to optimize the stability of the STS in the range of medium-/long-term integration times, i.e. $10 \leq \tau \leq 30$ days, not longer. It is also very difficult to optimize to stability over months or years with the clocks commercially available currently, due to the difficulties in estimating their very long-term behavior. Conversely, UTC, which is the ultimate reference time, has the best stability in the very long-term by definition and by its fundamental aims. Therefore, ensuring the agreement of the STS versus UTC means also ensuring the very long-term stability. In this case the accuracy can be seen as a long-term warranty that the system time is not degrading. Moreover, for practical reasons, it seems surely easier to maintain the agreement with an existing and well disseminated time scale, rather than creating a completely independent one. In addition, there are recommendations of standardization organizations as the CIPM, ITU, and military, as NATO, explicitly asking to use UTC as reference [1] - [3].
- The strongest remark anyway comes from the fact that a GNSS2 could be also a mean for **disseminating UTC** in almost real-time around the world. This clearly asks for a close agreement versus UTC. The current request in Europe for a system disseminating UTC is very strong and not only restricted to metrological institutions. The existence of a reference time scale with easy access, cheap, and accurate is requested by telecommunication companies, scientific laboratories and astronomical observatories, industries that synchronize their computers, banks, watch sellers, transportation systems, and so on. As a matter of fact, the market of Rb-standards disciplined to a GPS receiver that locks the frequency of the Rb-standard to the GPS time scale is still growing and new users are still arising. In such a case, since UTC exists only *"after the fact,"* and results are available with a delay of one month, the STS must ensure the best metrological qualities in the meantime, when UTC is still not known. This is another reason suggesting that the STS should be optimized over an integration time τ of about 10-20 days, i.e. the mean time before the publication of UTC results.

A possible easy and cheap solution to maintain agreement versus UTC, and also for sake of reliability and of safety, could be the frequent comparison of the STS versus a local intermediate time scale chosen among the *real-time* approximations of UTC versus which the STS could be more frequently compared (the same role of UTC(USNO) in GPS). This will be considered in Case 2.

EXPECTED FEATURES

The use of a STS not only based on the signal of a single clock, but obtained from an "ensemble" of oscillators ensures a better performance in terms of stability, accuracy, and reliability. This is true for any ensemble time. The case of an ensemble including also satellite clocks by means of ISL offers some peculiarities and advantages:

- Clocks are kept in more stable conditions. In fact, once they are appropriately insulated from temperature gradients, the environment is less noisy for vibration and e.m. disturbances. The clock behavior should then be more stable than on Earth and the same for the resulting ensemble time.
- Minor correlation among clocks is expected being spread on different satellites. Thus, the independence of clocks should be ensured and this avoids the appearance of correlated noises that degrade the quality of the ensemble time and whose detection is difficult.
- In case of optical links, the clock comparison schedule is guaranteed, since there will be no obstacles causes by bad weather. Therefore, the clock comparison series doesn't contain unexpected *missing data* with all the subsequent statistical problems of data reconstruction.
- On the other hand, the series of data may be not evenly spaced and measurement data can be not directly on the standard date requested for the computation of the ensemble time. Therefore, an appropriate smoothing and optimal estimation technique is necessary.
- The measurement uncertainty can be dependent on the geometry of ISL and, thus, not be constant. Moreover, multiple contemporary ISLs are possible, providing a redundant set of clock comparisons that should be processed by an appropriate least-squares estimator.

From the uncertainty of the clock inter-comparisons performed by ISL, from the intrinsic metrological qualities of the used clocks, and from the statistical capabilities of the ensemble algorithm, the qualities of the ensemble time can be estimated and validated by simulations. It is expected that

- ISL can guarantee clock comparisons with a subnanosecond uncertainty,
- Clocks on-board and on Earth could be atomic commercial standards with a medium-long-term stability up to the level of 10^{-14},
- The average algorithm could lead to an improvement of a factor $\sqrt{N}$ on the metrological qualities (N - number of clocks, $N = 22$ in Case 1, $N = 83$ in Case 2 as given below).
- It can be shown that the uncertainty on individual clock offsets from STS at the update epoch is negligible due to the low measurement uncertainty and large number of data which can be handled by means of appropriate smoothing and optimal estimation techniques, etc.

