NEW TRENDS IN TWO-WAY TIME AND FREQUENCY TRANSFER VIA SATELLITE

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Abstract

Recent developments performed with SATRE two-way time transfer (TWSTFT) modems resulted in significant performance upgrades and operational improvements of the TWSTFT method. These are aimed to reduce manpower effort and to provide reliable, real-time data via a centralized monitoring and control facility, which can be easily integrated into larger systems or ground-station installations.

New operational modes and advanced modulation techniques are aimed to significantly reduce transponder and other operational costs. Clock performance requirements at secondary sites can be significantly reduced as soon as two-way links operate on frequent schedule.

The results of a two-week test campaign to evaluate frequency transfer using carrier phase between USNO and NIST are presented. This technique opens another upgrade path exhibiting improved performance from 2-way links via satellite. A precision of 2 ps for a 1–second integration time has been achieved via two different, standard communication satellites. The initial frequency–transfer accuracy is on the order of 5E-14 for a 30 min observation time period. The frequency transfer stability approaches 1E-14 for a 100 s integration interval. Further tests are planned to extend the characterization to longer time periods. Remote control via Internet and centralized data collection have been used throughout the experiment.

INTRODUCTION

Two-Way Time and Frequency Transfer via Satellite (TWSTFT) is a well established method to compare primary clocks within regional networks and on intercontinental baselines [1]. Due to its unique ability to compensate most of the uncertainties of the radio signal propagation path, the method is highly recognized by national time and frequency laboratories. TWSTFT data are regularly used by BIPM for the calculation of TAI. The GPS reference ground station network uses TWSTFT as an independent means for time synchronization. Future navigational satellite systems are likely to benefit from these technologies [2].

Although advantages of TWSTFT are quite obvious, its use has been restricted so far to approx. 10 primary laboratories and other military establishments. It is believed that the reasons are not necessarily due to technical limitations, but rather of operational nature by requiring considerable manpower resources for system monitoring at each site, which is mandatory from some satellite operators. TWSTFT systems require transmit and receive elements at both sides of a link, which in turn requires satellite transponder access for all users. The satellite communications industry is quickly growing and low-cost satellite access is no longer a technical issue, aside from operational costs charged by the satellite operator.

VSAT ground-station technology becomes inexpensive and higher frequencies in Ka-band combined with wide-bandwidth transponders allows now for more advanced operational concepts. This may become an attractive solution for institutional and industrial users, as soon as transponder costs are reduced to economic levels. Availability of highly accurate 2-way links would enable even such laboratories not in the possession of high-performance clocks to share the benefits of existing time-transfer networks and to provide, in turn, traceable time and frequency data to commercial users.

The first part of the paper addresses operational and configuration aspects. The second part presents a new method to further enhance short-term system performance using 2-way carrier phase data.

This paper intentionally does not address such equally important issues like system and ground-station calibration and performance issues, because extensive literature already exists on these aspects [3] [4]. Although the features presented here are based on the company's SATRE (Satellite Time and Ranging Equipment) product, some configurations can be realized with other commercial instruments as well.

OPERATIONAL ASPECTS

Modern ground-station concepts mandate centralized administration of all functions. 2-way systems have to follow this trend in order to be an acceptable technology for system operators. As consequence, new systems exhibit full remote monitoring and control via local area network or Internet/intranet connections. This includes the 2-way modem itself, as well as the related ground station equipment. Unattended operation at individual sites becomes feasible as long as there is a centralized capability to perform all required operations. The important capability to shut down transmissions in case of interference or malfunction is realized via remote control. Links may be operated not only during day-time working hours – at both ends. Continuous links or at least frequent operations are feasible. Multiple access and multiple time-shared links between stations are scheduled automatically, reducing the central workload merely to a monitoring function. The original satellite operator requirement to have trained personnel at each site can be now reduced to have persons on call in case of emergencies.

Measurement data and as well as system status information are exchanged via the 2-way time link during normal operation. Real-time results are available within 3 seconds of the measurement. Because TWSTFT does not require any further external data (i.e. troposphere, ionosphere, satellite orbit, etc), full performance results are available merely in real time. Assessing the system operational status and health is easily performed at the central site for all links based on continuously available data quality and system status information. Malfunctions can be detected within seconds.

Long-term data consistency is guaranteed by keeping records of system performance over extended time periods and by logging of all non-nominal events. This allows one to demonstrate and guarantee continuous operation and data quality with minimum post-processing effort.

