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ULTRA-STABLE OPTICAL LINKS FOR SPACE AND GROUND APPLICATIONS

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ABSTRACT

We have demonstrated the feasibility of a free-space ultra-stable optical link on a 3 meters test bench, operating at 100 MHz. With this type of link, it is possible to transfer a 100 MHz signal with a relative frequency stability of a few 10^{-14} at one second integration time, 10^{-16} at one day and a phase stability of a few picoseconds per day in presence of moderate mechanical vibrations and thermal fluctuations.
The comparisons of modern clocks of distant (<100 km) Time and Frequency laboratories have a strong scientific interest. In this context we study a low noise frequency distribution via optical fibres. Some preliminary tests have been realized and the results are encouraging. We expect to transfer ultra stable oscillators with a relative frequency stability of a few 10^{-14} at one second integration time, 10^{-16} at one day.

1. INTRONDUCTION

Several high performances frequency standards experiments (Atomic Clock Ensemble in Space, Primary Atomic Reference Clock in Space and SUperconducting Microwave Oscillator) are scheduled to be simultaneously on board the International Space Station (ISS) around 2006. Accurate and low noise frequency comparisons between clocks could be of large benefit for the performances and the metrological results of the experiments. Without direct physical connections between experiments, only a free-space link (radio frequency or optical) gives the opportunity to share the best local oscillator among the clocks and to have multiple accesses to the space-to-ground time comparison systems. In this framework, we have demonstrated the feasibility of a stable free-space optical link for frequency distribution between on board clocks.

Modern cold atoms frequency standards in the microwave domain have already demonstrated an accuracy of 10^{-15} with the potential to reach the 10^{-16} level. Frequency stabilities of $10^{-13}\tau^{-\frac{1}{2}}$ are common for such standards and a few $10^{-14}\tau^{-\frac{1}{2}}$ has been demonstrated using more advanced techniques. Optical cold atoms clocks have the potential to reach the 10^{-17} level accuracy. The advent of modern microwave to optical synthesizers based of mode locked femto seconds lasers have opened the way to high resolution comparisons between micro-wave and optical clock. The opportunity of comparing these two types of clocks, even when the laboratories are separated by 100 km, could greatly help the evaluation of their accuracy and stability performances. In this case, optical fibre links offer a greater flexibility, frequency stability, and a better accuracy than the signals delivered by GPS. Long distance optical links could also be useful for antennae synchronization or VLBI activities. In this frame, we study a phase stable and low noise optical distribution system to disseminate atomic frequency standards. The idea of disseminating high phase stability signal through an optical fibre is not new (1; 2; 3; 4). In our case, we intend to realize a distribution system using a simple telecom fibre between distant laboratories to transfer an RF signal (0.1-1GHz), with a relative frequency stability of 10^{-14} at one second integration time and 10^{-16} at one day. Several optical links have been realized, using standard telecom fibre in various environments.

2. FREE-SPACE OPTICAL LINK FOR SPACE APPLICATIONS

2.1. Requirements

The scope of this system is to transfer signals with a relative frequency stability of about $\frac{\Delta\nu}{\nu} = 10^{-14}$ at 1 second integration time, which implies a residual phase noise for the link of:

$$S_{\phi}(f) \leq 10^{-12} f^{-1} + 10^{-14} f^{0} \; [rd^2/Hz] \; @ \; 100 \; MHz \quad (1)$$

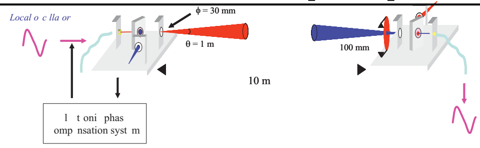

Figure 1. Free-space optical link setup.

The frequency stability over one day is specified to be below 10^{-16}. A long-term phase stability below 10 ps per day and a temperature coefficient of less than 1 ps/°C will be necessary to meet this requirement.

