Optical and Radio Calibration of the Repealite Based Indoor Positioning System

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***Abstract*— In order to achieve indoor positioning, and hence a real continuity of the positioning service in all environments, we proposed a new pseudolite-based system: the repealites. A single GNSS-like signal is transmitted from all the repealites (typically 4 for 3D positioning): this approach simplifies both the synchronization process (between transmitters) and the indoor interferences between pseudolites. In addition, in order to avoid intentional artificial multipath, the signals from two repealites are shifted in time by a few chips.**

The time shifts and the links from the central command and electronic control centre (where the signal is generated) and repealites are carried out with optical fibers in order to reduce size and power losses. There is therefore a need to calibrate the various induced delays (time shifts and links).

Two methods are fully described in the paper. The first one will serve as a reference and is based on optical measurements: the basic idea is to transmit low frequency radio signals over the fiber, of a few hundreds of kHz typically, depending on the length one has to measure, and to carry out differences of phase measurements. This leads to length determination accuracies in the range of a few centimeters for up to 1200 meters of fiber. The second method described is based on the auto-correlation function (ACF) of the composite signal received at a GNSS receiver's end. The principle is to connect the radio outputs of the repealites directly to a combiner being connected to the receiver. In such a case, the ACF has a number of main peaks corresponding to the number of repealites and the measurements of the distances between peaks give the corresponding time shifts.

The comparisons between the two methods lead to both reference and receiver uncertainties concerning the proposed repealite based approach.

Continuity of positioning, Indoor positioning, Pseudolites, Repealites, Calibration.

I. INTRODUCTION

In order to simplify and to provide a better positioning accuracy to the proposed repealite based system, there is the need to calibrate the delays, and hence the lengths, of the optical fibers used to introduce the time shifts between the transmitters (called repealites). Many methods can be imagined for this calibration phase: we choose to compare two of them. The first approach is based on the measurement of the transmission delay of a radio signal over the fiber and the second one uses the correlators of a GNSS receiver. Close, but different, results have been obtained.

After a brief presentation of the system (II), this paper describes the optical (III) and the GNSS based (IV) approaches. The following chapter (V) carries out a comparison between the two methods

II. BRIEF DESCRIPTION OF THE INDOOR SYSTEM

The continuity of the positioning service, mainly achieved outdoors with satellite navigation systems, is a fundamental aspect for the development of location based applications and services. Indoors, many techniques are proposed but no definitive answers have yet been given. Our proposition for indoor positioning is a new pseudolite-based system: the repealites. A single GNSS-like signal is transmitted from all the repealites (typically 4 for 3D positioning) in order to simplify both the synchronization process (between transmitters) and the interferences between repealites. In addition, in order to avoid intentional multipath, the signals from different repealites are shifted in time by a few microseconds. The main advantage of using a GNSS approach is the very high sensitivity of the receivers, allowing a typical range of several tens of meters to be reached with a reduced transmitted power.

The original idea of using pseudolites in order to achieve indoor positioning is based on the concept of a local constellation. In other words, the principle is to create a constellation of transmitters of GNSS signals in a similar way to how it works outdoors with satellites. Thus, each pseudolite transmits its own signal. The main advantage of this approach is clearly the similarity with outdoor GNSS and the possibility to implement almost all the techniques with minor modifications. Another approach using GNSS repeaters was designed in order to simplify the well-known problem of near-far by implementing time division transmissions. Unfortunately, this sequential approach is, in most cases, incompatible with carrier phase measurements, needed in order

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to efficiently cope with multipath and to provide accurate positioning.

With the repealites, which include the use of a unique signal, and the continuous transmission scheme implemented, carrier phase measurements are possible and will help the classical code phase measurements: the goal here is to reach decimeter accuracy in real indoor environments with a good reliability. The system consists of an infrastructure where the signal is generated and the delays implemented. The various repealites are connected to the main signal generator with optical fibers in order to reduce both the size and the signal attenuation of the system. Fig. 1 shows the principle of the transmission. We note Δ_{cable} the common part of the delay in the cable between the outdoor antenna and the first repealite, Δ_{uw} is the delay between the two repealites numbered u and w, d_k is the indoor geometric distance between the repealite number k and the receiver. PR_j is the pseudorange includes (outdoor) error and the clock bias between the GPS time and the clock of the receiver.

