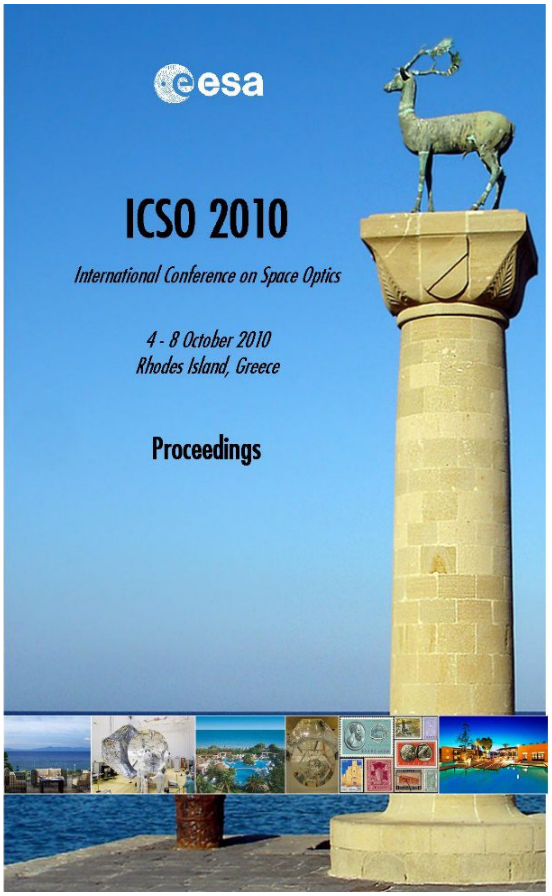

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A COHERENT FREE SPACE OPTICAL LINK FOR LONG DISTANCE CLOCK COMPARISION, NAVIGATION, AND COMMUNICATION: THE MINI-DOLL PROJECT

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ABSTRACT

We describe the realization of a 5 km free space coherent optical link through the turbulent atmosphere between a telescope and a ground target. We present the phase noise of the link, limited mainly by atmospheric turbulence and mechanical vibrations of the telescope and the target. We discuss the implications of our results for applications, with particular emphasis on optical Doppler ranging to satellites and long distance frequency transfer.

INTRODUCTION

Atomic clocks have been improving rapidly over the past years and are now reaching uncertainties in relative frequency of 2 parts in 10^{17} after less than 5×10^4 seconds of integration time [1]. Applications of such clocks in fundamental physics, geodesy, navigation etc... require their comparison over large distances without degrading their performance. In the longer term one expects applications of such clocks on board terrestrial and solar system satellites [2, 3], which require a high performance free space link from ground to space and/or between spacecraft. At present, no existing long distance comparison method reaches the required level of uncertainty [4], and even the improved microwave link of the ACES (Atomic Clock Ensemble in Space) mission [5] or the optical T2L2 (Time Transfer by Laser Link) link [6] will require several days of integration time to reach 10^{-17}. Over short to medium distances ($\approx 10^2$ km) optical fiber links have demonstrated sufficient performance [7], and our aim is to extend those methods to free space propagation and towards ground to satellite and intercontinental (via a relay satellite) frequency comparison of clocks. Other applications of coherent free space links are optical satellite Doppler ranging and broadband optical communications, the latter being the focus of much attention in recent years with the promise of Gb/s data rates over large distances. At such high rates the main limitation is strong amplitude fluctuation (scintillation) due to atmospheric turbulence, which has been investigated experimentally in a 142 km coherent optical link between two Canary Islands [8]. In contrast, we focus on the low frequency (< 1 kHz) part of the link phase noise spectrum, of relevance to clock comparisons and optical Doppler ranging, which is to a large extent independent of amplitude fluctuations. Recently a roof-top experiment over a 100 m distance has been reported [9], with the conclusion that free-space coherent optical links may only be suitable for short distance (< 1 km) clock comparisons. We arrive at the opposite conclusion showing not only that such links display high performance over our 5 km distance, but also that they hold great promise for satellite to ground links, with the perspective of reaching the performance of the best optical clocks in less than 100 s integration time. In this letter we present a brief description of the experiment and our main results.

EXPERIMENTAL SET UP AND RESULTS

Our experiment took place at the Observatoire de la Côte d'Azur (OCA) lunar and satellite laser ranging facility located on the plateau de Calern at an altitude of 1323 m, with data taken during several days in June and July 2009. The set up consists of a heterodyne Michelson interferometer with unequal arm lengths (see fig. 1), using a 1064 nm Nd:YAG laser (Innolight/Prometheus, ≈ 1 kHz linewidth).

The local arm passes about 50 cm of optical fiber for mode cleaning and is then frequency shifted by 200 MHz using an Acousto-Optic Modulator (AOM) and recombined with the distant arm on the photodiode. The resulting heterodyne beat signal is used to phase lock a Voltage Controlled Oscillator (VCO) with the locking bandwidth set to around 50 kHz. The frequency of the VCO is counted using a zero dead-time counter with a 1 kHz data rate. We also generate a quadrature signal (mixer M2) with respect to the phase locked loop (mixer M1), which is proportional to the beat signal amplitude but independent of its phase (to first order) when the loop is closed. It thus allows monitoring of the signal amplitude. The distant arm is fed into the Lunar Laser Ranging 1.5 m aperture telescope at OCA. The beam diameter at the exit of the telescope is about 380 mm. The distant arm is reflected by a 5 cm corner cube mounted on an iron tripod ≈ 3.5 m off the ground on a mountain top ≈ 2.5 km from the telescope. We feed ≈ 275 mW of optical power into the telescope for a received average power on the photodiode of ≈ 20 µW. The main sources of loss are the small size (relative to the beam diameter) of the corner cube and the low transmission of the telescope at 1064 nm (optimized for 532 nm). As expected, we observe large amplitude fluctuations in the heterodyne beat signal, caused by scintillation from atmospheric turbulence.