The optical path between clocks varies because of mechanical deformations due to vibrations and temperature fluctuations. These variations are converted to phase fluctuations on the received signal. The introduced phase shift is related to the optical path by the following equation:

$$\Delta\phi = \frac{2\pi n}{\lambda_{RF}}\Delta l \qquad (2)$$

with n the index of refraction, λ_{RF} the RF modulation wavelength and Δl the optical path variation. To correct these fluctuations we need a two-way system to measure phase variations and a compensator servo loop with a control bandwidth of 1-2 kHz.

The system need to be designed to be tolerant to angular displacement and position misalignment. By assuming a distance between clocks ranging from 10 to 30 meters, we set the system tolerance to 20 mrd and the emitted beam divergence to 10 mrd to make sure that the spot covers the receiver.

We also assume as working hypothesis that the optical path length fluctuations due to the mechanical vibrations is bounded by a sinusoidal perturbation of amplitude 1mm peak-to-peak and a frequency of 1 Hz. The consequent phase modulation (100MHz) is -60 dB rd^2 @ 1Hz. To be able to obtain -120 dB rd^2 @1Hz an attenuation of 1000 (60dB) of the amplitude of the perturbation is needed. We also assume that the amplitude of the perturbation scales as 1/f between 0.01 Hz and 1kHz.

The operation frequency of the link is not defined as a requirement. Nevertheless a 100 MHz metrological signal is available in all the space clock experiments. At this frequency, the availability of low phase noise electronic components simplify the prototyping of a breadboard. A modulation frequency of 100 MHz allows the design of angular tolerant optical receivers.

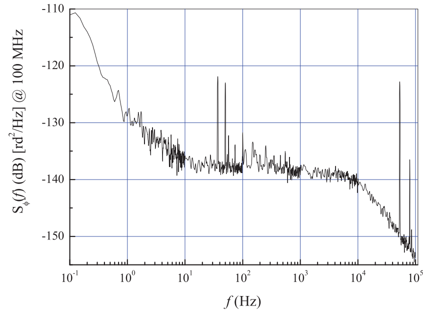

Figure 2. Measured residual phase noise of our transceiver at 1.55 μm for a frequency modulation of 100 MHz, a modulation depth of 30% and an optical power of 3 mW.

2.2. Optical transceiver

The phase compensation require to have a two-way optical system. The optical path of each way must be symmetrical to experience the same perturbations and to facilitate the optical alignment between the emitter and the receiver (superimposed beams).

Both to ensure a good system tolerance and to have a good signal-to-noise ratio, the error signal cannot be generated by a simple back-reflection system, e.g. using a semi-transparent corner cube. Each module must be equipped with a laser source and a photodetector, which are combined on the same mount to insure a high mechanical stability.

The optical transmitter is a 10 mW direct-modulated laser diode. The laser diode is pigtailed and connected to the telescope. A beam splitter permits to isolate the emitted from the returned beam. The return beam is collected by using a lens with a diameter of a 1.5 centimeters and detected by a 350 μm active surface InGasAs photodiode (1 GHz bandwidth).

The cross-talk between the two ways could affect the performances of the link. By using two different wavelengths we greatly improve the optical isolation (>120 dB on the detected RF signals).

Four optical systems (laser diode + photodiode) have been built, showing the same phase noise spectrum (figure 2). These noise performances fit the link specifications.

For the evaluation phase, a scale-down prototype (3 m distance) has been realized, including a corner cube reflector, moving on a translation table, to simulate optical path variations. The figure **??** shows the optical setup.

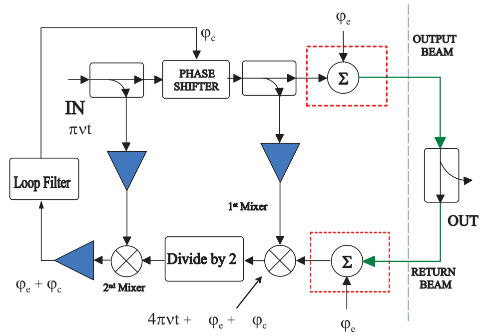

Figure 3. Block diagram of the electronic phase compensation.