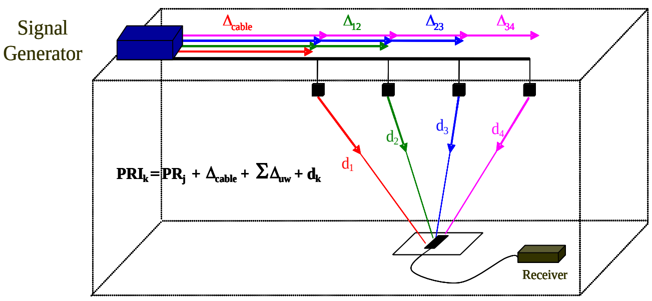

Figure 1. Principle of the repealite based positioning system

The fact of using a single signal is an advantage in comparison to pseudolites, but does not allow the synchronization problem to be completely removed since transmitters still have to be synchronized. This is currently achieved through optical fibers. Thus, they have two goals: create the required delays between repealites, but also transmit the signal to the repealite antennas. Note that in this paper, the current implementation of the system uses only three repealites, numbered from 0 to 2, thus allowing only 2D positioning.

The question is now to measure the real delays induced by the various fibres since the positioning algorithms have to take these data into account. Errors in the evaluation of these delays will directly impact the pseudorange measurements.

III. Optical Calibration Approach

The first method developed to estimate the delays of the fibers is based on an optical approach. Among the different methods that are available and detailed in this section, we retained the phase-shift method as a good trade-off between precision and simplicity. The next two chapters deal with the methods used to measure these delays.

A. State of the art of distance measuring techniques

Optical Time Domain Reflectometry (OTDR) instrumentation consists in recording back reflections as a function of time. To this end, a short optical pulse is injected into the fiber. By measuring the arrival time and magnitude of these signals, the locations and types of faults along the optical fiber can be determined. Fig. 2 shows the basic experimental setup for OTDR measurement with a backscattered trace.

In a typical fiber, each nanosecond of laser pulse equals about 20 cm of fiber length. If the optical pulse travels through a splice, bend, or a connection, the signal will be attenuated. However, when the splice or the break is reflective, then the OTDR trace shows a peak above the backscattered radiation. In all cases the total travel time is the round-trip time to either the defect or the end of the fiber.

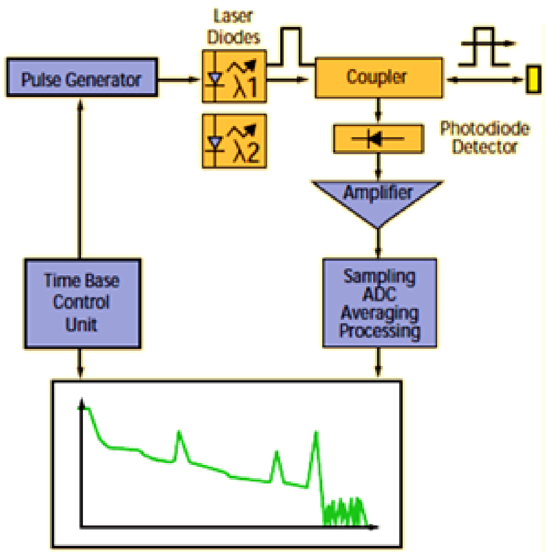

Figure 2. OTDR experimental setup

Since this technique is based on transmitting a pulsed signal, it is obvious that the finest resolution is obtained with minimum pulse widths, even though with shorter pulses, we have a lower backscattered light. The accuracy reached with OTDR is about one meter for a hundred meter fiber length. Owing to the fact that we need sub-meter accuracy for our delay measurements, this technique is not suitable for our system requirements.