DATA QUALITY AND DATA FORMATS

TWSTFT data are traditionally stored as a set of parameters derived from a second-order regression for a two-minute observation period. This follows the actual operational scheme of TWSTFT networks. Such data sets further include statistical tests on data quality, as well as station-specific calibration data. The SATRE modem extends this data reduction feature to 1st, 2nd and 3rd-order data regressions performed in parallel. An internal data base holds the last 30 minutes of raw data; older data are stored in the regression format. The user can access this data base to inquire the data history over the past 2 weeks. This feature reduces the amount of data traffic and post-processing efforts. Data regression smoothes noisy measurements and allows data extrapolation in case of an RF-link failure. Malfunctions can be easily detected by comparing extrapolated and actual data.

Based on typical instrument configurations and link-budgets, the following time-to-alarm figures are readily achieved:

2.5 MChip/s	3 ns @ 1 s 1 ns @ 10 s
20 MChip/s	300 ps @ 1 s 100 ps @ 10 s
Carrier Phase	15 ps @ 1 s

2-WAY TIME SYNCHRONIZATION

The features described above directly lead to systems where a remote clock is automatically synchronized to a central site (**Fig. 1**). Real-time TWSTFT data are input to the control-loop steering the remote clock [5]. A continuously available satellite link would give best performance with minimum requirements on the remote clock, which has to flywheel during link interruptions and during the time constant of the control loop. Like in a GPS-disciplined oscillator, control-loop parameters are optimized for lowest oscillator phase noise and for optimum short-term stability, while preserving long-term stability. It is obvious that requirements on the remote clock can be relaxed in the same way, as the performance and availability of the RF link increases. As long as overall operational constraints are not violated, i.e. other hold-over requirements, a remote clock using just a medium-quality crystal oscillator in the control loop exhibits a similar stability as the master clock. Its outputs are directly traceable to the master reference. After a service interruption, fast re-synchronization is achieved fully automatically.

SATELLITE TRANSPONDER COSTS

Satellite transponder costs are considered as main drawback by present TWSTFT users, who rent appropriate bandwidth and transponder time slots on an exclusive basis. This leads to short measurement sessions using the minimum feasible bandwidth. Such restrictions limit the use of TWSTFT to laboratories equipped with high-performance clocks, which are able to bridge gaps between measurement sessions. Primary laboratories operate on a 2- or 3-day schedule. The GPS ground-control network performs several sessions per day. The rather narrow RF signal bandwidth further limits achievable system accuracy [6].

However, from a system point of view, it is most desirable to use the widest possible RF bandwidth ideally on a continuous basis, which is clearly the highest cost option when traditional transponder channel allocation schemes are to be used.

There are several alternatives available when planning for new installations, which rely on co-existence of the timing signals with regular transponder traffic. 2-way signals can be equally well used for satellite tracking and ranging purposes. These additional data might be of considerable value to the satellite operator easing the accommodation process.

TRANSPONDER SHARING USING HIGH SPREADING RATES

Existing satellite traffic is virtually unaffected by TWSTFT signals operating at high spreading rates and using power levels well below the nominal traffic. A 20 MChip/s PN-coding scheme is a good compromise for best link performance over standard transponders. As long as the TWSTFT signal power observes certain limits within a given bandwidth, there is no discernible interference or deterioration of bit-error-rate to the existing traffic. Established ratios between the TWSTFT signal (S) and total other power (N) are:

- Direct TV **Analog FM**:	**S/N - 30 dB**
- Direct TV **Digital QPSK**	**S/N - 23 dB**
- Other **Communication Traffic**	**S/N - 20 .. – 12 dB**

The TWSTFT signals can be generated using small individual earth stations located directly at the user's premises. The appropriate signal power level is controlled at the transmit site. Its power ratio to the existing traffic is monitored independently at the receive site.

TRANSPONDER SHARING USING SPREAD SPECTRUM COMBINED WITH TONE MODULATION

A new scheme has been developed to minimize total RF bandwidth requirements while preserving the full RF link performance characteristics found in wide-bandwidth spread-spectrum systems. The idea is based on an optimum combination of a tone modulation, which is known from satellite tone-ranging systems, and spread-spectrum modulation. Spreading of each sideband using established pseudo-noise codes for TWSTFT resolves the ambiguity inherent to a tone system, while maintaining a low RF spectral density. The PN-coded signal and the 'tone' travel at group velocity. Both data can be directly combined into an unambiguous high precision measurement. The modulation scheme is shown in **Fig. 2**. The resulting two narrow-band signals **(Fig. 3)** can be assigned to such portions of the transponder band, where they cause no interference to existing traffic. This might include the edges of a transponder or guard-bands, if there are no dedicated slots available. The resulting RF link quality is even slightly better (approx.1 dB) when compared to a pure spread-spectrum signal at the same overall bandwidth.