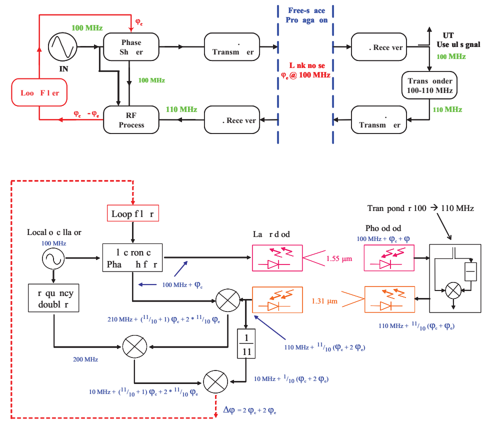

Figure 4. Dual-frequency electronic phase compensation system.

2.3. Phase compensation principle

A basic phase compensation system is described in figure 3.

φ_e is the phase shift introduced by the path variations and φ_c is the phase correction term. After one round trip the accumulated phase is $2\varphi_e + \varphi_c$ at the frequency ν. This signal is mixed with the emitted signal and the resulting phase is $2 \times (\varphi_e + \varphi_c)$ at the frequency 2ν. The obtained signal is frequency divided by two signal and mixed down to DC to obtain the phase information: $\varphi_e + \varphi_c$. The phase condition $\varphi_e = -\varphi_c$ is realized by an analog servo loop which controls the phase shifter. This electronic compensation system allow to have a sufficient control bandwidth, limited by the electronic phase shifter to about 20 kHz.

2.4. Design of the electronic compensation

The real design is fairly more complicated than the compensation principle. A system with two non-harmonic modulation frequencies (one for each way of the distribution) has been realized. This arrangement improves isolation and reduce parasitic high order mixing products in the phase measurement process (as explained below). The rejection factor (ratio of the phase variations, in open and closed loop, between the source and the received signal) is limited by various phenomena, which adds unwanted phase terms to the main signal due to the real optical path variations.

First at the detection level, the emitted and detected beams are not collimated and thus, a variation of the optical power induces a variation of the RF power detected at the output of the photodiode. The amplitude variations are converted to phase by the measurement process itself. Even in quadrature the mixers rejects the amplitude modulation only by 15-20 dB. This phenomena called AM to PM conversion can seriously corrupt the phase measurement process. The typical coefficients of AM to PM conversion are of the order of 0.1-0.5 mrd/dB, which bound the amplitude fluctuations to be well below 0.1 dB to fulfill the rejection specifications.

A second possible cause of phase fluctuation at the detection level are the photodetector delays inhomogeneities. Due to the optical misalignment the spot moves on the photodiode active area It is very difficult to prove and evaluate this effect, for example if we assume that the photodetector delay is about 1ns, inhomogeneities of 10 ppm gives 10 fs of delay fluctuations, which translates in spurious phase shift of 10 μrd @ 100 MHz, about 1% of the maximum phase signal we want to measure).

Another source of inaccuracy in the phase measurement process is the intrinsic high orders mixing products generated by the mixer non linearity. The main contribution comes from the "$3f - f$" mixing term. The consequence of this phenomena is the generation of an interference signal at the useful output frequency (Ex: from the mixing of two signals at 100 MHz, we obtain a main signal at 200 MHz (100 + 100 MHz) but also a parasitic signal at 200 MHz resulting from 3*100 - 100 MHz with an unwanted phase term which adds to the expected phase.

In this case, it is necessary to separate and to filter each contribution around the carrier. This is possible by increasing the hardware complexity and choosing two non-harmonic modulation frequencies (for each way), shifted by 10 MHz (100 and 110 MHz) for example.

