GPS-over-fiber architecture with relative cable delay monitoring for high precision GPS applications

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BIOGRAPHY

Daniel Macias-Valadez received a bachelor degree in Electronic and Telecommunications Engineering from the Instituto Tecnológico y de Estudios Superiores de Monterrey in Mexico City in 1997 and a M.Sc. degree in Geomatics Sciences from Université Laval in Quebec City in 2006. He has 6 year experience in Microwave Engineering at Nec de México. He is currently a PhD student in both Geomatics and Electrical Engineering departments of Université Laval. His research interests include GNSS high precision applications and radio-over-fiber applications.

Rock Santerre is a full professor of Geodesy and GPS in the Department of Geomatics Sciences and a member of the Centre for Research in Geomatics at Université Laval. He is also the director of the bachelor’s degree program in geomatics engineering at this University. He received a bachelor and a M.Sc. degrees in Surveying Engineering from Université Laval in 1981 and 1984, respectively. He also worked as a GPS research assistant at UNB then he obtained his Ph.D. degree (Surveying Engineering) at this university in 1989. Since 1983, his research activities have been mainly related to high precision GPS for static and kinematic positioning. Dr. Santerre is author and coauthor of more than 150 publications and he holds three patents related to GPS equipment.

Sophie LaRochelle received a Bachelor's degree in engineering physics from Université Laval, Canada, in 1987; and a Ph.D. degree in optics from the University of Arizona, USA, in 1992. From 1992 to 1996, she was a Research Scientist at the Defense Research and Development Canada - Valcartier, where she worked on electro-optical systems. She is now a professor at the Department of Electrical and Computer Engineering, Université Laval, where she holds the Canada Research Chair in Optical Fibre Communications and Components. Her current research activities are focused on active and passive fiber optics components for optical communication systems including fiber Bragg gratings, optical amplifiers, multi-wavelength and pulsed fiber lasers. Other research interests include packet-switched networks with photonic code processing and transmission of radio-over-fiber.

René Jr. Landry received a PhD degree at SupAero / Paul-Sabatier University and a Post Doc in Space Science at the Centre National d’Etudes Spatiales (CNES), both at Toulouse, France, in 1997 and 1998 respectively. Since 1999, Professor Landry is involved in receiver design and robust navigation in severe environment for the Canadian Navigation and Communication Industries. One of his major interest concerns the development of new innovative mitigation techniques for GNSS receiver robustness design including those of electronic Inertial Navigation System based on low cost MEMS. He is actually working on several digital signal processing applications in high resolution navigation, receiver design, indoor navigation and inertial navigation systems.

ABSTRACT

We propose a novel multi-antenna to one receiver GPS-over-fiber architecture with real-time relative hardware delay monitoring. The purpose of this architecture is to perform receiver single difference observation processing without having to deal with a relative receiver clock error parameter and thus to achieve millimetric vertical precision for short baselines. Indeed, past simulations have already shown that a 2 to 3 factor improvement in vertical precision is expected if relative receiver clock error is eliminated in single difference processing and if the relative receiver hardware delay is monitored at millimeter-level precision.

In this paper, the proposed GPS-over-fiber setup is first presented and explained. Then, the results of the experiments to test the GPS-over-fiber performance and the relative delay monitoring system are presented. Finally, the calibration procedure and GPS observation processing methodology are described.

Results show that with proper oscillators' synchronization in the RF front-end, signal-to-noise degradation by the opto-electrical circuit can be kept below 2 dB with no significant effect on positioning accuracy. At the same time, the proposed relative delay monitoring system can track the relative delay variations at millimeter-level. The complete system is still under development.

INTRODUCTION

In standard GPS positioning applications, it is not possible to get the same precision for the vertical component as for the horizontal components. Experiments and simulations show that the vertical component is 2 to 3 times less precise than the horizontal components. As it is already well known, both the homogeneity of the satellite sky distribution and the systematic errors in the observations can explain this difference. Indeed, since GPS satellite sky distribution can never be homogenous on the vertical component, as there are no visible satellites under the horizon, systematic errors on the pseudorange and phase observations propagate more adversely on the vertical component than on the horizontal components (Santerre 1991). This is why errors such as tropospheric delays and receiver clock errors mostly affect the vertical component precision. For small baselines (up to a few kilometers), in which relative ionospheric and tropospheric errors can be accurately modeled, the relative receiver clock error remains the main limiting factor in the vertical component precision. This relative receiver clock error parameter must be estimated in a least-square adjustment, either explicitly for single difference between receivers processing, or implicitly for double differences processing. However, this clock parameter remains highly correlated with the vertical baseline component and thus limits its precision.

To deal with this problem, a special GPS architecture was proposed in (Santerre & Beutler, 1993), in which all the antennas are connected to a single GPS receiver. Along with a careful calibration of the relative delay between the antenna cables, receiver clock errors can be eliminated by single differentiation between antennas. Through simulations, it was shown that this configuration would lead to a two to three times improvement in the precision of the vertical component determination (Santerre & Beutler, 1993). With this improvement, one could reach millimetric vertical precision for baselines of up to a few kilometers. This breakthrough implies that applications where 3D millimetric positioning precision is needed, such as deformation monitoring of civil engineering structures, for example dams or bridges, could use GPS technology with all its benefits: autonomy, continuous operation and lower cost on the long term. However, to implement a GPS architecture based on this principle, two main issues must be resolved to successfully implement this multi-antenna-to-one-receiver system. First, the distance between the antennas and the single receiver can reach several kilometers. Second, height precision improvement can only be reached if the relative propagation delay between the antennas and the receiver is monitored at the millimeter-level. By using "GPS-over-fiber" solutions, we can address the first issue but existing commercial solutions do not include real-time monitoring of these relative propagation delays. Additionally, phase stability is very important for high precision applications that must use GPS carrier phase measurements, so additional noise added by the optical components must be minimized and controlled.

PROPOSED ARCHITECTURE FOR GPS-OVER-FIBER AND RELATIVE DELAY MEASUREMENTS

Generally, existing GPS-over-fiber solutions consist of 2 devices, one for electrical-to-optical conversion at the antenna side (remote-station) and one for the optical-to-electrical conversion at the receiver side (local-station) with an optical fiber between them. At the remote-station, as the received GPS signal is very weak, some conditioning of the signal must be done. Two kinds of approaches are generally used: 1) amplify the received RF signal enough to modulate an optical source (RF-over-fiber) or 2) amplify and downconvert the signal to an intermediate frequency (IF) prior to modulation of an optical source (IF-over-fiber). Both approaches have their advantages and disadvantages. In the first case, the main advantage is that the remote-station circuitry is simpler as no external oscillator is needed. However, amplifiers, optical modulators and optical sources working at RF are more expensive and the system is more sensitive to dispersion in the fiber. In the second case, the main disadvantage is the use of additional external oscillators but, as will be explained shortly, this can turn into an advantage if these oscillators are used to monitor the relative delay.

If each remote-station has its own external oscillator to downconvert the RF signal, this introduces a different oscillator reference to each received signal and thus a relative clock error that will not be eliminated by single differentiation between antennas. As pointed out previously, it is very important that a common oscillator and clock reference is used in all the system. A proposed solution is to send a common reference oscillator generated at the receiver (local-station) to all remote-stations. This reference oscillator will then be used to downconvert the RF signals to IF. This adds some complexity to the system, which now would be bidirectional, and one would be tempted to rather stick to the RF-over-fiber solution. However, with a refinement of this kind of configuration, the real-time relative propagation monitoring can be realized. Indeed, the reference oscillator would be used, not only for the IF downconverting but also as a reference signal to measure the relative propagation time between each path that goes from the local-station to each remote-station. The signal is split at the local-station and makes a round-trip to each remote-station before their relative phase is compared.