The resulting ensemble time scale could thus reasonably reproduce the UTC, in real-time, with a time error comprised in some tenths of nanoseconds .

GENERAL DEFINITION

Several ingredients are necessary. Apart from the smoothing on measurements data, the STS has to be defined as a weighted average of clock readings, where clock weights are to be appropriately fixed. Moreover, since time or frequency steps are to be avoided to ensure stability, each time that a clock enters or leaves the ensemble, a correction is necessary. Such a correction needs the prediction of the clock frequency, and thus mathematical tools typical of the signal processing analysis have to be introduced. Moreover, to ensure reliability, often an upper limit of weight is introduced. In addition, to avoid any degradation of the stability and reliability of the ensemble time, any check on possible anomalies in the clock behavior is necessary. Lastly, the offsets between each clock and STSareobtained and can be used to update the satellite clocks.

The basics of the average algorithm will not be given here, seeming to be commonly known to this community. The here-applied definition of an ensemble time is at the basis of most algorithms for ensemble time scales currently used and that have differently added some other stability improvements [4] - [6].

RESULTS

Simulation results will be given in the following for both assumed GNSS2-scenarios (Case 1, Case 2) as given in the introduction.

STS STABILITY – CASE 1

The stability of the 22 simulated clocks and of the STS is reported in **Fig 2**. The integration intervals from 10^4 s (~2.5 hours) up to 10^7s (~100 days) are chosen, which constitute the range of interest either for the ISL periodicity or for the update interval of STS and on-board clocks. It can be easily extended down to 10^2 s, if necessary, because the noise affecting clocks from 10^2 s to 10^4 s is a white frequency (WFM) or random walk phase noise (RWPM) for all the clocks considered. It can be seen that the instabilities of the different RAFS follow more or less the same pattern, so is for H-Maser and Cs clocks.

It was decided to optimize the STS stability over the medium-long-term to provide a time reference useful for the estimation of single clock behavior and for maintaining an agreement versus UTC. To this aim, the instability over $\tau = 30$ days is of particular interest because it determines the weight of the clock in the computation of the ensemble STS. As expected, since long-term stability has to be optimized, the weights attributed to Cs clocks will be larger than the others. In particular it appears that due to the presence of linear frequency drift, the weights attributed to RAFS are almost negligible, compared to the Cs-weights. This stresses the fact that if long-term stability is to be obtained, then clocks with good long-term stability have to be used and the best solution is using Cs-standards.

It means that in reality the weighted average is mostly driven by Cs clocks, while the other clocks add a small gain. Nevertheless, the STS inherits a small frequency drift that generates a low instability. Such residual drift is very low and should not cause a problem from the stability point of view. From such considerations, it appears that the STS has more or less the same behavior of Cs clocks (WFM plus random walk frequency noise - RWFM), but at a lower level. From such simulation tests, it can be assumed that the instability of the STS would be mostly due to WFM for 10^4 s $\leq \tau \leq 20$ days and RWFM for $\tau \geq 20$ days.

STS ERROR & UTE – CASE 1

With the STS stability as estimated before, the uncertainty on the STS prediction can be evaluated by using the theory of random walk and the associated uncertainty. Let's suppose that the STS computation has an updating period equal to T_{STS}. The error gained by STS was evaluated, see **Tab. 1**. This means that, if STS is updated at least once a day, the uncertainty in the STS prediction remains below the level of 5 ns. This error is below the level of the corresponding errors in predicting RAFS and Cs-clock offsets, but it is worse than the error gained by an H-Maser. On the other hand, the stability of STS continues to increase for observation times up to 20 days, while the stability of an H-Maser can be deteriorated by the frequency drift. Such STS could then be a good long-term reference for estimating frequency offsets and drift of RAFS and H-Maser, but it can hardly be a good reference for estimating the long-term behavior of Cs clocks. Such results strongly depend on the fact that the long-term stability of STS can only be ensured by the 4 Cs standards, and an ensemble STS obtained with only four clocks cannot exhibit better accuracy.