The principle scheme of the dual-frequency electronic phase compensation system is the following:

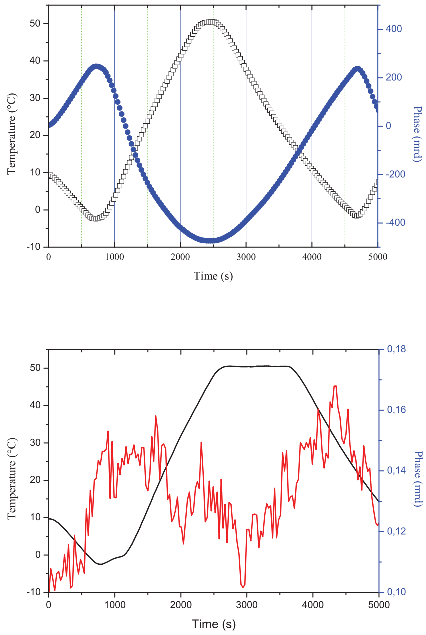

Figure 5. Phase fluctuations at 100 MHz for 50° C temperature variation without compensation and with compensation (1 km fibre spool).

3. RESULTS OF THE FREE-SPACE OPTICAL LINK

3.1. Rejection factor

Rejection factors above 300 have been measured, in a bandwidth (0.1-30Hz). The results are not reproducible above 100 and depend strongly on optical alignment and the level of spurious amplitude modulation.

In order to verify that the rejection efficiency is limited by the optical system, we have independently tested the electronic compensation system. A fibre optical link is assembled and the perturbation is realized by heating 1 km of optical fibre between 0° C and 50° C, with a response time of 30 min. The simulated phase variation is 50 times larger than the one generated by moving the corner cube reflector, for the same stray amplitude modulation level.

Figures 5 shows the phase modulation induced by fibre temperature variations, respectively in open-loop and closed-loop configuration.

These measurements confirms that the phase fluctuations rejection is not limited by the electronic system (a rejection factor of a few thousands are currently realized).

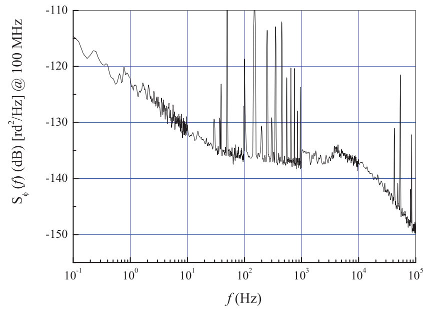

Figure 6. Residual phase noise at 100 MHz of the free-space optical link with compensation.

3.2. Phase noise

Figure 6 shows the measured phase noise of the link (optical system coupled to the compensation electronics).

The results we obtain in terms of phase noise, fit the requirements and are reproducible. Associated with the best rejection we have observed, they ensure the possibility to transmit a metrological signal with a frequency stability of about 10^{-14} at one second integration time in a regime of moderate mechanical vibrations.

subsectionLong-term phase stability and temperature coefficient

The long-term phase stability of the link is about 2 ps/d (conservative evaluation). A temperature coefficient of about 1 ps/°C is realistic taking into account the obtained phase stability (not fully evaluated).

4. LOW NOISE GROUND FREQUENCY DISSEMINATION VIA OPTICAL FIBRES

4.1. Objectives

With the development of standard telecom fibres, most institutions and laboratories are connected by optical fibres. The redundancy of the network makes possible the use of a dedicated fibre for metrology applications. In this context we began to study a low phase noise and high frequency stability transfer of metrological signals using standard telecom fibre link in a urban environment. Several links have been realized for various applications:

BNM-SYRTE Optical Distribution: This system is composed of several few hundreds meters fibre links to distribute frequency standards of the BNM-SYRTE (H-MASERs and Cryogenic Sapphire Oscillator) to all of experiments

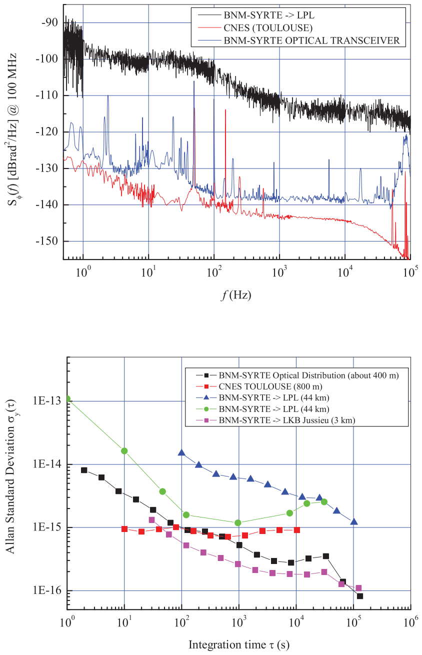

Figure 7. Phase noise and frequency stability measurements realized on the various optical links of BNM-SYRTE.