As an alternative, Optical Frequency Domain Reflectometer OFDR [1] is one of the finest methods available to detect and localize discrete reflections occurring in optical fibers. An OFDR setup is used to record reflectograms that are similar to OTDR traces. Hence it can be employed to evaluate the time needed for the light to propagate through a fiber by localizing in the reflectogram the reflection peaks (with a reflection coefficient typically in the -30dB range for FC-APC connectors at the fiber-end).

This technique presents some important advantages that need to be highlighted. In particular, it provides a very high sensitivity (down to -150dB) together with a very high temporal resolution (around 30µm with reflections located

200m away). It means that the OFDR technique is one of the most precise methods available to evaluate time delays. It is also particularly well-suited to guided-wave propagation measurements (e.g. mono-mode fiber characterization), as needed in our application.

Although very promising and efficient, the components required (a reference interferometer, a tunable laser mode-hope free) are complex to integrate into the repealite system. As a consequence, it is not suitable for our application (but could be used for the development of the system).

The last technique (phase shift method) is based on the Time-of-Flight theory (ToF): the time taken by the signal to reach the target is converted into the distance that separates the signal source and the target. When using the phase shift method, distance "d" is calculated using the following expression with the value of the phase difference between the reflected (by the target) sinusoidal signal and the reference signal transmitted by the source:

$$d = c*\Delta\varphi/(2\pi fn) \quad (1)$$

Where f is the frequency of the sinusoidal signal, c the speed of light in vacuum and n is the refractive index of the environment.

The existing phase shift setups can be divided into four main methods according to the processing applied to the signal carrying the phase shift value. The signal is generally the optical one which is reflected by the target or picked up after traversing a waveguide (such as optical fiber or a phase shifter).

The simplest setup uses an electronic device such as a voltmeter [2] to measure the phase difference between the clock signal, taken as a reference, and the reflected one. In this case, the sinusoidal clock signal modulates an optical source (a Laser Diode, LD). Then at the reception, the resulting optical signal is demodulated by a photodiode and compared to the reference signal in order to obtain the phase difference.

The second possible architecture uses an optical coupler to divide the optical modulated signal into two synchronous signals: the reference and the phase shifted ones. At the reception these two signals are mixed using a coupler or other mixing procedures [3]. A so-called analog synchronous heterodyne technique is generally used with such an architecture to calculate phase shift [2], [4]. In this technique, there is the need to convert the phase shifted channel into In-phase I(t) and In-quadrature Q(t) signals. When multiplying I and Q with the reference signal and after low pass filtering, we obtain the following expressions:

$$I = 0.5\alpha S\cos(\Delta\varphi) \text{ and } Q = 0.5\alpha S\sin(\Delta\varphi) \quad (2)$$

The third architecture uses the approach named self-mixing interferometry [5]. It is based on the fact that a fraction of the reflected signal is allowed to reenter the laser cavity. So the resulting optical signal is modulated in both amplitude and frequency. The amplitude modulation term generates a variation of the power transmitted by the LD which depends on the phase shift value of the reflected signal. In such a technique the phase measurement and consequently the distance computed are based on a fringe counting technique (see paragraph III in [5]).

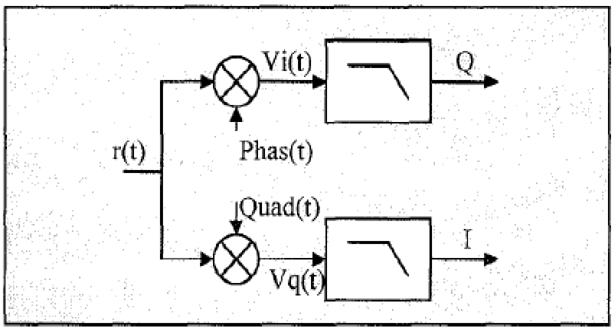

Figure 3. Analog synchronous technique

The last architecture is based on mixing (after Optic/Electric, O/E, demodulation) the reflected signal at a frequency f_1 with a local generated signal at a different frequency f_2. The phase shift is measured at the intermediate frequency $f_i=|f_2-f_1|$ [6], [7] between the reference signals and the delayed one (both of them mixed with the signal at f_2). In this technique we can use a phase meter [7] to measure phase shift values. This device converts the analog signals to digital ones and then it works the counting gate out, whose length is proportional to the phase shift to be measured.