T_{STS}	$u_{STS,\,max}$
5 min	0.3 ns
15 min	0.5 ns
30 min	0.7 ns
1 hour	1.0 ns
...	...
24 hours	5.0 ns

Tab. 1: STS uncertainty for different update intervals in Case 1

In case the time dissemination purpose was to be fulfilled, the STS should provide an accurate information of time, and the error versus the UTC has to be estimated. In fact UTC is known only a posteriori and if STS runs freely between one UTC update and the other, it can accumulate a large time error only due to its random noise, which is mostly due to the WFM. Therefore, in case the UTC steering was possible only any 30 days, the gained error after 30 days could amount to about 27 ns. It could be worthwhile, for sake of accuracy and also for safety, considering the possibility of using another real-time UTC approximation as a second reference useful for a more frequent and accurate steering of STS, as done in GPS with UTC(USNO).

The uncertainty on the clock offset wrt. STS of a single satellite clock is equal to the User Time Error (UTE). The knowledge of the offset of any single clock versus STS in real-time is limited by at least two sources of uncertainty: the uncertainty due to the limited knowledge and predictability of the behavior

- of the single clock
- of the STS.

By assuming that STS and clocks on-board are updated with the same periodicity denoted by T_{STS}, it appears that $t-t_0$, i.e. the time since the last update, can vary in the region $0 < t-t_0 < T_{STS}$. The behavior of the total uncertainty for the three different types of clocks is reported in **Fig. 3**. In case of H-Maser, the uncertainty is dominated by the uncertainty due to STS noise, in case of RAFS and of Cs clocks, the larger contribution is due to the RAFS or Cs clocks themselves. The result of the overall (UTE) clock error evaluation for the different

T_{STS}	$u_{UTE,maser,\,max}$ [ns]	$u_{UTE,RAFS,\,max}$ [ns]
5 min	0.3	0.7
15 min	0.5	1.2
30 min	0.7	1.7
1 hour	1.0	2.4
...	...	...
24 hours	5.0	12.4

Tab. 2: Maximum values of the overall clock error (UTE) for different satellite clocks wrt. STS(1σ) – Case1

satellite clocks of the selected scenario is given in **Tab. 2** for $t-t_0=T_{STS}$.

Clock Errors on Navigation Solution, UERE clock component – Case 1

The UERE combines the individual satellite errors to an overall error, and is defined following [7] as that component of system accuracy being independent of location and time that represents the receiver ranging error among the four satellites in view that provide the lowest Geometric Dilution of Precision (GDOP)-value. The uncertainty in evolution of the STS between two updates is not of importance for the UERE clock component. This can be explained with the fact that the STS error evolves in the same manner for all system clocks, thus, producing only a common bias. This bias, because it is common to all satellite pseudo-ranges, plays no role for the navigation user's position solution. Thus, the corresponding STS clock error can be excluded. The UERE clock uncertainty $u_{\mathrm{UERE}(M),\mathrm{clock}}$, by tracking $M \geq 4$-satellites ($M=4$ for the classical definition, $M>4$ for today's state-of-the art receivers) with individual satellite clock uncertainties $u_{x_i(t)}$, can be estimated with

$$u_{\mathrm{UERE}(M),\,\mathrm{clock}} = \frac{\sqrt{\sum_{i=1}^{M} u_{x_i(t)}^2}}{M} \quad ; M \geq 4 \qquad \textbf{Eq. 2}$$

The result for $M = 4$ is given in **Tab. 3**. In the last column the case of 4 H-Maser clocks has been shown for comparison. The good impact of such a constellation is quite visible.

# H-maser	**0**	**1**	**2**	**3**	**4**
# RAFS	**4**	**3**	**2**	**1**	**0**
T_{STS}	U_{UERE} **[ns]**	U_{UERE} **[ns]**	U_{UERE} **[ns]**	U_{UERE} **[ns]**	U_{UERE} **[ps]**
5 min	0.30	0.26	0.21	0.15	3
15 min	**0.55**	0.48	0.39	0.28	6
30 min	0.80	**0.69**	**0.56**	0.40	8
1 hour	1.10	0.95	0.78	**0.55**	11
2 hours	1.60	1.38	1.13	0.80	16
...	...	...	...	...	...
24 hours	5.70	4.94	4.03	2.85	93

Tab. 3: UERE(4) cock error (1σ) for different clock combinations vs. update interval – Case 1

Stability and UERE in a USO Scenario with Case 2

In this case we considered a scenario with 83 clocks, namely 64 USOs (on-board Low Earth Orbiting (LEO)-satellites), 9 RAFS in orbit and 1 H-Maser, 9 Cs on ground with the typical stability pattern as given in **Fig. 4**.