In Figure 1, the proposed architecture is shown (Macias-Valadez, et al. 2009) (US61/162,320, US provisional patent). At the local station, where the receiver is located, a 1.5 GHz oscillator is generated and modulates a laser diode. The optical signal is then sent through optical fibers to the remote stations, where the antennas and the RF front-end are located. The 1.5 GHz signal is converted back to electrical and used by the first stage to downconvert the received GPS RF signal to IF. This GPS-IF signal modulates the optical carrier sent by the local station through direct modulation of a semiconductor optical amplifier (SOA) acting as an external optical modulator. The optical carrier, with both GPS-IF and RF carrier modulations, is sent back to the local station through a second optical fiber. On the receiver side, the signal is converted back to electrical and the 1.5 GHz and the GPS-IF signal are separated. The 1.5 GHz signal, which made a round-trip to each remote station, is used to estimate the relative delay associated to each remote station (Mechels, Schlager and Franzen 1997) whereas all the GPS-IF signals are fed to the GPS receiver.

PERFORMANCE OPTIMIZATION OF THE ELECTRO-OPTIC CIRCUIT

Before deploying the whole setup, the proper choice of components and their operation points have to be controlled. For the optical components, choice was primarily made based on performance but also on cost issue. With RF signals in the GHz range to be carried on a few kilometers of fiber, monomode fiber was preferred over multimode fiber, normally used for smaller bandwidths and distances. Also, for monomode fibers and GHz bandwidth, laser sources are needed. A directly modulated Distributed FeedBack (DFB) laser in the standard 1550 nm band was used. The choice of the external modulator was less straightforward, having considered the use of acousto-optic modulators, Mach-Zehnder (MZ) modulators and Semiconductor Optical Amplifiers (SOA). Acousto-optic modulators are more limited in bandwidth. MZ and SOA have similar performance and cost for our particular configuration but SOA had the benefit of less sensitivity to light polarization. This was a major concern because, after propagation through several kilometers of deployed fiber, the received polarization state is unknown unless polarization maintaining fibers are used. In this system, we are proposing the use of the less expensive standard single-mode fiber. Regarding performance, we were concerned principally about the degradation of the GPS

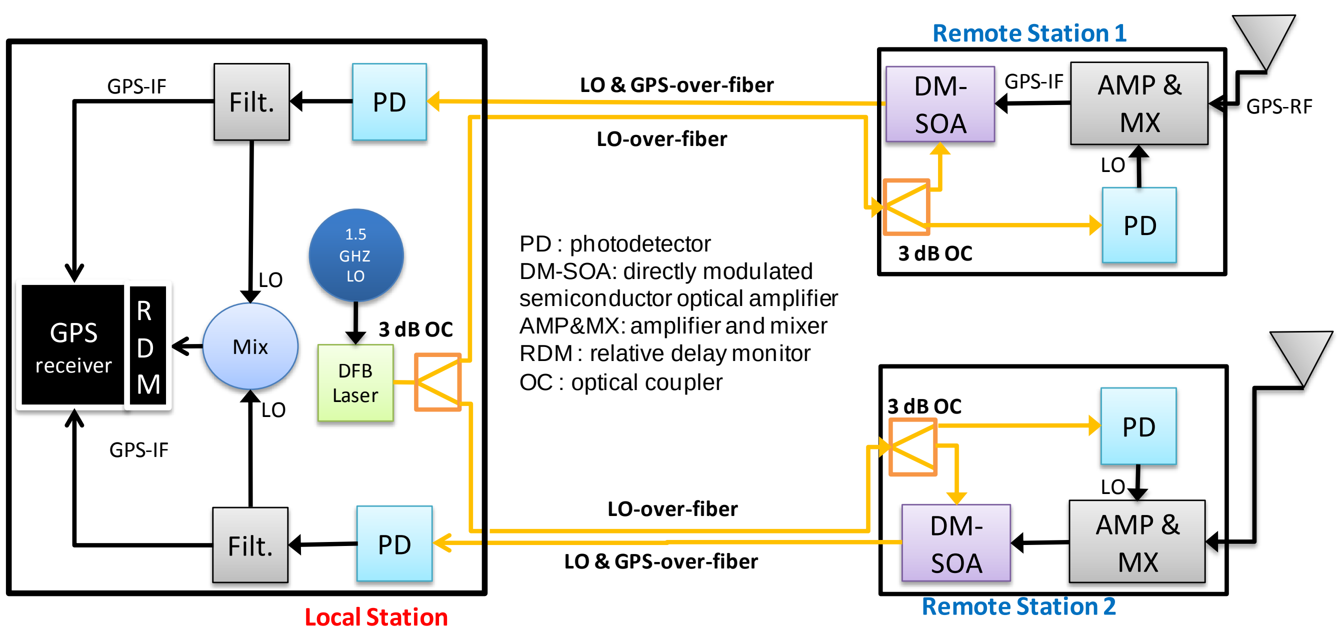

Figure 1 Proposed GPS-over-fiber architecture

signal after optical conversion and transport on optical fiber and about the capacity of the system to effectively measure the relative propagation delay at millimeter-level. The next sections will deal with the performance evaluation of the system.

Performance evaluation using Carrier-to-Noise Ratio (CNR) measurements

To quantify the signal degradation and since we are dealing with analog (RF/IF) signals, we measured the Carrier-to-Noise-Ratio and the third order intermodulation distortion (IMD3) after the electrical-to-optical conversion, optical transport and optical-to-electrical conversion. Since the Semiconductor Optical Amplifier (SOA) is the device that adds the most noise, the two main controlled parameters were the input DC current (I_{SOA}) and the optical input power at the SOA (P_{SOA}). These parameters were adjusted in order to find the optimum operation points of the optical devices, i.e. where added noise and distortion are minimal. On the other hand, since the optical fiber transports two signals, the GPS signal and the oscillator, cross-talk effects may arise, so we also controlled the oscillator power to check for cross-talk effects that could degrade the CNR. The first two experiments, experiment 1 and 2, were done using a carrier at the GPS-IF frequency (15 MHz). The experimental configuration is shown on Figure 2.

Results of these experiments are shown on Figure 3 to Figure 5. As can be seen on Figure 3, maximum CNR is reached when the SOA operates at saturation, that is, for maximum optical input power. This result agrees with the results found by (Vacondio, et al. 2006), who proposed the use of SOA's as external modulators. Additionally, operation at saturation minimizes cross-talk interference. For instance, at $P_{SOA} = -14$ dBm, CNR degrades by as much as 15 dB if the input RF oscillator power (P_{osc}) is 15 dBm. At $P_{SOA} = -1$ dBm, CNR does not degrade by cross-talk. On the other hand, looking at Figure 4, CNR is higher for input current at SOA below 300 mA. Regarding IMD3, as shown on Figure 5, maximum value is reached for I_{SOA} = 300 mA. With these results, we can see that the optimal operation points of the SOA is near optical saturation (0 dBm) and at I_{SOA}=300 mA.