It is also possible to use a micrometer which is able to detect a null phase shift. Indeed, in order to measure the phase difference, we add an artificial phase shift (using a phase shifter) to the reference channel until we re-establish the null point (signals in phase).

B. Optical procedure followed

In all the techniques mentioned in the literature for phase shift measurement, a calibration test is needed beforehand for the transmitting and receiving modules. It is important for our positioning system to design a technique for fiber length measurements (associated to delays) which is simple and easy to integrate. If possible, this setup would not require any specific device or operation (but only the equipment already included in the repealite). This will be an advantage to measure time delays introduced by fibers routinely since they may depend on the environmental parameters such as temperature, vibrations, etc... In particular, the signal delivered by the photodiodes is digitized to record the reference signal (that is sinusoidally modulated) and its delayed replicas. Then, they are saved in text files that are processed by a Matlab program to measure phase difference. Fig. 4 represents an overview of the phase shift measuring setup for our system.

In our measuring setup, we use two photodiodes to acquire the reference and the delayed signals. Such a circuit gives additional information on the delay added by the laser modulation and demodulation steps carried on both channels (reference and delayed one). The measured delay, in this case, is strictly the one induced by the propagation over the fiber.

Moreover, in order to guarantee that the two channels are synchronized, a calibration step is carried out. Indeed, before measuring the fiber length, the residual delay (without fiber) is saved for each clock frequency. This delay is measured when the two channels are directly connected to the photodiode.

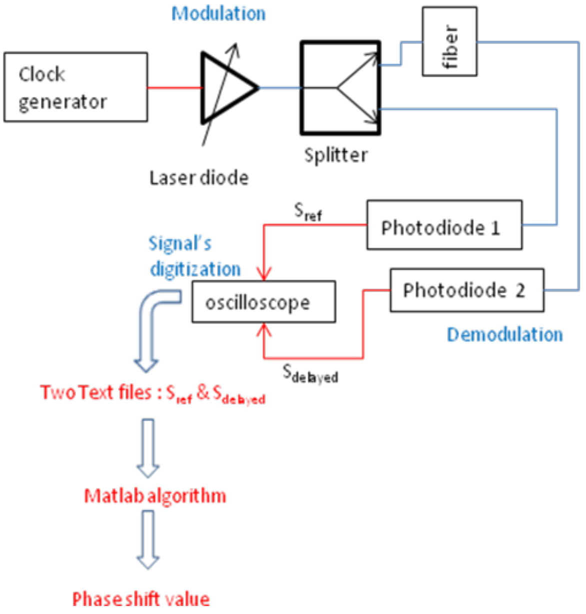

Figure 4. Phase shift measuring setup

After sampling and digitizing these two output signals, they are saved in a text file that is processed by a Matlab program to measure phase shift and deduce the fiber length. The Matlab algorithm uses the Hilbert Transformation to associate a complex analytic signal to the real one. Then it extracts the phase of each signal for each saved value and calculates the phase difference between them. The final given phase shift value is the average of the computed ones for each digital value of saved signals. Fig. 5 represents the interface of this Matlab program using the saved signals in the text files and an input parameter and Fig. 6 resumes the used algorithm in a block diagram format.

C. *Main results*

The final step of this experimental procedure is the evaluation of the accuracy of the measurements. However in the case of optical fiber, we cannot rely on any fiber length standard. This is because the length values given by the fiber provider have a precision above one centimeter for a 1.5 meter fiber. Hence, for a long fiber (600 meters in our system) it was too difficult to estimate the real length accurately. In previous works [7], we presented the method used to evaluate the accuracy. This method combines the standard dispersion given by the reproducibility tests and the experiments carried out to evaluate the linearity of the technique. It shows that our electronic setups and Matlab processing presented previously gives satisfying accuracy especially for short lengths (1 to 6 meters).