We concentrated on the short-term here, because the considered USOs have their best stability even in this observation range, a low measurement and update interval (up to 5 min) can be expected from the ISL-scenario, and steering to UTC can be maintained by frequent comparison of the STS versus a local real-time approximation of UTC versus which the STS could be very frequently compared. The application of USOs would make a system less expensive and increases reliability. Different STSs were examined:

- STS with all the 83 clocks;
- STS with all the clocks except USO;
- STS with USO only,

all optimized for τ = 1000 s. The instabilities obtained are illustrated in **Fig. 5** adding also the typical ADEV pattern of USO and H-Maser. It can be seen that an optimization on τ = 1000 s, gives the larger weight to the H-Maser (99%), and at τ = 1000 s the stability of STS is very similar to that of the H-Maser. Nevertheless,the presence of the USOs gives a large impact on the long-term behavior of the STS which inherits a frequency drift.

If the USOs are excluded the short-term is not worse, but the long-term is much better. It must also be stressed that in case the H-Maser is only one, so the STS largely relies on such a unique clock giving a very high weight and such a situation could raise some reliability problems.

The last STS is obtained with the USOs only. It can be seen that the stability of such STS is very similar to the USO instability, but at a lower level due to the high number of USOs at one's disposal. The solution of not using USOs in the STS could result in better stability. By plotting the instability of the clocks together with that of STS obtained without USOs in **Fig. 6**, it can be seen that the instability of the STS is much lower than those of the single clocks over the optimized interval of τ = 1000 s, apart from the H-Maser case, whose instability is more or less the same of the STS. For the observation intervals 100 s < τ < 10000 s, the dominating noise of the STS is a WFM corresponding

# USO	**0**	**1**	**2**	**3**	**4**
# RAFS	**4**	**3**	**2**	**1**	**0**
T_{STS}	U_{UERE} **[ns]**	U_{UERE} **[ns]**	U_{UERE} **[ns]**	U_{UERE} **[ns]**	U_{UERE} **[ns]**
5 min	0.30	0.26	0.21	0.15	0.03
15 min	**0.55**	**0.48**	0.41	0.31	0.17
30 min	0.80	0.73	**0.66**	**0.57**	**0.47**
1 hour	1.10	1.17	1.23	1.29	1.35
...	...	...	...	...	...
24 hours	5.70	87.64	123.81	151.58	175

Tab. 4: UERE(4) cock error (1σ) for different clock combinations vs. update interval – Case 2

to RWPM, so the uncertainty analysis of the STS follows the same approach as described above. Finally the UERE clock component for the different satellite clock combinations have been calculated as given in **Tab. 4**.

CONCLUSION

In both study cases ISL and two-way clock comparisonhavebeen considered. The proposed pseudo cross-link should be further investigated, being of interest for future ISL-scenarios in general. The low measurement uncertainty (of course also depending on the frequencies and signal structure, transmitting power etc. used) and the large number of redundant data handled by means of appropriate smoothing and optimal estimation techniques led to the assumption that the uncertainty on each clock offset wrt. STS is negligible at the update epoch. This approach has to be examined in more detail through numerical simulations.

We have shown that an ensemble time scale should be preferred for a GNSS2's STS. This ensemble can be generated as a weighted average of the mutual clock difference readings. In Case 1 the long-term optimization of STS has been stressed to enable UTC-reproduction by the STS itself. The simulated STS uncertainty can reach a value of up to 5 ns, the UTE is 5 ns for an H-Maser and about 12 ns for a RAFS, all values after one day. The UERE clock requirement can be met with an update interval not larger than 30 min in all combinations. More H-Masers would relax the update constraints. In case 2 the STS's short-term has been optimized. It has been shown that while generating the STS the USOs should better be excluded. But these clocks show a good (and cost-effective, reliable) influence on the UERE clock uncertainty in such a considered ISL-scenario within shorter integration times. With an update interval not larger than 15 min the requirement can still be satisfied in any combination.

