Recent studies have shown the capabilities of Global Positioning System (GPS) carrier phases for frequency transfer based on the observations from geodetic GPS receivers driven by stable atomic clocks. This kind of receiver configuration is the kind primarily used within the framework of the International GPS Service (IGS). The International GPS Service/Bureau International des Poids et Mesures (IGS/BIPM) pilot project aims at taking advantage of these GPS receivers to enlarge the network of Time Laboratories contributing to the realization of the International Atomic Time (TAI).

In this article, we outline the theory necessary to describe the abilities and limitations of time and frequency transfer using the GPS code and carrier phase observations. We report on several onsite tests and evaluate the present setup of our 12-channel IGS receiver (BRUS), which uses a hydrogen maser as an external frequency reference, to contribute to the IGS/BIPM pilot project.

In the initial experimental setup, the receivers had a common external frequency reference; in the second setup, separate external frequency references were used. Independent external clock monitoring provided the necessary information to validate the results. Using two receivers with a common frequency reference and connected to the same antenna, a zero baseline, we were able to use the carrier phase data to derive a frequency stability of $6 \times 10^{-16}$ for averaging times of one day. The main limitation in the technique originates from small ambient temperature variations of a few degrees Celsius.

While these temperature variations have no effect on the functioning of the GPS receiver within the IGS network, they reduce the capacities of the frequency transfer results based on the carrier phase data. We demonstrate that the synchronization offset at the initial measurement epoch can be estimated from a combined use of the code and carrier phase observations. In our test, the discontinuity between two consecutive days was about 140 ps. © 1999 John Wiley & Sons, Inc.

INTRODUCTION

Nowadays, Global Positioning System (GPS) time transfer is based mainly on the common view method using data from single-channel C/A code receivers. Several authors have recently demonstrated the capabilities of geodetic GPS receivers for time and frequency transfer based on their code and carrier phase observations (Larson and Levine, 1997, 1998; Petit, 1997; Petit, Moussay, and Thomas, 1996; Petit and Thomas, 1996; Schildknecht, Beutler, Gurtner, and Rothacher, 1990). These receivers are mainly in operation within the frame of the International GPS Service (IGS) (Kouba, Mireault, Beutler, Springer, and Gendt, 1998). The IGS/Bureau International des Poids et Mesures (IGS/BIPM) pilot project (Ray, 1999) aims at taking advantage of the IGS receivers, which are driven by very stable atomic standards, to enlarge the network of Time Laboratories contributing to the realization of the International Atomic Time (TAI). However, the requirements for geodesy and time transfer applications are different, so that the potentials of geodetic GPS receivers must first be investigated. Some receivers have obvious drawbacks for time trans-
fer applications. For example, the receivers used in this study (Rogue SNR-8000 and Rogue SNR-12 RM) systematically reset their clock after each tracking interruption, even if they are driven by a stable atomic standard, causing discontinuities in the estimated clock differences. This problem is very familiar to the IGS community and will not be discussed in the present article.

The Royal Observatory of Belgium (ROB) is one of the few time laboratories that contributes to TAI and also has a collocated GPS station contributing to the IGS network. Three Cesium clocks and two hydrogen masers are in operation and continuously monitored at the ROB. Given the collocation of the atomic clocks and our hydrogen maser–driven IGS receiver, our station is perfectly suited to participate in the IGS/BIPM project. Although the quality of the data from our IGS station has been confirmed previously through geodetic applications (Bruyninx et al., 1997), we show here the improvements to be done to participate in a time transfer network.

A first part of this article is devoted to a theoretical outline on the use of GPS code and phase data for time and frequency transfer. We then describe some tests we conducted to evaluate the quality of the data delivered by a geodetic IGS receiver in relation to the IGS/BIPM project. We also investigate different types of experiments, zero baseline or short baseline using common or different frequency references, which allow us to identify the contribution of each hardware component in the system (receiver, antenna, cable, clock) to the frequency transfer determination. We determine, in each case, the potential frequency stability from the modified Allan variances. Note that all results were obtained on zero or short baselines and that the statistics are optimistic compared to results for long baselines where the ionosphere needs to be eliminated using the ionospheric–free combination of both carriers, which is at least 3 times noisier than the original L_1 carrier phase.

**PRINCIPLE OF TIME AND FREQUENCY TRANSFER USING GPS CODES AND CARRIER PHASES**

In this section, we describe the basic quantities used for time and frequency transfer, which are the so-called code and phase residuals. We detail how these quantities may be manipulated to yield the synchronization errors between external clocks, and we point out the error sources.

**Modeling**

**Code observables**

The GPS code observable $R_p^i$ (signal emitted by satellite $i$ and observed by a receiver $p$) can be modeled as

$$R_p^i(l) = c\tau_p^i + c(dt_p^i - dt^i) + \varepsilon_R$$

(1)

where $dt_p^i$ and $dt^i$ are respectively the receiver and satellite clock offsets with respect to GPS time, $c$ is the speed of light, and $\varepsilon_R$ is the measurement noise. The code travel time $\tau_p^i$ can be written as

$$\tau_p^i = \frac{d_p^i}{c} + \delta_k + \delta_R + T^i_p + T^i_p + \frac{\delta M_p^i}{c}$$

(2)

where $d_p^i$ is the geometric distance the signal traveled from the satellite antenna location (at signal emission time) to the receiver antenna location (at signal reception time). $T_p^i$ and $T_p^i$ are respectively the ionospheric and tropospheric delays; $\delta_k$ and $\delta_R$ are the receiver and satellite hardware group delays. $\delta_R$ includes the effect of the delays within the antenna, the cable connecting it to the receiver, and the receiver itself. $\delta M_p^i$ is the code error due to multipath, expressed in units of length.

The single difference code observable $R_{pq}^i$ is the difference between code observables simultaneously measured at two receivers (called $p$ and $q$):

$$R_{pq}^i = \rho_{pq}^i + cdt_{pq} + c(T_{pq}^i + T_{pq}^i) + \delta_{pq} + \delta M_{pq}^i + e_{pq}$$

(3)

In Equation (3), the tropospheric and ionospheric perturbations $T_{pq}^i$ and $T_{pq}^i$ can be modeled or eliminated (depending on the distance between receivers), and the range $\rho_{pq}^i$ is known from the known satellite and receiver positions. Removing these terms from $R_{pq}^i$ yields the code residual

$$\Delta R_{pq}^i = R_{pq}^i - \rho_{pq}^i - c(T_{pq}^i + T_{pq}^i)$$

$$= cdt_{pq} + \delta_{pq} + \delta M_{pq}^i + e_{pq}$$

(4)

where $e_{pq}$ includes the modeling errors in $\rho_{pq}^i$, $T_p^i$, and $T_p^i$.

**Carrier phase observables**

For both the L_1 and L_2 GPS carrier waves, the phase observable $\Phi_p^i$ (expressed in range units) can be modeled as