Optimized receiver designs exist, which allow considerable signal interference levels in between and outside of the actually occupied signal bandwidth. Suitable 'tone' frequencies range from 5 MHz to approx. 150 MHz for advanced, wide-band Ka-band transponders. A PN-modulation of 0.5 or 1 MChip/s is sufficient for ambiguity removal. One can easily recognize that by selection of a high 'tone' frequency, a nearly arbitrary high link performance can be achieved, without changing the total output power of the ground transmitter and without any increase of total occupied transponder bandwidth. The individual sidebands do not have to use the same physical transponder, as long as the symmetry between both link directions is observed, i.e. the signals from both stations shall pass the transponder(s) on a satellite at the same nominal frequency using the CDMA properties of PN-coded signal.

Such minimum-bandwidth systems are an attractive candidate for simultaneous time-transfer and satellite-ranging operations.

TWO-WAY FREQUENCY TRANSFER USING CARRIER PHASE

A new method which further increases the short term stability of two-way links has been developed and tested recently. Like standard TWSTFT, it uses standard satellite transponders, i.e. there is no dedicated hardware to be installed on board the satellite. The method relies on additional carrier-phase measurements performed with standard TWSTFT signals. The system is able to reduce measurement noise by two or three orders of magnitude with respect to PN-coded signals. The unknown phase and frequency component of the satellite's on-board local oscillator (LO) as well as the different Doppler frequencies for each path are cancelled by using an additional receive channel tuned to the own signal at each site (**Fig. 4**). The configuration resembles a combined ranging- and time-transfer setup for simultaneous operation. In effect, both ranging and TWSTFT data are generated in parallel. From the 4 receiver measurements, the contribution of the satellite's LO is determined and the different Doppler shifts are eliminated from the 2-way carrier phase data. An earlier measurement campaign was performed to demonstrate the feasibility of the 2-way carrier phase principle [5]. It is believed that the ultimate performance (**Fig. 5**) of that earlier test was limited due to the use of one active and one passive maser, by non-optimized station cabling and signal distribution, and by the use of off-the-shelf VSAT equipment. Another test campaign using well prepared installations at both sides has been performed recently between USNO (MC2) and NIST (AOG3). The tests have been conducted under real-time remote control of the modems at USNO and NIST directly from TimeTech, Stuttgart.

The good knowledge of both clocks allowed to determine the stability and rough order of accuracy of the frequency-transfer results. Due to the limited test time available, the stated accuracy refers to this test only. It is not to be seen as a limitation of the method itself. The mathematical model has been verified experimentally and it is believed that the simplifications used do not introduce significant errors at the level required to characterize active H-Masers or cold-atom standards.

As reference, the performance of typical TWSTFT sessions using 2.5 MChip/s (**Fig. 6**) and 20 MChip/s (**Fig. 7**) are given. The link budget was approximately the same for both chip-rates. The performance gain at higher chip rates is obvious. **Fig. 8** shows carrier phase data for the link USNO-NIST. Although the data at 1 s interval do not yet show the expected level, the link quality approaches active H-maser performance for time intervals of approx. 100 s. Session time was 30 minutes, limiting MDEV data to time intervals of 256 s. An example TDEV plot for carrier-phase data is shown in **Fig. 9**. Carrier-phase data from 2.5 MChip/s signals and 20 MChip/s signals exhibit similar performance, as theory predicts. There was no attempt so far to single out individual error sources. The main objective was demonstration of system performance and assessment of frequency transfer accuracy.

The residuals between the modem's two receiver channels receiving the <u>same signal</u> (**Fig. 10**) indicate that there is some room for further improvements at short time intervals.

Frequency transfer accuracy was verified using

a) clock data provided by the labs,
b) using the relative frequency offset calculated from daily TWSTFT measurements, and
c) from the relative frequency offset calculated from TWSTFT for each session.

