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# Time and frequency comparisons using radiofrequency signals from satellites

## *Comparaisons de temps et fréquences par signaux radiofréquences satellitaires*

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ABSTRACT

The comparison of distant clocks has always been an important part of time metrology. It is important in science in general as well as in everyday applications. Signals from the satellites of the Global Positioning System (GPS) started to be used for the purpose in the early 1980s. The methods of signal processing have improved to an extent that time transfer with ns-accuracy and frequency transfer with $10^{-15}$ relative instability have become routine. The usage of signals from other Global Navigation Satellite Systems gets more and more common and examples of the improvements related to that will be given. Two-Way Satellite Time and Frequency Transfer (TWSTFT) is another method relying on the exchange of signals in the microwave range. Time transfer accuracy at the 1-ns level was demonstrated, and recently new signal structures and processing schemes showed the way for further improvements.



RÉSUMÉ

La comparaison d'horloges distantes, qui a toujours été une part importante de la métrologie du temps et des fréquences, concerne aussi bien la science en général que les applications quotidiennes. Une des techniques utilisées repose sur les signaux des systèmes de radionavigation par satellites (GNSS pour *Global Navigation Satellite System*), qui ont commencé à être exploités au début des années 1980 avec les signaux du *Global Positioning System* (GPS) américain. Les méthodes de traitement de ces signaux se sont améliorées au cours du temps, permettant d'obtenir aujourd'hui de façon routinière des transferts de temps avec une exactitude de l'ordre de la nanoseconde, et des transferts de fréquence avec une instabilité de $10^{-15}$ en fréquence relative. L'utilisation de signaux d'autres constellations GNSS se développe de plus en plus, et des exemples d'améliorations attendues sont présentés. Une autre technique de transfert de temps à « deux voies » (TWSTFT pour Two-Way Satellite Time and Frequency Transfer) est basée sur l'échange de signaux dans la gamme des fréquences micro-ondes, via des répéteurs de satellites géostationnaires de télécommunications. Une exactitude des transferts de temps au niveau

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de 1 ns a été démontrée, et de nouvelles structures de signal associées à de nouveaux traitements ont récemment montré la voie vers d'autres améliorations.



## 1. Introduction

In our daily life, we take it for granted that mobile communication, distribution of electrical power, and location-based services on smartphones are available at all times. The operation of the underlying systems requires time synchronization at various levels of accuracy. Time and frequency references of superior quality and traceable to the SI unit of time ensure inter-operability of such services over country borders and continents. One gets so used to the function of these systems that one disregards the need for stable and reliable frequency sources, subject of other contributions in this dossier, and, at the same time, means of comparison at the required uncertainty. Time and frequency comparisons on local and regional scale can be achieved with electrical signals transported in cables, but the utmost accuracy could be demonstrated by using optical fibres to transport either stabilized laser radiation or modulated laser signals [1,2]. On a global scale, however, the transmission of radio signals via satellites is the first choice [3,4]. In this contribution I report on two satellite-based methods, the reception of signals of Global Navigation Satellite Systems (GNSS), subject of Section 2, and Two-Way Satellite Time and Frequency Transfer (TWSTFT), subject of Section 3. When signals from the satellites of the Global Positioning System (GPS) started to be used for the purpose in the early 1980s, time-keeping was revolutionized [5]. The methods of signal processing have improved to an extent that time transfer with ns-accuracy and frequency transfer with $10^{-15}$ relative instability have become routine. The usage of signals from other Global Navigation Satellite Systems gets more and more common and examples of the improvements related to that are given below. TWSTFT was introduced as early as 1980, but its routine use started in the early 1990s only [6]. It is another method relying on the exchange of signals in the microwave range, and the smallest uncertainty for time transfer could be verified [7]. The literature on the achievements over the years is abundant, and the reader is referred to the compilations of the Precise Time and Time Interval (PTTI) meetings that allow following the historical development quite nicely. Section 4 briefly deals with time transfer equipment calibration which is prerequisite for accurate time transfer. The paper is concluded with an outlook on current developments.

## 2. Current status of GNSS-based time transfer

### 2.1. General introduction

Signals from the satellites of the Global Positioning System (GPS)—the first Global Navigation Satellite System (GNSS) [8,9]—started to be used since the late 1980s for time comparisons. The primary purpose of GPS (as all GNSS) is to serve as a positioning and navigation system, but the entire system relies on precise timing, in more detail, the satellite ranges used to calculate position are derived from propagation time measurements of the signals transmitted from each satellite. The result of such a measurement, when multiplied by the speed of light, represents not the true geometric range but rather the so-called pseudorange. Deviations come from the lack of time synchronization between the satellite clock and the receiver clock, by delays introduced by the ionosphere and troposphere, and by multipath and receiver noise. The signals broadcast by GNSS satellites are derived from on-board atomic clocks (caesium beam clocks, rubidium gas cell clocks, passive hydrogen masers) and contain timing and positioning information. In details, the signals transmitted and the on-board configuration of the satellites differ between the GNSS existing today [4]. Here we restrict ourselves to a brief explanation of the measurement principle using GPS signals. The nominal output frequency of the GPS on-board clocks is $f_0 = 10.23$ MHz. From this fundamental frequency the two microwave frequencies $f_1 = 1575.42$ MHz (L1) and $f_2 = 1227.60$ MHz (L2) are derived. More recently signals on two more frequencies are transmitted but have not been used widely in the context of time transfer yet. The two carriers are phase modulated with pseudorandom noise codes (PRN-codes). These are binary codes with a chip rate of 1.032 MHz on L1, named coarse/acquisition (C/A) code, and a binary code with 10.23 MHz chip rate on both frequencies, called precision (P) code. These codes are unique for each satellite. All satellites transmit their signals on the same frequencies. A receiver generates a local copy of the PRN-code derived from its internal oscillator. This local copy is electronically shifted in time and multiplied with the incoming antenna signal. If the received satellite PRN-coded signal, which is extremely weak and hidden in the noise, and the replica signal coincide, the receiver's tracking loops can lock to the satellite signal. When this has happened data at a rate of 50 bit per second can be transferred to the receiver, reporting the almanac, orbit parameters and parameters that refer the individual satellite clock to the underlying GPS time (the system time which is calculated from an ensemble of clocks in the satellites and on Earth).

Specific GPS timing receivers have been developed, which come in two distinct configurations. Receiver type one uses the received signal to discipline an inbuilt oscillator to GPS time and delivers a 1 PPS output or even a set of output signals (standard frequency signals, signals for telecommunication applications). This application, although widespread, is not covered further here.