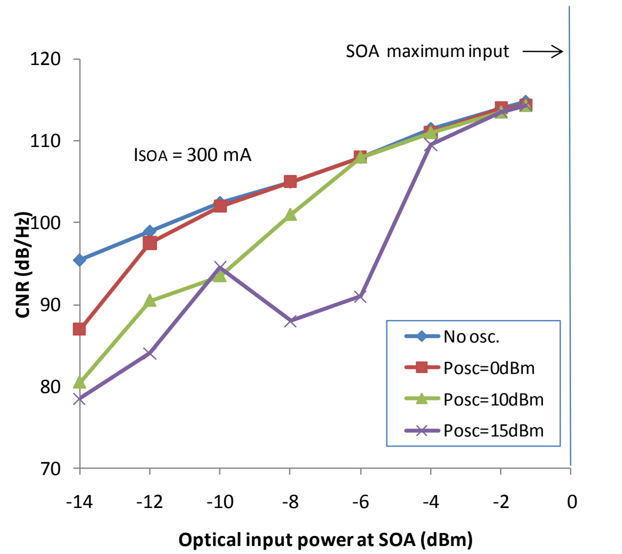

Figure 3 CNR as a function of optical input power at SOA

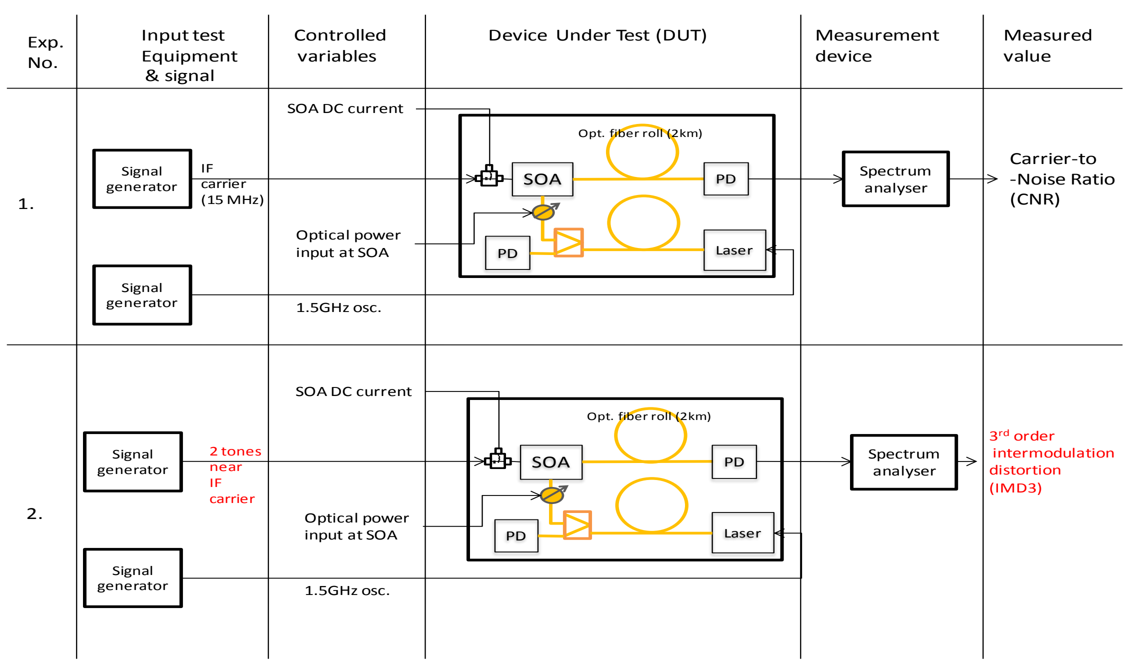

Figure 2 Setup for experiments 1 and 2, using a IF carrier instead of a GPS-IF signal

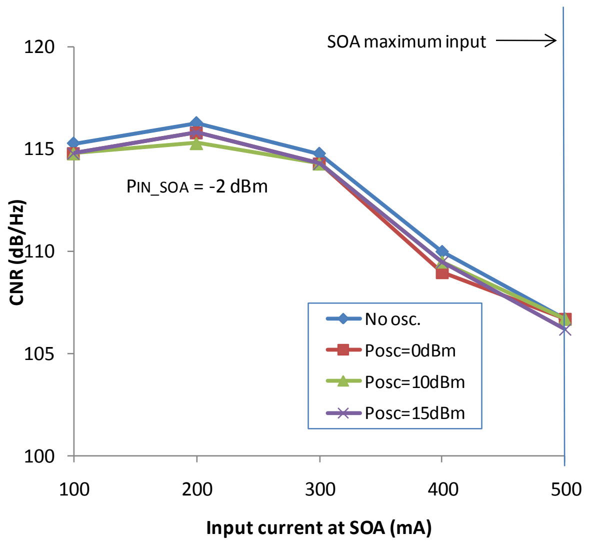

Figure 4 CNR as a function of optical input current at SOA

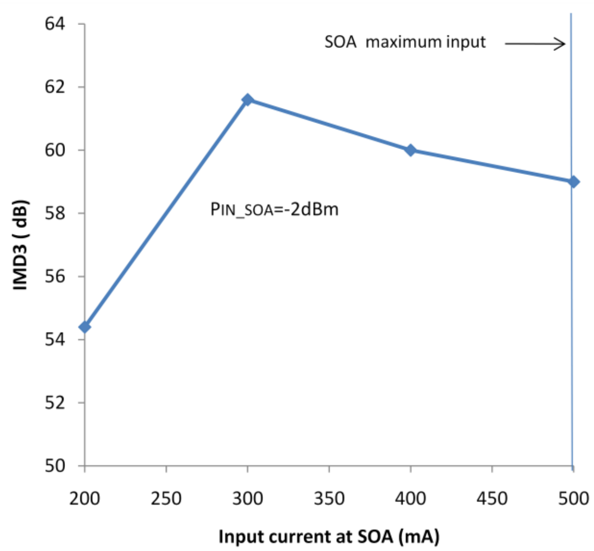

Figure 5 IMD3 as a function of input current at SOA

With the optimal operations points chosen, experiments with a simulated and a real GPS signal were done. Setup of these experiments is shown on Figure 7.

For experiments 3 and 4, as the reference signal is not a carrier but a spread-spectrum GPS signal, the CNR is calculated by comparing the correlation peak power after signal de-spreading as it is done on standard GPS receivers. Also, comparison was made with a reference CNR value corresponding to the case where the Device Under Test (DUT) was removed. For experiment 3, the signal generator provides a Pseudo-Random sequence of one of the GPS satellites modulated onto an IF carrier. This signal is buried 20 dB under white noise as would be the case for a real GPS signal. At the receiver end, the signal is captured and sampled by a data acquisition device and signal de-spreading is done by post-processing in a Signal Processing Software. For this experiment, the reference CNR was 47 dB. After testing the DUT, the obtained CNR was 45 dB, thus representing 2 dB degradation.

The experiment 4 uses a Field Programmable Gate Array (FPGA) based GPS single frequency receiver developed by the École de Technologie Supérieure (ÉTS) at Montréal (Sauriol and Landry 2007). This receiver offers great flexibility and geodetic-type performance. The CNR was monitored and compared with the reference case where no DUT is used. Results for the CNR for the visible satellites during 3 hour observation session are shown on Figure 8. As can be seen, the mean CNR deterioration due to the DUT, that is, the optical-electrical circuit, is between 0 and 2 dB. These results confirm what was observed with the simulated GPS signal and show that added noise by the DUT is low. The main purpose of experiment 4 was to evaluate the performance of the GPS-over-fiber circuit. However, in this configuration, the RF front end still uses independent external oscillators instead of the intended 1.5 GHz “oscillator-over-fiber”.

In experiment 5, whose configuration in shown in Figure 6 and Figure 12, the 1.5 GHz “osc-over-fiber” for the RF front end was used. However, in the actual version of the ETS software receiver, the RF front-end is a two-step downconverter which therefore needs 2 oscillators which should be synchronized for better phase locking of the receiver. For experiment 5, an independent 55 MHz oscillator in addition to the 1.5 GHz “osc-over-fiber” was used. Results are shown on Figure 9. As shown on this figure, mean CNR deterioration is worse, reaching up to 6 dB. The lack of synchronization between the two oscillators in the RF front-end is the suspected reason of this increased deterioration. A special oscillator synchronization circuit is currently under development to cope with this problem. This circuit consists of a series of Phase-Lock Loop (PLLs) that take the 1.5 GHz signal to generate a 55 MHz that is in lock with the input signal. The setup that will be used is shown on Figure 6, experiment 6.