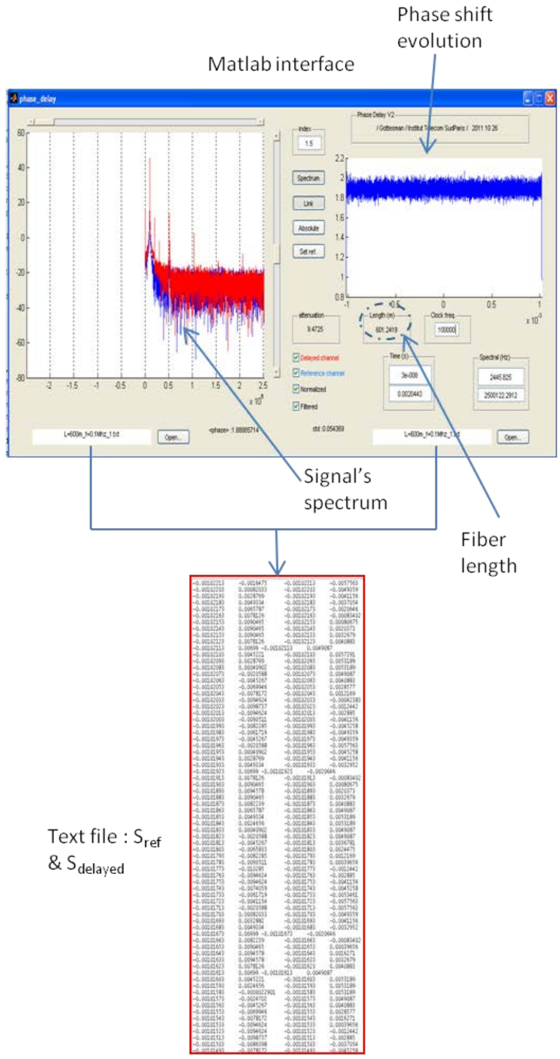

Figure 5. Interface of the MatLab program for phase shift computing

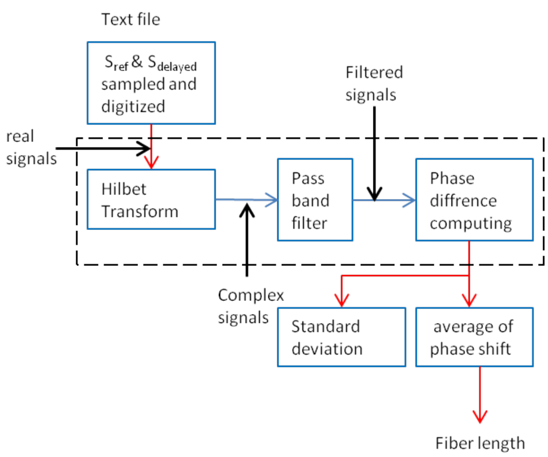

Figure 6. MatLab algorithm for phase shift computing

For the two delays considered, the length measurement procedure is repeated fifty times, for each chosen frequency (0.1 MHz and 0.4 MHz), without modifying the experimental conditions. In Fig. 7 and Fig. 8, we represent respectively the results of these two series for lengths L_1 and L_2. Note that the values in Fig. 7 and Fig 8 are equivalent to the free space propagation distance associated to the fiber lengths.