Measurements have been performed via two different satellites, one satellite for 2.5 MChip/s and another one for 20 MChip/s. Obviously, both satellite LOs are different, whereas the frequency-transfer results match to within approx. 2 E-14. **(Fig. 11)** Comparison to simultaneous code-phase measurements agree to within 3E-14 to carrier-phase measurements. The agreement to the average frequency calculated from daily TWSTFT code-phase measurements is within approx 5 E-14. **(Fig. 12)**

Fig. 13 shows achievable short-term (1 s integration) performance of carrier phase (2E-12, 1σ) versus code phase (5E-11, 1σ) using the same signal. Carrier-phase data merely appear as straight line at this scale. An interesting feature is shown in **Fig. 14**, where the same raw carrier-phase data are shown after removal of the linear component. The level of precision is clearly visible, however, there are unexpected periodic elements, whose origin is presently unknown. **Fig. 14** is shown to demonstrate the capability of two-way carrier phase measurements for quick performance assessment and for its short time-to-alarm capability at the level of 15 ps.

SUMMARY

The achievable performance of frequency transfer via satellite can be summarized as follows for integration intervals of 1s and 100s:

Stability:

MDEV	**1s**	**100s**
PN @ 2.5 MChip/s	4 E-10	4 E-13
PN @ 20 MChip/s	6 E-11	1 E –13
Carrier Phase	2 E-12	1 E –14

Appox. accuracy of carrier phase using test data: **2..3 E –14 @ 1200 s**

Corresponding TDEV of carrier phase: **< 0.5 ps @ 2 .. 100 s**

CONCLUSIONS

The TWSTFT method has established its recognized position for comparison of primary clocks. The instrumentation has demonstrated its maturity to be readily used by secondary labs and commercial users. Industry-standard monitoring and control concepts have been implemented, which allow easy integration into ground stations and larger systems. Several methods to reduce transponder bandwidth requirements are available, which provide flexibility for the implementation of new systems at minimum transponder costs.

Generation of real-time data allows for time-critical applications. Low-performance clocks at a remote site, but within the TWSTFT-based control loop, can be used with minimum impact on overall system performance.

A new method using carrier-phase data further improves the short-term link performance, which ultimately could lead to very high-performance systems using low-cost crystal oscillators being fully synchronized to a single, high-performance master reference.

Continuation of the carrier-phase experiments is envisaged to further isolate and characterize individual error sources and to perform a long-term verification.

ACKNOWLEDGMENTS

This work was only possible by the provision of time-signals, dedicated ground-station equipment and transponder time by USNO and NIST, as well as due to the invaluable and continuous support by the time-transfer groups at both laboratories.

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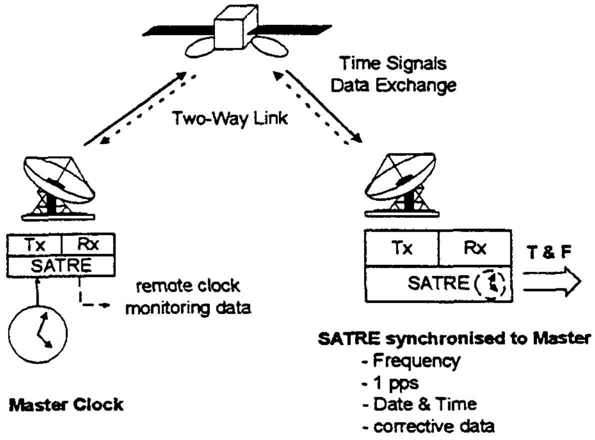

Figure 1: Two-way time synchronization

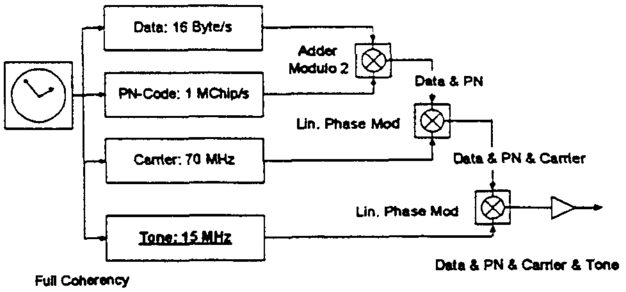

Figure 2: Spread-Spectrum with tone modulation, signal generation, and modulators