(atomic fountains, optical frequency synthesis chain, inertial sensors ...)

CNES (Toulouse) One 800 meter optical fibre to share the CNES H-MASER with the PHARAO test facilities.

BNM-SYRTE → LPL Optical distribution system using standard telecom fibres of the urban telecom network of Paris and suburbs and interconnecting a few different sections of buried standard single mode fibres cable, between the BNM-SYRTE and the Laboratoire de Physique des Lasers. The continuity of the link is ensured by soldering the fibre ends at the network interconnection points. Total length of the link approaches 44 km, for a physical distance between the two laboratories of about 15 km, with a one way attenuation around 10 dB at 1.55 μm.

BNM-SYRTE → LKB Jussieu An optical link of about 3 km relies BNM-SYRTE and one laboratory (Laboratoire Kastler Brossel) of the Paris Jussieu University (Paris VI).

4.2. Link measurements

Some metrological features of the links available at BNM-SYRTE was measured and presented on Figure **??**.

These measurements, realized for a modulation frequency of 100 MHz, show the non stationary effects

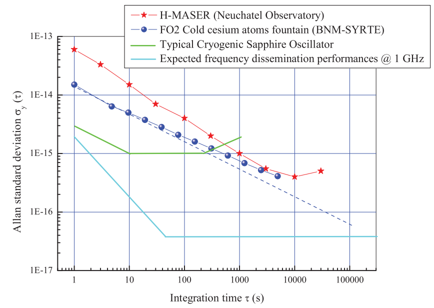

Figure 8. Optical link performances.

on a optical link in a urban environment. That is particularly true in the case of the BNM-SYRTE to LPL link. Indeed, frequency stabilities of this link, calculated from different phase measurements samples highlight changing effects due to temperature variations and activities according to the hour or the day of the year.

4.3. Requirements

To begin with, the aim of the frequency dissemination is to transfer the short and long-term stability of the H-MASER through optical fibres. However this system should be able to transfer better short-term oscillators, like cryogenic sapphire oscillators.

Frequency stabilities of a few 10^{-15} at one second integration time and about $5{\times}10^{-17}$ at one day, seem to be realistic and sensible for the optical distribution system. The equivalent phase noise spectral density [rd^2/Hz], at 100 MHz, for the system is:

$$S_\phi(f) = 10^{-13} f^{-1} + 10^{-14} f^0 \qquad (3)$$

The temperature coefficient is less critical since the equipments are in a laboratory environment.

The preliminary measurements of the link intrinsic stability (fig **??**,**??**) shows that a minimal rejection factor of about a few hundreds is needed to obtain the required short and long-term phase stability with a control bandwidth of a few hundreds hertz, limited by the fiber round trip delay (about 0.5 ms).

4.4. Breadboard

The distributed reference signal, is obtained by direct current modulating the laser diode (at 1.55 μm) and is detected on a pigtailed InGaAS photodiode. We use optical circulators (optical isolation greater than 60 dB) to separate emitted and returned beam.

The phase fluctuations corrections can be obtained either by an electronic compensator or an optical phase shifter, associated with a phase measurement process, similar to the one used previously. In both cases, the corrections signals are obtained by applying the opposite phase fluctuations to the emitted beam after a round-trip phase measurement. As usual, we assume that the emitted and reflected signals see the same perturbation. Choosing a higher modulation frequency (1 GHz), the phase noise requirements on the components could be relaxed by 20 dB for the same expected performances. Since the AM level is fairly independent of the modulation frequency, the AM to PM noise contribution also decrease by a factor of 10.