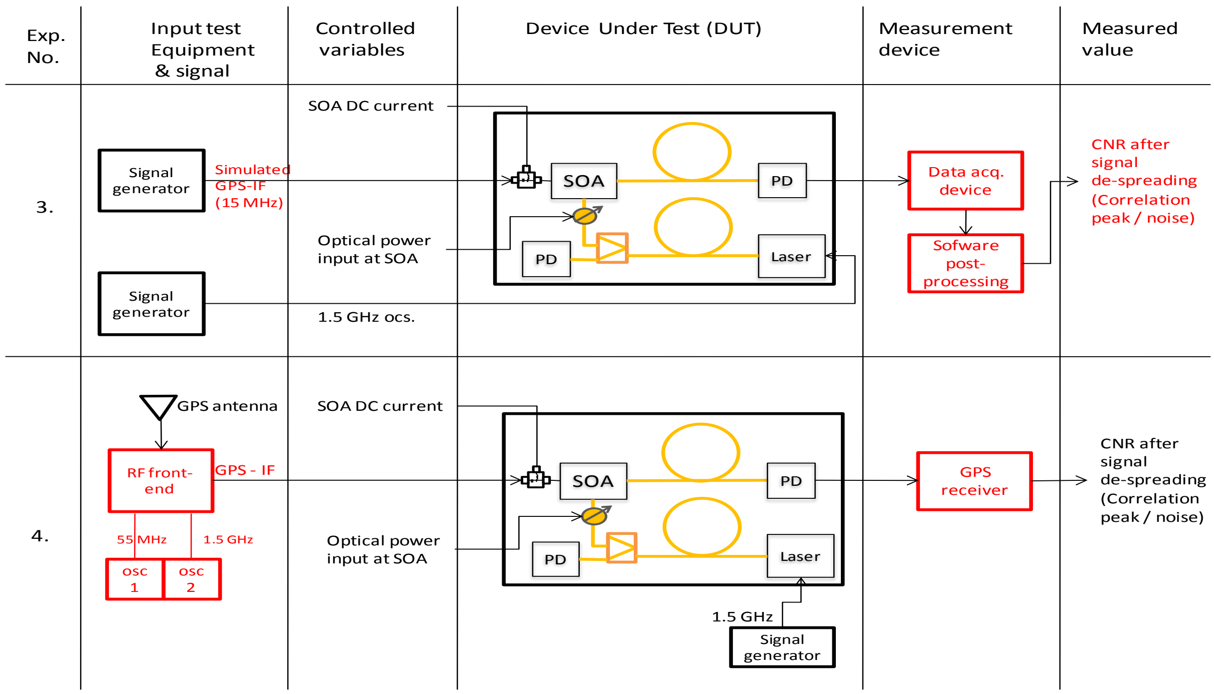

Figure 7 Setup for experiments 3 and 4 to test GPS-over-fiber performance, using a simulated GPS signal and a data acquisition receiver (exp. 3) and a real GPS signal and receiver (exp. 4)

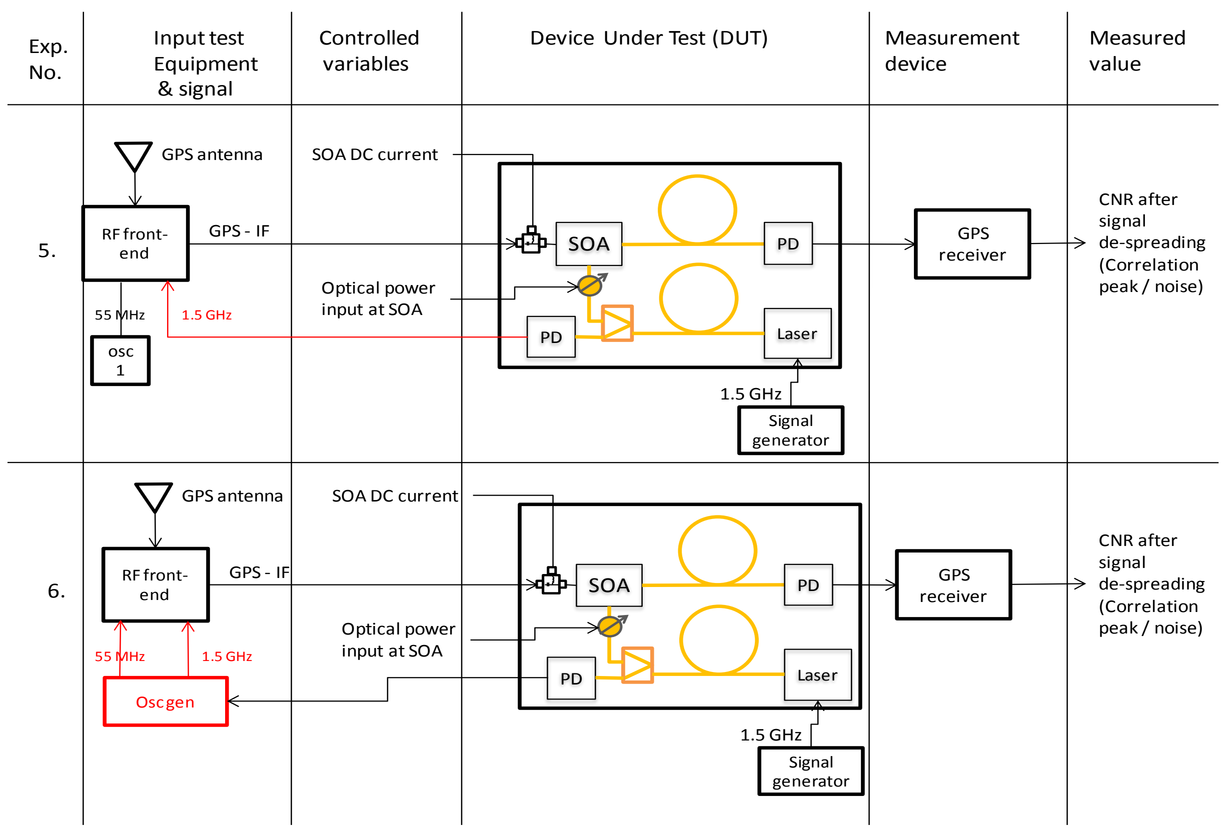

Figure 6 Setup for experiments 5 and 6 to test both GPS-over-fiber and osc-over-fiber