It has been discussed why the steering of STS to UTC is so important. The UTC-dissemination with a future GNSS2 must be addressed in the development phase, because there are requests from many users world-wide. The ISL-scenario in general has a good impact and offers some more possibilities on the time-keeping system of the considered GNSS2.

ACKNOWLEDGMENT

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REFERENCES

[1] Comptes rendus des séances de la quinziìeme Conférence Générale des Poids et Mesures, Paris, 1975
[2] ITU-T Telecommunication standardisation sector of ITU, International Telecommunication Union, Definition and terminology for synchronisation networks, 1996.
[3] Recommendation CIPM 1996, Comite International des Poids et Mesures, Comptes rendus 85th meeting, Paris, 1996.
[4] L. A. Breakiron: Timescale algorithms combining cesium clocks and hydrogen masers, in Proc. 23th Precise Time and Time Interval Meeting, Los Angeles, CA, 1991, pp. 297-305.
[5] S. R. Stein: Advances in time scale algorithms, in Proc. 24th Precise Time and Time Interval Meeting, Washington, DC, 1992, pp. 289-298.
[6] C. Thomas, P. Wolf, P. Tavella: Time scales, Monographie BIPM 94/1, Bureau International des Poids et Mesures, Sèvres, France, 1994.
[7] TECHNICAL CHARACTERISTICS OF THE NAVSTAR GPS, developed by the NATO Navstar GPS Technical Support Group, Sept. 1989.

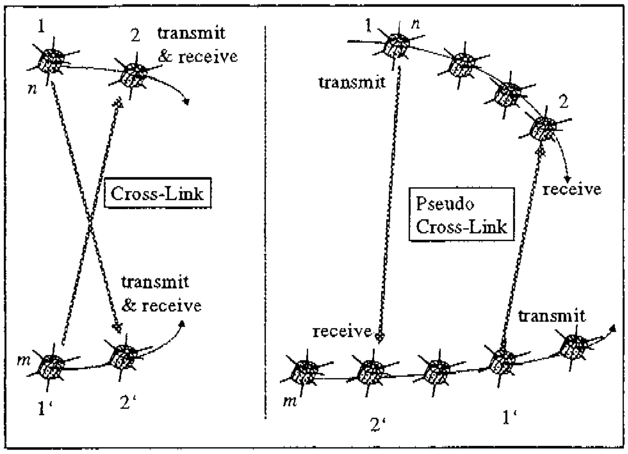

Fig. 1: Two-way cross-link and pseudo cross-link between two satellites

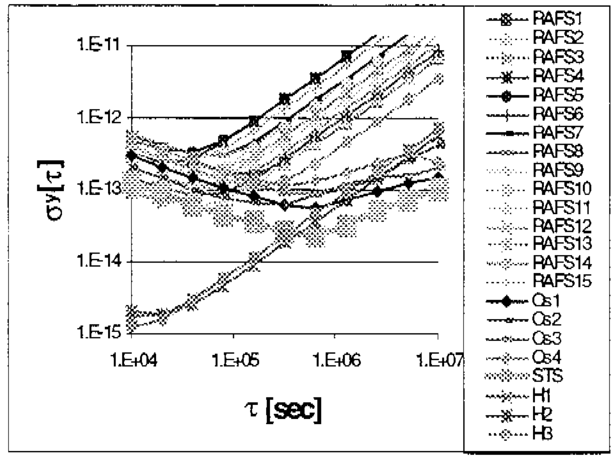

Fig. 2: Allan Deviation (ADEV) of the STS together with that of the 22 simulated clocks in Case 1