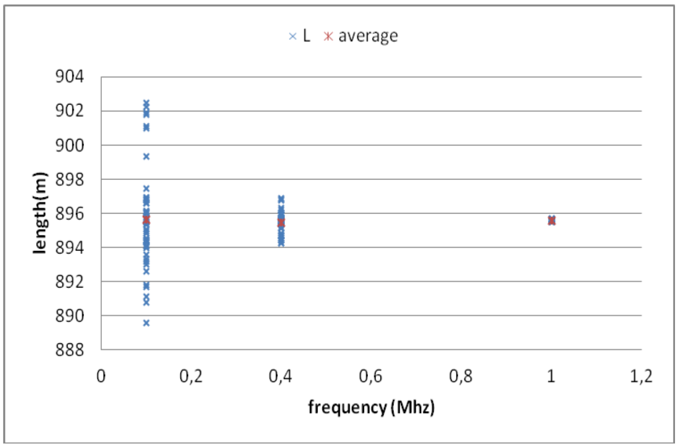

Figure 7. Measured lengths between repealites 0 and 1

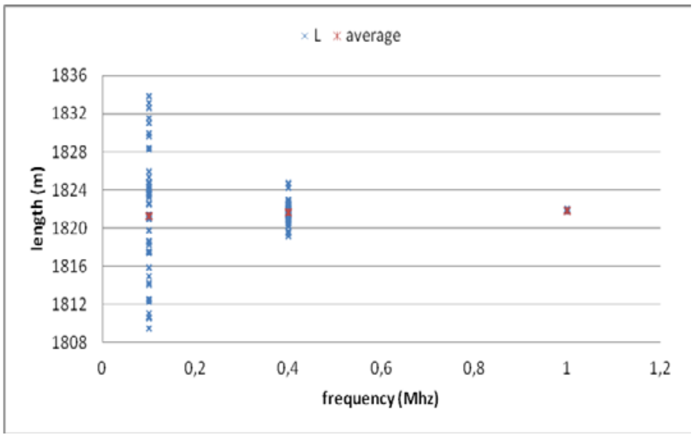

Figure 8. Measured lengths between repealite 0 and 2

The results obtained in both cases confirm the fact that the standard deviation decreases with higher clock frequency. Consequently, the best measuring performances are reached with f_2 = 0.4 MHz for L_1 and L_2. The computed average length (equivalent distances in free space) and the associated standard deviation of each series of measurements (L_1 & L_2) are presented in Table I and Table II.

TABLE I. THE AVERAGE OF THE MEASURED LENGTHS BETWEEN REPEALITE 0 AND 1

Frequency (MHz)	0.1	0.4	1
Fiber length (m)	895.65	895.46	895.59
Standard deviation (m)	2.86	0.62	0.04

TABLE II. THE AVERAGE OF THE MEASURED LENGTHS BETWEEN REPEALITE 0 AND 2

Frequency (MHz)	0.1	0.4	1
Fiber length (m)	1821.28	1821.68	1821.88
Standard deviation (m)	6.39	1.21	0.05

The results obtained of average length and standard deviation for each delay will be compared later in this paper to the measurements carried out with a GPS receiver and they will be helpful for the calibration step of the positioning system.

Here the precision of the measuring technique is evaluated by the standard deviation value deduced from the reproducibility test. It is the case for the majority of the experimental phase measuring procedures in the literature. In some other cases the performances of the techniques are compared to a standard high accurate technique, like OTDR or OFDR.

In order to improve our technique's precision, we focus on the error source existing in phase measuring systems. When dealing with phase shift measurements, the main error source mentioned in the literature is the instability of the frequency generator [9] and other measuring devices [10] due to the clock drift distortion. This factor can affect the precision of the phase shift measurements especially for very low values.

The crosstalk between the transmitting circuit and the receiving one 6] can be considered as an error source for some phase shift measuring systems. In this case, the electronic circuit of transmission and reception (laser modulation and demodulation) should be shielded to keep out undesired signals. In our system architecture, the transmitting module is located farther away from the receiving one. So the crosstalk error cannot participate in deteriorating the measuring system performance.

Another error source could be the signal noise [2], [9] induced by the optic modulation and demodulation. The influence of this type of noise can be limited when using a selective pass band filter applied to both signals before measuring the phase difference.

IV. GNSS BASED CALIBRATION APPROACH

Accurate knowledge of the delays induced by the system is essential. Indeed, we intend to measure the pseudoranges from each repealite antenna: the receiver must therefore measure the time delays induced by the free space propagation. It is therefore necessary to determine the delays induced by the optical system accurately: this can be achieved in a preliminary GNSS based calibration phase.

A. *GNSS receiver based procedure followed*

The optical system is used to delay the GPS signals from a signal generator, so that they do not interfere when they are received by the receiver antenna [11]. In the current implementation of the system, we are still using a GPS signal (but with power levels compatible with current US and European regulations). The choice of the satellite is the subject of special attention due to the problem of Near-Far [11]. The PRN 31 meets these specifications. Fig. 9 shows the correlation figures at the receiver.