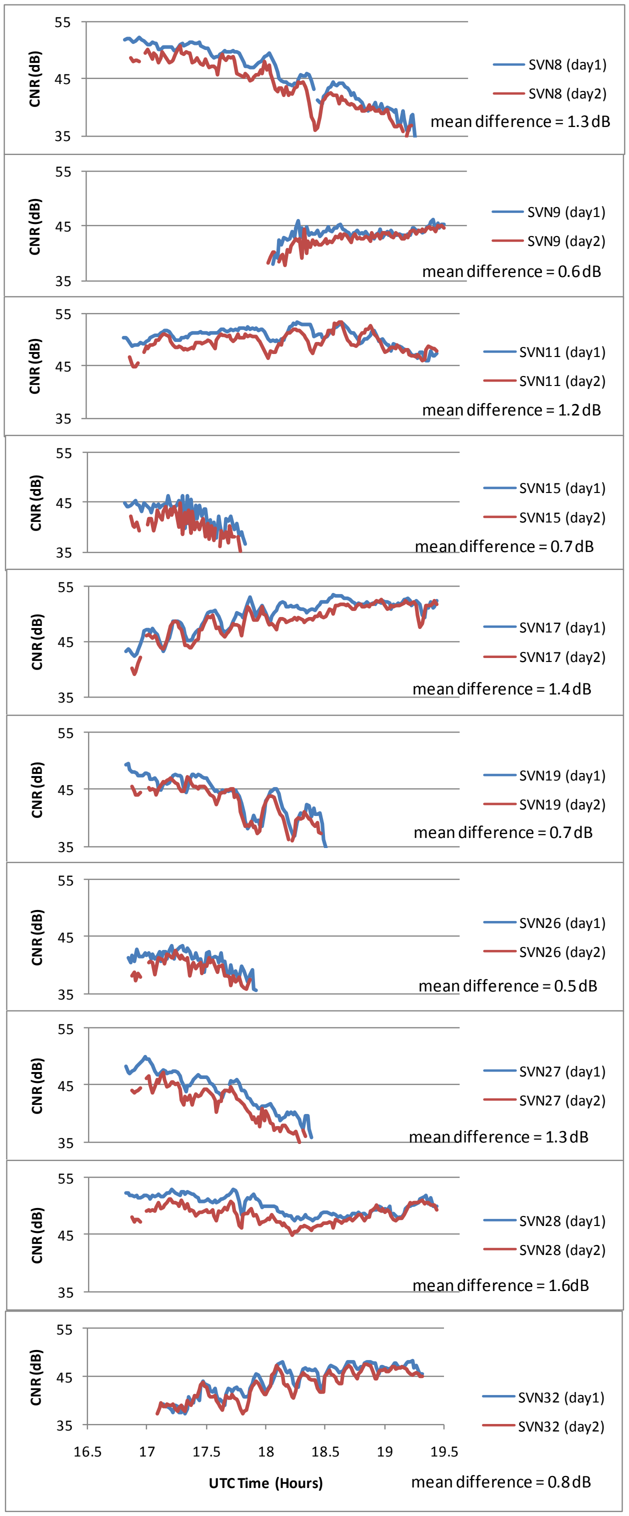

Figure 8 Comparison of CNR for visible satellites between day 1 (without DUT) and day2 (with DUT) for experiment 4. A 4 minute shift was done on day 2 to take into account the 11hr 58 min periodicity of the orbit of the satellites.

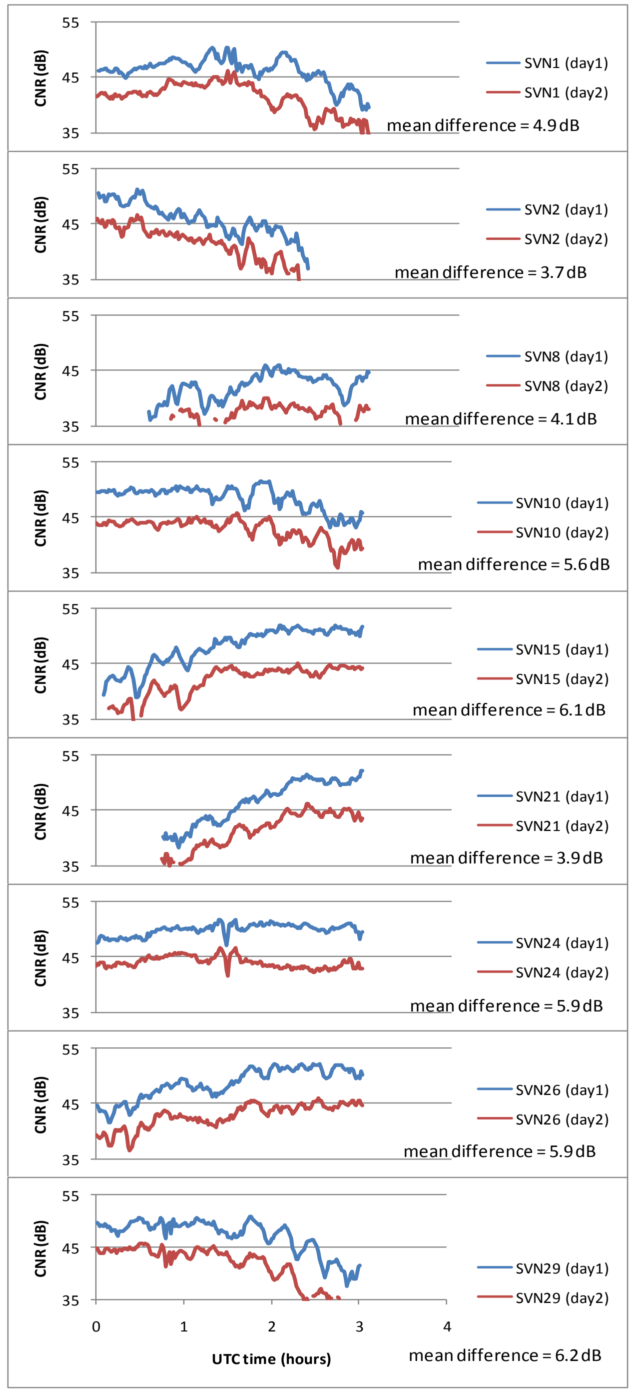

Figure 9 Comparison of CNR for visible satellites between day 1 (without DUT) and day2 (with DUT) for experiment 5. A 4 minute shift was done on day 2 to take into account the 11hr 58 min periodicity of the orbit of the satellites.

Performance evaluation using GPS positioning solutions

By using the same setups used for experiments 4 and 5 Figure 7 and Figure 6), a GPS positioning solution was realized. The purpose, once again, is to see if there is significant degradation in performance by using the DUT. In this case, this was quantified by comparing the 3D baseline components. The FPGA-based GPS receiver was connected to a geodetic Ashtech antenna located on top of the COPL (Centre d'Optique Photonique et Laser) building and the second receiver station was located on top of the PEPS building on the Laval University's campus in Quebec City. The second receiver is a geodetic Ashtech reveiver using a chokering antenna. This 600 m baseline has been established using GPS-over-cable (no DUT) and the GPS-over-fiber configurations. For these preliminary results, standard double difference processing was used since proposed single difference processing is not yet possible until the special oscillator synchronization is ready (experience 6). The difference between experiments 4 and 5 is that in the former, only the GPS signal is carried on fiber whereas is the latter, both the GPS signal and the 1.5 GHz are carried on the optical fiber.

Results for experiment 4 are shown on Figure 11. We can see that CNR deterioration caused by the DUT has practically no impact on the error for the east and north baseline components, this was also true for the case of experiment 5, in which CNR deterioration could reach up to 6 dB. For these components, differences are under 4 mm. However, in the case of experiment 5, for the height component, error increases appreciably, up to 14 mm. The lack of oscillator synchronization in the RF front-end, probably causes this deterioration. We are expecting that configuration of experiment 6 (Figure 8) will help to counter this behavior.

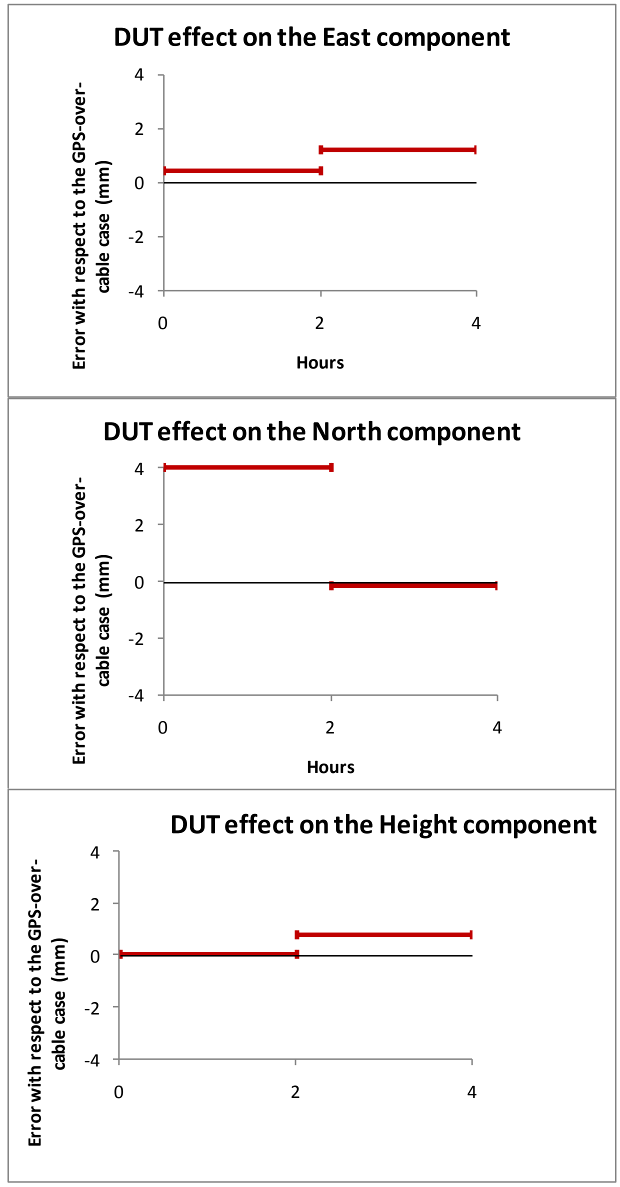

Figure 11 3D positioning error of GPS-over-fiber (with DUT) with respect to GPS-over-cable (without DUT) for experiment 4

Performance evaluation of the relative delay measurement

Another important and crucial part of the project is the real-time monitoring of the relative propagation delay in the optical fibers between the antennas and the receiver. As explained previously, this delay must be monitored at millimeter-level in order to achieve millimetric vertical precision in positioning. To control this, the setup shown on Figure 10 was deployed.