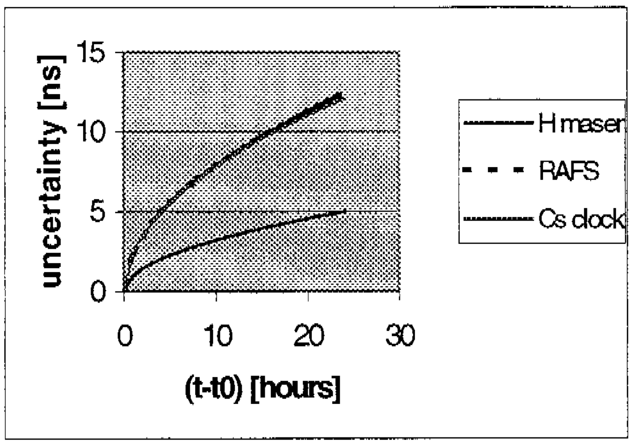

Fig. 3: Total uncertainty on the clock offset wrt. STS (UTE clock component) vs. time since the last update

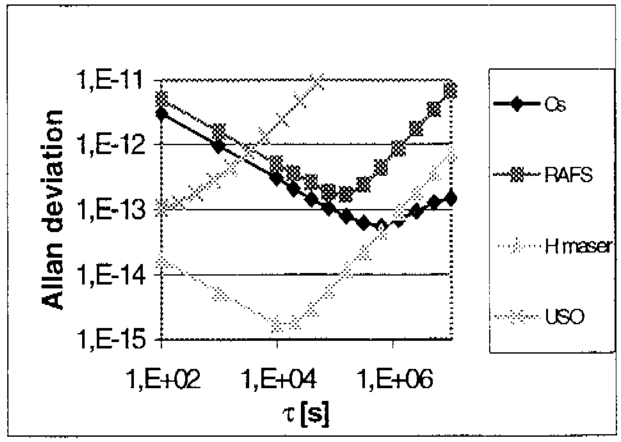

Fig. 4: Typical instabilities of the clocks considered in Case 2

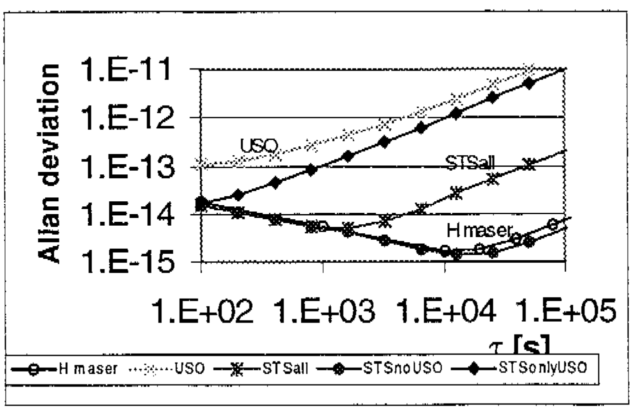

Fig. 5: Instability of the STS in Case 2 obtained with different ensembles of clocks & typical ADEV pattern of USO and H-maser

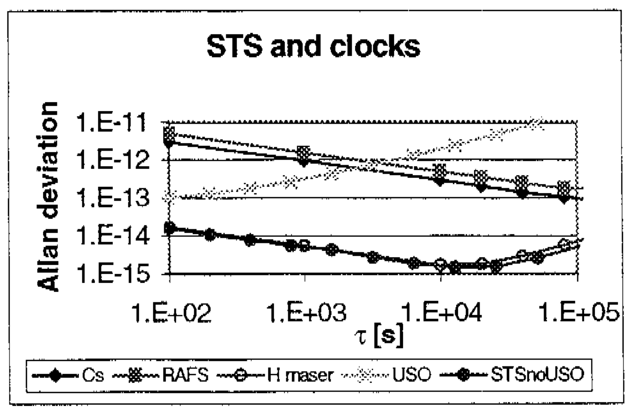

Fig. 6 Plot of the instability of the clocks used together with that of STS in Case 2 obtained without USO

Questions and Answers

DENNIS McCARTHY (USNO): Could you comment on how this would work with existing systems, or if you have considered that?

JOERG HAHN (DLR): We have not considered that. We only know that within GPS we have the two satellites where inter-satellite links are considered. We only have seen one simulation study – I think from The Aerospace Corporation. I do not remember all the numbers now, but it is the only thing I have seen on this, no other studies.

Of course, if the people here would listen to us, we would be quite thankful for any help in such investigations.