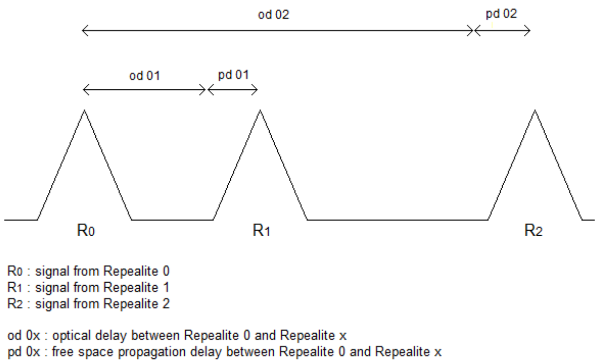

Figure 9. Correlation figures of the received signal

As shown in Fig. 9, the delays have two components: a systemic one (from the optical delay) and another one related to the propagation in free space. To evaluate the systemic delays, we must carry out specific measurements with no delays associated to propagation. This is achieved by directly connecting the three outputs of the system to a splitter/combiner which is then connected to the receiver. There is then no longer any propagation component. The remaining errors are now only related to the splitter and are considered as negligible. Fig. 10 shows the corresponding assembly.

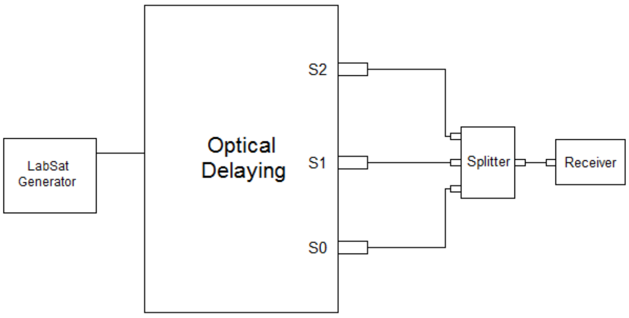

Figure 10. GNSS based calibration assembly for measuring fiber delays

We use an IFEN SX-NSR software receiver. It allows us to implement the specific algorithms required to process the repealite signals. It can also record the signal samples and replay them: we know perfectly the behaviour of the receiver for this record. So we programmed the receiver for the following procedure (see Fig. 11):

- Acquisition. Each receiving channel (3 channels here) follows the same procedure in acquiring signal S0 (the one that is not delayed).

- Tracking step 1. Since the three channels follow the same signal S0, the correlators of each loop are centred on the same peak and the three pseudorange measurements are equal.

- Tracking step 2. At a given time, we set rough phase shifts on channels 1 and 2 of the receiver so that the tracking loops can hold on to signals S1 and S2 respectively. This of course requires having an idea of the approximate values of the delays. After a while, the correlators of channels 1 and 2 are aligned with the correlation peaks of S1 and S2 (see Fig. 10, step 2).

- Tracking step 3. The recording continues for 15 minutes by retrieving pseudorange measurements.

- Final step. We calculate the average of the differences between pseudoranges from channels 0 and 1, and from channels 0 and 2. These values, added to the phase shifts that were induced, correspond to the delays that we want to evaluate.

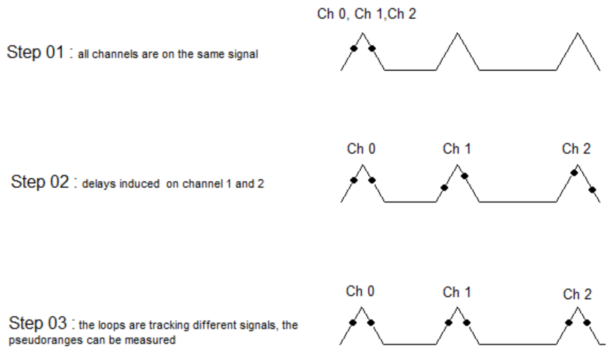

Figure 11. Summary of the various steps of the calibration procedure

To check the validity of the measurements, it is possible to restart the process by inducing the previously measured delays instead of rough values. The final delay measured should then be equal to 0. This is a very simple and easy to implement process.