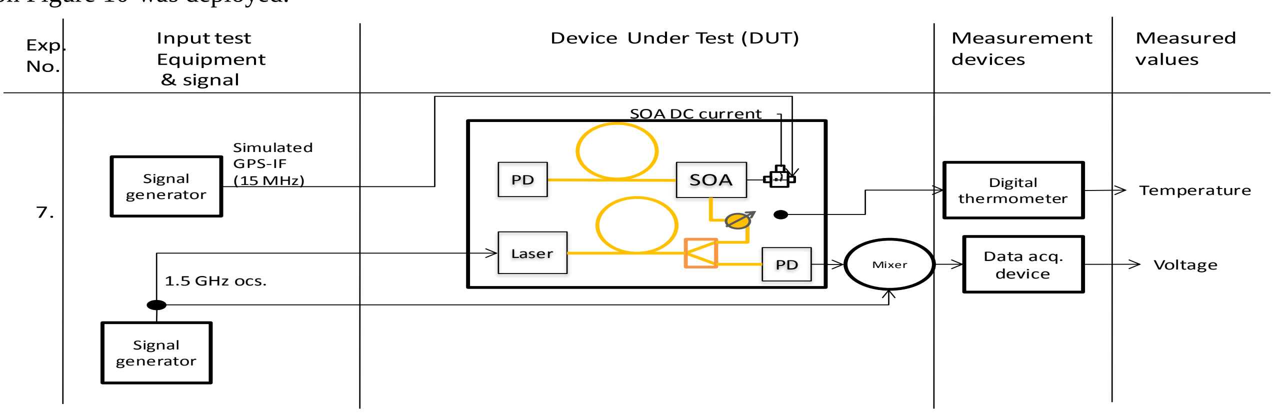

Figure 10 Setup for experiment 7 to test the relative delay monitoting circuit

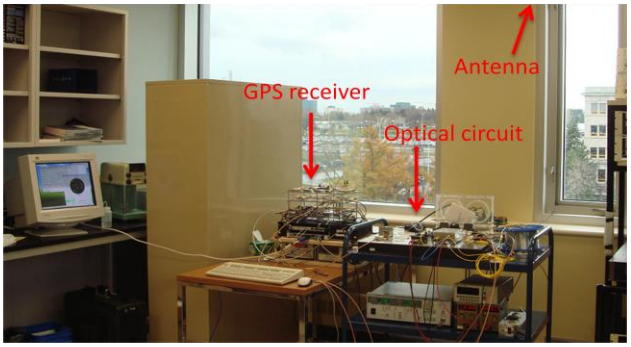

Figure 12 Experimental setup for experiments 4 and 5

The purpose of experiment 7 is to control if the system can "follow" millimetric variations of fiber length that naturally arise due to temperature variations. Indeed, once the final setup will be deployed, as the optical fiber will reach lengths up to a few kilometers, its thermal dilatation or contraction can reach several millimeters. For standard SMF-28 monomode fiber, the thermal coefficient is approximately 5 ppm/°C or 5 mm per km of fiber per degree Celsius. In experiment 7, a roll of 2 km of optical fiber was used so that a variation of only 0.1°C in temperature is roughly equivalent to 1 mm length change. The results of the experiment are shown on Figure 13. It was possible to follow the small millimetric variation of fiber length with the mixer.

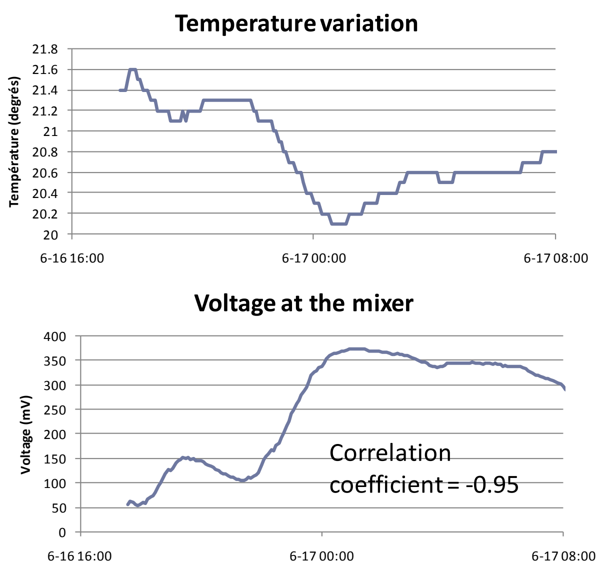

Figure 13 Comparison of temperature variations and voltage at the mixer

DATA PROCESSING AND TOTAL RELATIVE HARDWARE DELAY CALIBRATION

As previously mentioned, to obtain millimetric precision in the vertical component with the multi-antenna-to-one-receiver GPS-over-fiber system, single difference between receivers observations processing and real-time relative propagation delay monitoring are needed. In this section, details will be given regarding the processing of the GPS observations, the integration of the additional measurement of relative delay and the calibrations needed.

The conventional (between-receiver) single difference carrier phase observation equation is:

$$\Delta\Phi^{\mathrm{i}} = \Delta\rho^{\mathrm{i}} + \lambda\Delta N^{i} - \Delta I^{i} + \Delta T^{i} + \Delta d_{hw} + \Delta dt + \Delta\varepsilon$$

Where,

$\Delta\Phi^{\mathrm{i}}$: Single difference carrier phase observable towards satellite i (m)

$\Delta\rho^{\mathrm{i}}$: Geometric range between receiver and satellite i (m)

ΔN^{i} : Initial phase ambiguity (cycles)

ΔI^{i} : Range delay due to ionospheric refraction (m)

ΔT^{i} : Range delay due to tropospheric refraction (m)

Δd_{hw} : Relative hardware delay (includes fibers, coaxial cables and all optical and electronic devices between the antenna and the receiver) (m)

Δdt : Relative receiver clock bias (m)

$\Delta\varepsilon$: Residual noise and other non modeled effects such as multipaths and antenna phase center

With the proposed multi-antenna-one-receiver configuration, the receiver clock term is eliminated:

$$\Delta\Phi^{\mathrm{i}} = \Delta\rho^{\mathrm{i}} + \lambda\Delta N^{i} - \Delta I^{i} + \Delta T^{i} + \Delta d_{hw} + \Delta\varepsilon$$

However, the relative hardware term remains. This is the one that must be carefully calibrated in real-time, the one that was called "relative propagation delay" in the previous section. Let's see into more detail what this term represents and how it is related with the one that is measured by the RDM circuit.