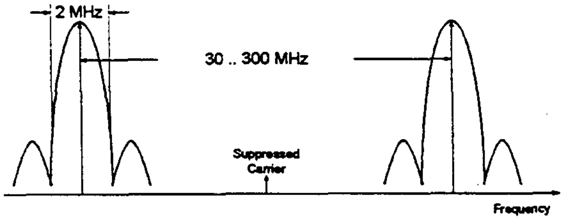

Figure 3: Spread-Spectrum with tone modulation, RF signal spectrum

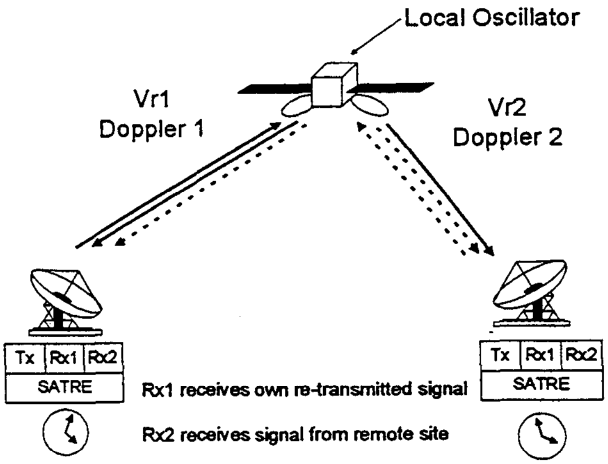

Figure 4: Two-way frequency transfer using carrier phase

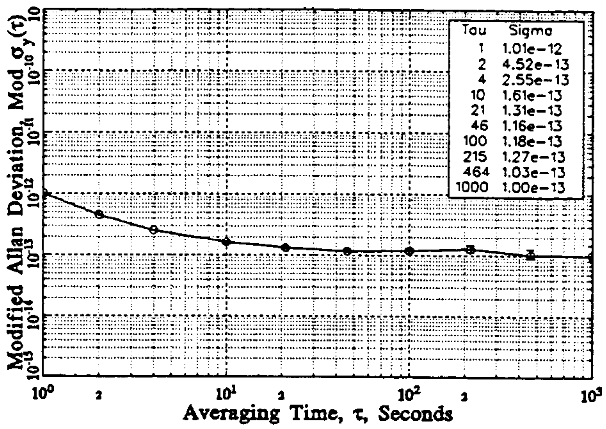

Figure 5: MDEV, carrier phase, signal 5 MChip/s, PTB vs DLR, [5]