Optical phase shifter

Fast fluctuations can be compensated by stressing an optical fibre around a cylindric piezo-electric actuator. The used fibre length depends on the operating modulation frequency, the piezo-electric actuator movement amplitude, and thus on the correction to apply. A large bend radius is necessary to minimize the Polarization Depending Losses (PDL), introduced by bend losses, micro-bends, and fibre geometry modification generates amplitude modulation which can in some cases, via the AM-PM conversion process, be of the same order as the generated phase correction. For the long-term phase variations, the correction can be realized by applying temperature variation on a fibre spool. First tests show that the optical method is not well suited for our application. The rejection factor is not reproducible and not very high (about 10 to 30). Moreover the need of an high voltage piece driver adds some complexity to compensator hardware.

Electronic phase compensation

It is possible to use an electronic compensation system, similar the one used for our previous link. In order to simplify the setup, we transpose the RF compensator, originally designed by the JPL ((1)), to 1 GHz. The simplified scheme is shown in figure (9):

4.5. Preliminary evaluation

The preliminary tests will be realized on a representative breadboard in terms of optical attenuation, soldering connections, length (2x2.5Km, 10dB attenuation and 10 joint points). This set-up permits to study and debug the compensation system. The phase fluctuations will be simulated by a climatic chamber in a range from 0 to 50°C.

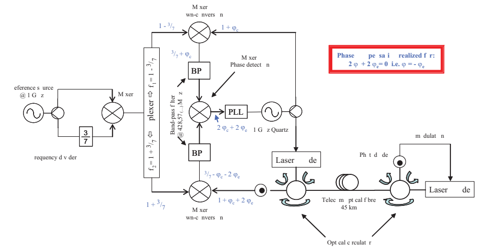

Figure 9. Phase compensator scheme operating at 1 GHz.

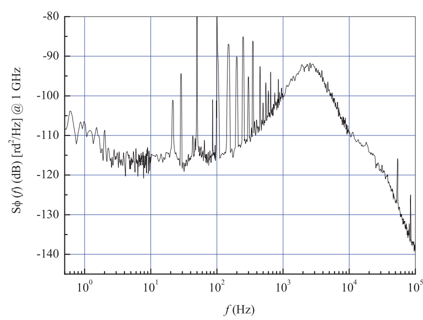

Figure 10. Measured phase noise spectrum of tests with phase compensation breadboard with 2.5 km fibre spool.

4.6. Phase compensation

The preliminary phase noise performance of the compensator is presented in fig.10, this spectrum is nearly compatible with our application. We perform also a preliminary measurement of the phase difference between the source oscillator (reference signal) and the detected signal at the end of 2.5 km of telecom optical fibre, in presence of the previous electronic phase compensation system. A rejection factor of a few hundreds was observed and compliant with our preliminary objectives.

5. CONCLUSION

Two full set-ups of the free-space ultra-stable optical link (one at 1.55 μm and one at 1.3/1.55 μm) have been realized and tested. In the best operating conditions, it is possible to transfer a 100 MHz signal with a relative frequency stability of 10^{-14} at 1 s integration time (10^{-16} at one day), with a phase stability of a few picoseconds per day, by compensating moderate optical path variations due to mechanical vibrations and thermal fluctuations. Far from being exhaustive, this study shows the feasibility of a free-space ultra-stable optical link.

A minimum rejection factor of 100 up to 300 has been measured. However, the objective of 1000 is not realized. The future step is to verify the AM effects on our compensation system. We also plan to improve the side-bands separation and to reduce parasitic signals in the phase detection process.

The preliminary phase measurements on the long distance ground frequency distribution link shows that a rejection factor over 100 is needed to fulfill the scientific objectives. The breadboard of the compensation system has already shown some interesting results. In the next future we expect to be able to further reduce the residual phase noise.

After debugging we will build two complete systems to fully prove the transfer of the short-term and the long-term frequency stability of frequency standards on this type of link.

ACKNOWLEDGMENTS

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