By examining Figure 14, the hardware delay for one remote station may be decomposed in the following way:

$$d_{hw} = d_1 + d_2 + d_3 + phase\ of\ \ (d_a + d_b)$$
$$= d_1 + d_2 + d_3 + (z_a + z_b)$$

Where,

d_1: propagation delay from the antenna to the SOA, passing through the RF front-end

d_2: propagation delay from the SOA to the filter, passing through the optical fiber and the photodetector

d_3: propagation delay from the filter to the receiver

d_4: propagation delay from the filter to the RDM

d_a: propagation delay from the 1.5 GHz oscillator to the 50/50 optical splitter, passing through the laser and the optical fiber

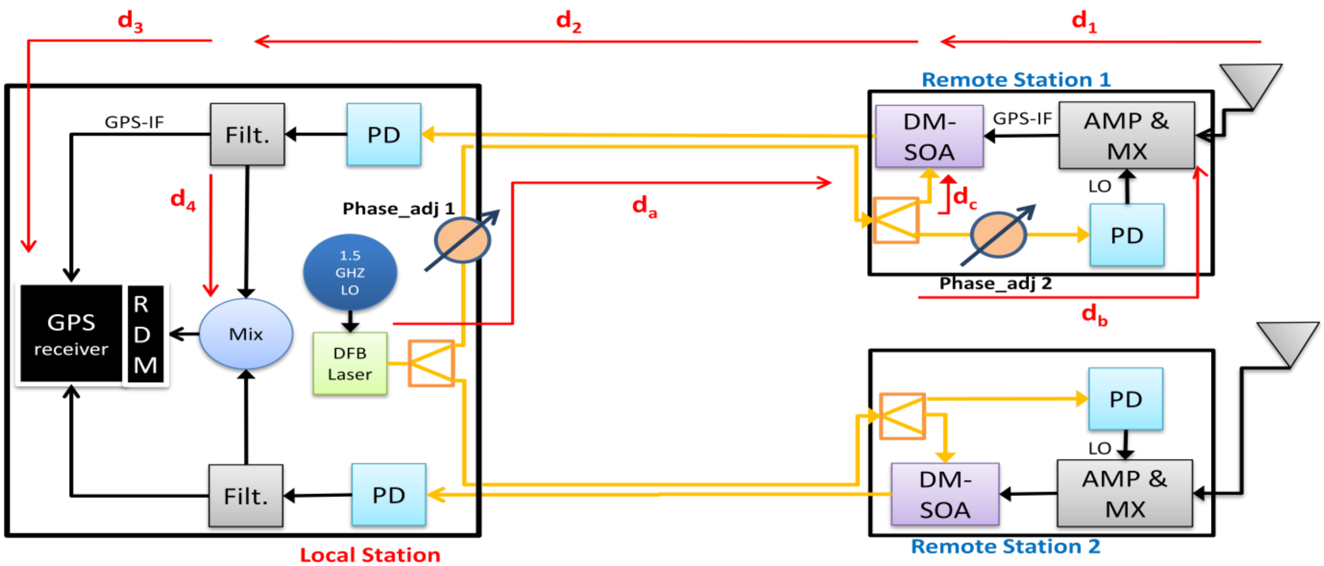

Figure 14 Receiver Hardware delays

d_b: propagation delay from the 50/50 optical splitter, passing through the photodetector, to the RF front-end

d_c: propagation delay from the 50/50 optical splitter to the SOA

z_a: phase of d_a or fractional part of d_a in cycles

z_b: phase of d_b or fractional part of d_b in cycles

N_a: integer part of d_a in cycles

N_b: integer part of d_b in cycles

$d_a = N_a + z_a$

$d_b = N_b + z_b$

The reason of the use of z_a and z_b instead of d_a and d_b is that the mixer at the RF front-end adds the phase of the 1.5 GHz oscillator to the received GPS signal.
The propagation delay to the RDM circuit is different:

$$d_{RDM} = d_a + d_c + d_2 + d_4$$

The difference (in relative mode) is the following:

$$\Delta d_{hw} - \Delta d_{RDM} = \Delta(d_1 + d_3 + d_4 + d_b + d_c - N_a - N_b) = C$$

Our main interest is to estimate Δd_{hw} by measuring Δd_{RDM}. If C is considered as almost constant, that is, with a variation of less than 1 mm, we may consider that Δd_{RDM} will follow Δd_{hw}. This is quite reasonable since segments d_a and d_2, which correspond to the optical fibers, are not included in C. These are the longest ones and the ones that are expected to vary the most, principally due to thermal variations. The N_a term is still present in C but, if we consider that expected optical fiber length variation is much less than one cycle (19 cm for 1.5 GHz signal), it is still reasonable to consider C as a constant. Still, we need to make sure that all the remaining terms of C have low variation. This is why small coaxial cable lengths between antennas, RF front-end and SOA are recommended as well as identical components for all remote stations. Temperature control of remote stations may also be necessary. All these assumptions need to be validated in future work.
To estimate the value for C, a zero baseline configuration is proposed, as shown on Figure 15. In this figure, two new devices, named *phase_adj1* and *phase_adj2*, are shown. These are variable optical delay lines which can adjust at sub-millimeter scale the fiber length. Their use will be explained later.

For a zero baseline, the phase observation equation is the following:

$$\Delta\Phi^{i} = \Delta d_{hw} + \Delta\varepsilon = \Delta N_{hw} + \Delta z_{hw} + \Delta\varepsilon$$

Where,

ΔN_{hw}: hardware delay ambiguity (integer number of cycles)

Δz_{hw}: fractional part of the hardware delay

Thus, by taking single differences on a zero baseline, the hardware delay is obtained but with an ambiguity and residual noise. Since there is one observation per observed satellite, we have different estimations for the hardware delay. To have a better understanding, let us separate in two parts the Δz_{hw} term: one common part that corresponds to the hardware delay between the antenna and the common input at the receiver and one part that corresponds to the delay inside each channel of the receiver:

$$z_{hw} = \overline{z_{hw}} + z_{ch\_j}$$

Or, in relative mode :

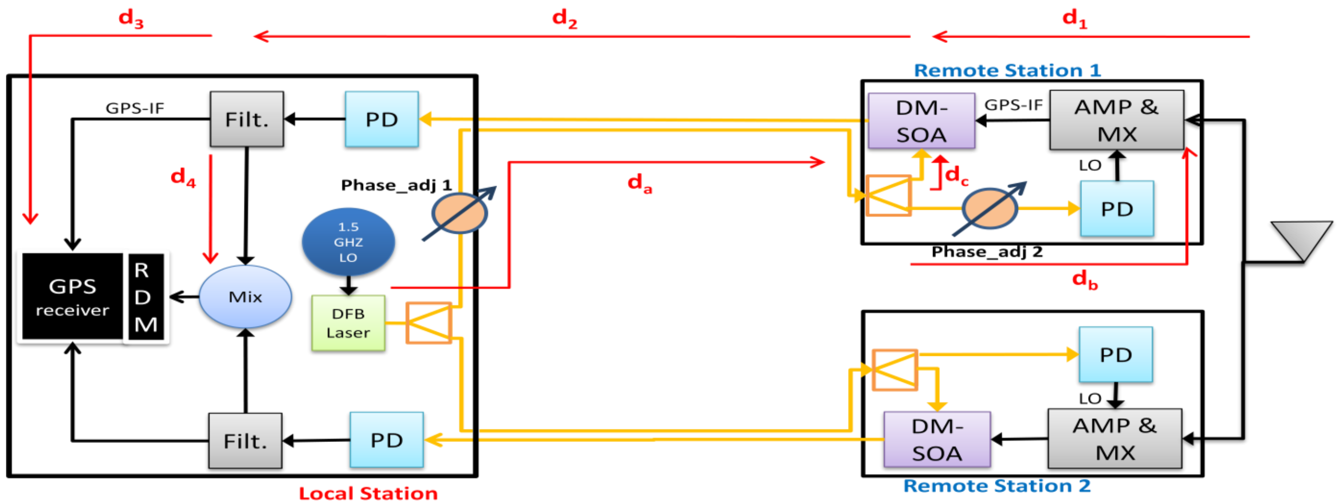

Figure 15 Zero baseline configuration

$$\Delta z_{hw} = \Delta\overline{z_{hw}} + \Delta_{jk} z_{ch}$$

Where,

$\overline{z_{hw}}$: fractional hardware delay common to all channels of the receiver

Δ_{jk} : Difference operator between channel j and channel k

z_{ch} : inter-channel delay

For example, in a hypothetical case, if we have 4 satellites (1 to 4) and that the channel number corresponds to the satellite number, the observation equations for a zero baseline are the following:

$$\begin{pmatrix} \mathcal{Z}\{\Delta\Phi^1\} = \Delta\overline{z_{hw}} + \Delta_{11} z_{ch} + \Delta\varepsilon^1 \\ \mathcal{Z}\{\Delta\Phi^2\} = \Delta\overline{z_{hw}} + \Delta_{22} z_{ch} + \Delta\varepsilon^2 \\ \mathcal{Z}\{\Delta\Phi^3\} = \Delta\overline{z_{hw}} + \Delta_{33} z_{ch} + \Delta\varepsilon^3 \\ \mathcal{Z}\{\Delta\Phi^4\} = \Delta\overline{z_{hw}} + \Delta_{44} z_{ch} + \Delta\varepsilon^4 \end{pmatrix}$$

Where,

$\mathcal{Z}$ is the fractional part operator.