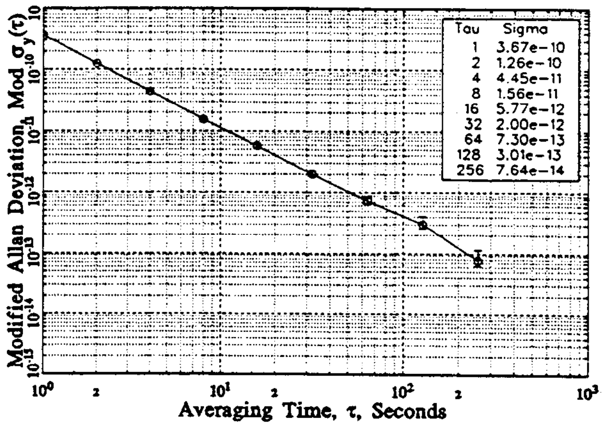

Figure 6: MDEV, code phase, 2.5 MChip/s, USNO vs. NIST

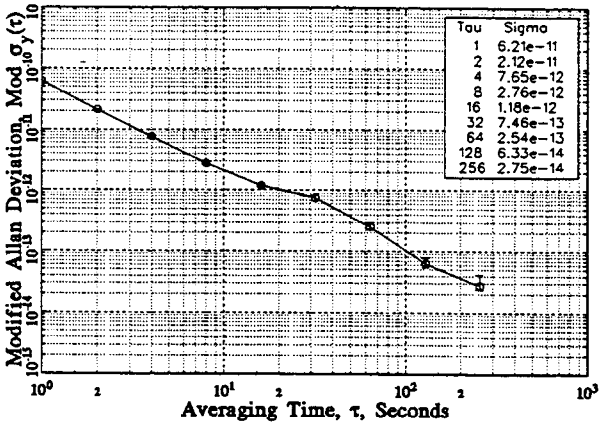

Figure 7: MDEV, code phase 20 MChip/s, USNO vs. NIST

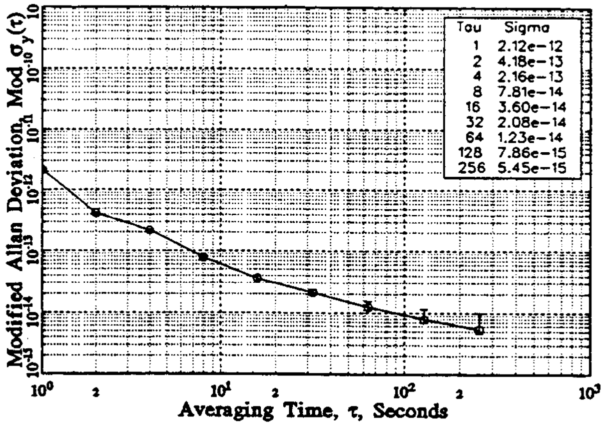

Figure 8: MDEV, carrier phase, signal 2.5 MChip/s, USNO vs. NIST

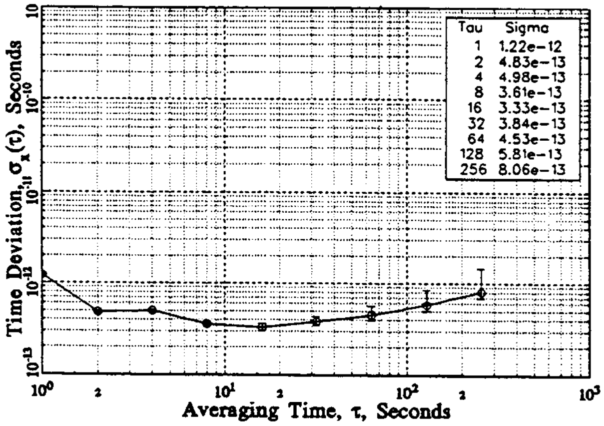

Figure 9: TDEV, carrier phase, signal 2.5 MChip/s, USNO vs NIST

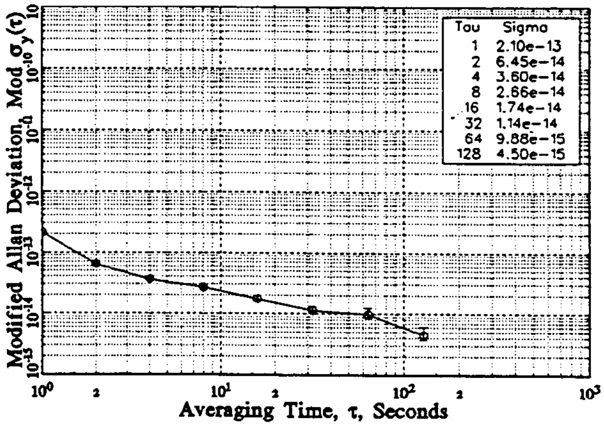