B. Main results

We used a SPIRENT GSS 6567 signal generator instead of our repealite system. The GNSS signal generator has the ability to create scenarios, and more specifically to generate indirect paths. So we can create a scenario in which a single signal, the GPS PRN 31, is duplicated twice with different delays, as if there were indirect paths. Thus we reproduce the optical system.

By connecting the receiver to the output of the SPIRENT generator, we applied the calibration method described above. If the delays that are measured correspond to those we have induced in the scenario, this means that the calibration method is at least as accurate as the SPIRENT generator. Fig. 12 shows the new assembly.

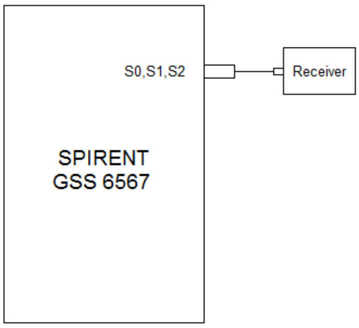

Figure 12. Assembly used for the evaluation of the calibration method

The recombination of the signals on a single track is provided by the generator. Table III gives the results obtained.

TABLE III. ESTIMATION OF THE CALIBRATION METHOD WITH A SIGNAL GENERATOR

	Channel 0 / 1	Channel 0/ 2
GSS6567 Delays (m)	732.6306	1465.2613
Measured Delays (m)	732.6334	1465.2598
Difference (m)	0.0028	-0.0015

The differences are in the range of millimetres. Of course, this situation is the ideal & takes into account the noiseless signals generated by the SPIRENT, the perfect coherence of the generated signals and the fact that the specific values of the delays considered here are exactly 2.5 and 5 chips.

We proceed in the same way with the system itself and we obtained the results reported in Table IV. Note that a few additional microwave components had to be added to the assembly described in Fig. 12 between the repealite system and the receiver in order to compensate for the differences in the power levels. In addition, O/E and E/O conversions and connectors are bound to increase the noise level: these contributions have not yet been thoroughly evaluated.

TABLE IV. MEASURED DELAYS (IN METERS) OF THE REPEALITE SYSTEM

	Channel 0 / 1	Channel 0 / 2
Measured Delays (m)	898.54	1823.53

V. DISCUSSION ABOUT THE TWO METHODS

We carried out two different methods in order to propose a calibration technique for evaluating the real delays induced by the optical fibers. Of course, this evaluation is of uppermost importance since the pseudorange based positioning will highly depend on the reliability of these delays. Let us now compare the results of the two approaches, summarized in Table V.

TABLE V. COMPARISON OF MEASURED DELAYS (IN METERS) FOR GNSS BASED AND OPTICAL APPROACHES

	Channel 0 / 1	Channel 0/ 2
GNSS method	898.54	1823.53
Optical method	895.59	1821.88
Δ (GNSS-Optical)	2.95	1.65

Further investigations are required in order to provide us with an acceptable explanation of the remaining error obtained with the GNSS based approach. An interesting point is the fact that the accuracy is better for the longer fibers. The way the receiver actually copes with the correlators is probably part of the solution: works are also currently oriented in this direction.

VI. SYNTHESIS AND FUTURE WORKS

The accurate estimation of the delays in the fibers is quite important in order to reduce the complexity of the GNSS signal processing required for positioning. The typical two meters accuracy range obtained with the GNSS method described in this paper is not sufficient. In order to reach the sub-meter positioning accuracy the repealite based system has been design to use code phase measurements. Thus, in the current implementation there is still the need for combined code and carrier phase measurements.

A complete estimation of the potential performance of the repealite based indoor positioning system has been started and should last a few additional months. First results, with carrier phase measurements (thus assuming the initial location is known), give typical accuracies in the range of a few decimeters. Absolute static positioning is currently in the range of 2 to 3 meters with no multipath mitigation technique implemented.

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