The number of equations is not enough to resolve for $\Delta\overline{z_{hw}}$ and each of the inter-channel delays. Additionally, there is the residual noise $\Delta\varepsilon$. However, we can make the following approximations:

$\Delta\overline{z_{hw}} \gg \Delta_{jk} z_{ch}$ and $\mathbb{E}\{\Delta\varepsilon_i\} = 0$

Where $\mathbb{E}$ is the expectation or mean value operator.

The first approximation considers the inter-channel delay negligible compared to the common delay. The second one considers the residual noise as white. With these approximations, we can consider:

$$\Delta\overline{z_{hw}} \approx \mathbb{E}\left\{\mathcal{Z}\{\Delta\Phi^i\}\right\} = \frac{\sum_{i=1}^{n} \mathcal{Z}\{\Delta\Phi^i\}}{n}$$

Where n is the number of observed satellites.

Thus, using single difference phase observations, taking the fractional part and making an average, we get the fractional part of the relative hardware delay. This observable ($\Delta\overline{z_{hw}}$), along with a rough estimation, within one L1 cycle, of the fiber length difference between the two fibers (ΔN_{hw}), is the one that will be used as an additional observable in the GPS processing software. Initially, *phase_adj1* and *phase_adj2* are to be adjusted so that $C = \Delta z_{hw} = \Delta z_{RDM} = 0$.

The following steps are necessary for calibration with the zero baseline configuration and GPS data processing.

A new GPS processing software using single difference processing is being adapted based on the one developed by (Santerre and Lamoureux 1997). Additionally, this software will use the additional observable from the RDM device. The processing in this software will have the flexibility to offer variable observations' accumulation period so that a new position is computed at every epoch or after *n* epochs. This type of solution is used as the intended movements of monitored engineering structures are relatively slow. The processing steps are shown on Figure 16.

CONCLUSION AND FUTURE WORK

The proposed GPS-over-fiber architecture is intended to perform simultaneous GPS antenna remoting over optical fiber and real-time calibration of the relative propagation delay. Each of these two functions was tested and optimized to minimize their impact on each other and maintain the GPS signal integrity. Results show that this can be achieved by carefully selecting the operation points and power levels of the devices. Indeed, added noise by the opto-electrical circuit is below 2 dB for the GPS-over-fiber case and the 3D position error is below 4 mm for each component when compared to the traditional GPS-over-cable approach. For these preliminary results the data was still process in double difference. However, for the preliminary tests, if osc-over-fiber is added, the lack of oscillators' synchronization in the RF front end affects negatively the baseline components.

Work is still done to solve issues with the oscillators' synchronization for the RF front-end. Once the whole architecture is completed, a small (1m) calibration beam whose 3D components are known at submillimeter-level and on which controlled, millimetrical, vertical displacements can be made (Santerre and Lamoureux 1997), will be used as a reference baseline. Also, a complete calibration and a modified GPS data processing procedure will be necessary. With this setup, it will be possible to prove that the proposed architecture can achieve vertical millimetric precision, which is the main objective of this project.

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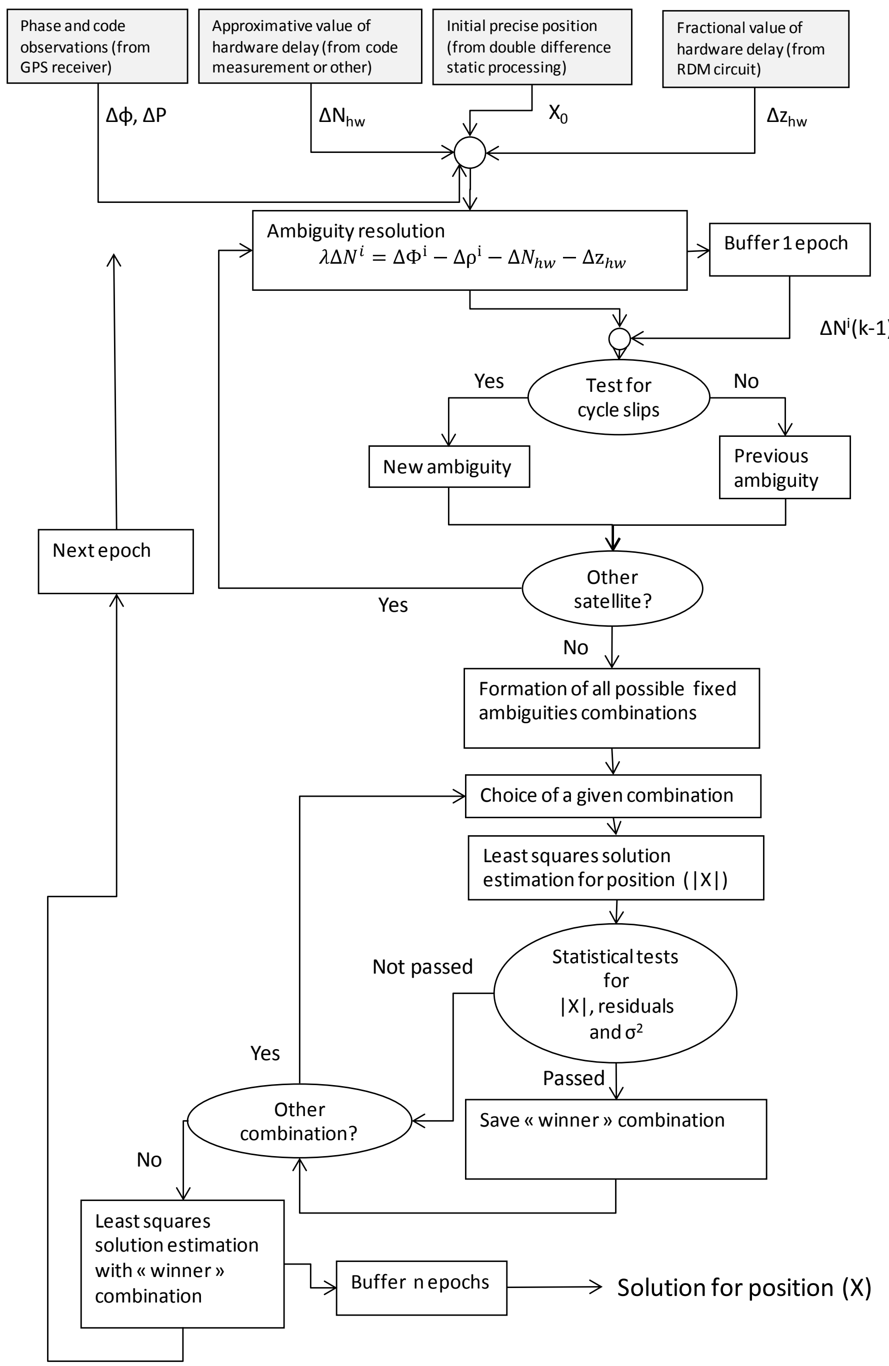

Figure 16 Flux diagram of the developed GPS processing software

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