Figure 10: MDEV, residuals between receiver channels receiving same signal

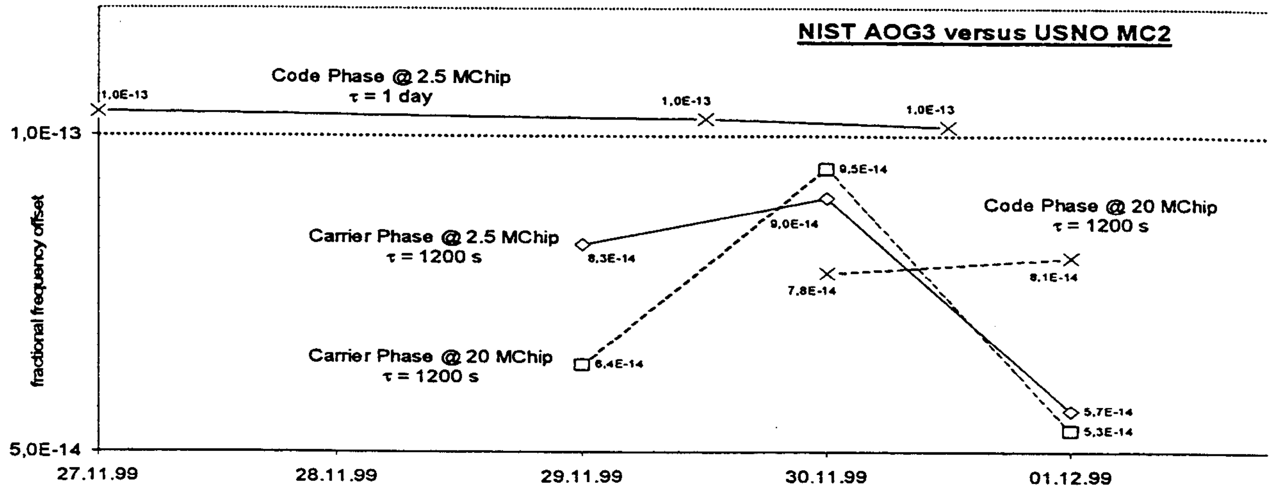

Figure 11: Frequency Transfer, PN 2.5 and 20 MChip versus Carrier Phase

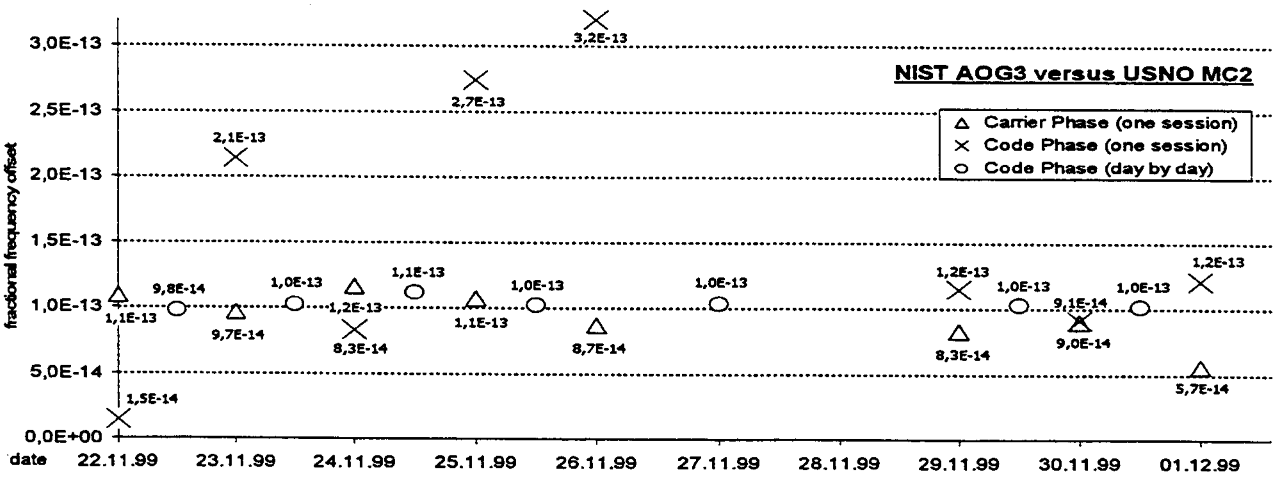

Figure 12: Frequency Transfer, PN versus Carrier Phase

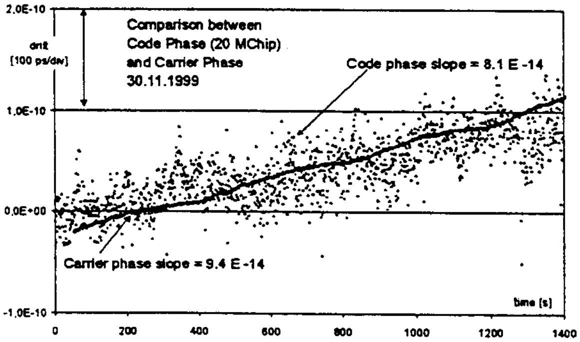

Figure 13: Frequency Transfer, PN 20 MChip/s versus Carrier Phase, Detail

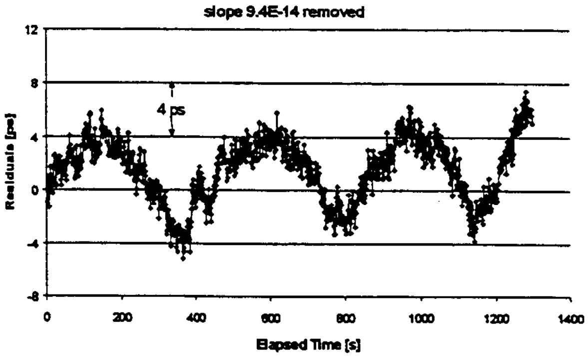

Figure 14: Frequency Transfer, Carrier Phase Residuals, 20 MChip signal