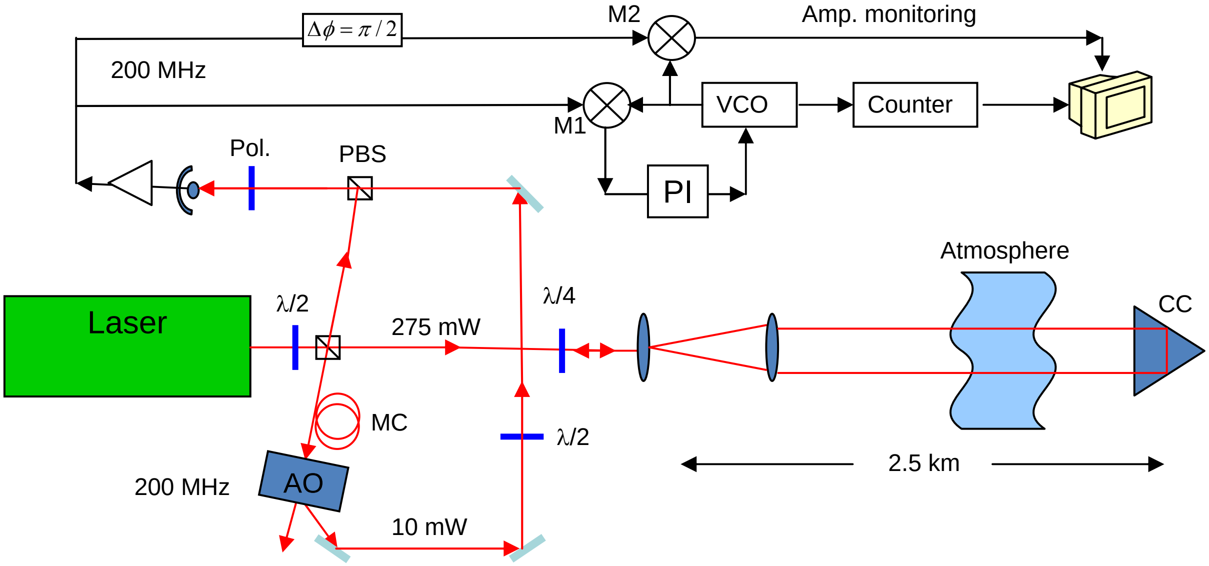

Fig. 1. Principle of the experiment: AOM, Acousto-Optic Modulator; Pol., Polarizer; PI, Proportional-Integrator filter; VCO, Voltage Controlled Oscillator, CC, corner cube.

In a ground-ground or ground-satellite free space coherent optical link the main limitation in the low frequency part of the spectrum is expected to arise from fluctuation of the refractive index of the atmosphere due to turbulence. Models to estimate the phase noise from turbulence can be found in [10] and references therein. Using those models for our horizontal 2.5 km return path we obtain a phase noise estimate about two orders of magnitude worse than for a zenithal ground to satellite link from the same location. Therefore, in order to obtain conditions representative of a vertical link, we have taken data during the calm periods of inversion of the temperature gradient (about 1 h after sunrise) where the observed turbulence level was significantly lower than during the rest of the day. This is also confirmed by the fact that the observed noise during those calm periods was close to the one reported in [11] obtained by interferometric observation of light from stars crossing the atmosphere vertically during average turbulence conditions. In [11] turbulence is quantified by the phase noise structure function defined as $D_x(\tau) = \langle [x(t+\tau) - x(t)]^2 \rangle$ where $x(t)$ is the optical path length traveled by the signal received at time t. The obtained structure functions for $0.1\ \mathrm{s} \leq \tau \leq 10\ \mathrm{s}$ can be described by a power law of the form $D_x(\tau) \cong C\,\tau^{\beta}$ with typical values in [11] of $D_x(1s) \approx 20\ \mu m^2$ and $\beta \approx 1.45$ and large variations around those values. We typically obtain structure functions following a similar power law with $D_x(1s) \approx 25\ \mu m^2$ and $\beta \approx 1.25$, which compare well with the results of [11], as shown on figure 2. Both results show significantly lower power law slopes than predicted from standard Kolmogorov turbulence theory (β = 5/3). We thus estimate that the phase noise from turbulence on our horizontal link during calm periods is representative (at least in order of magnitude) of the phase noise expected in a one-way ground-satellite link in average conditions.

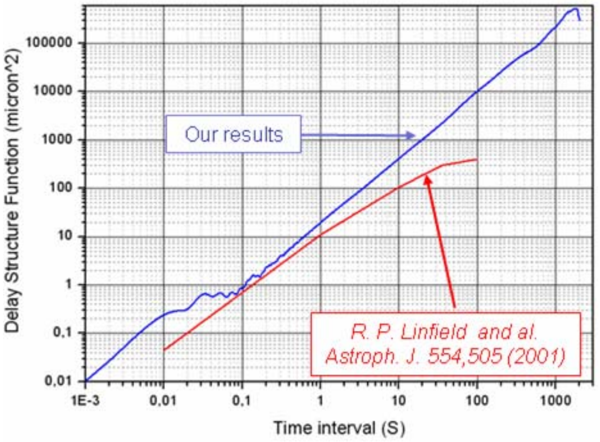

Fig. 2: Structure function showing turbulence phase noise of our measurement and measurements reported from stellar interferometry, showing good agreement between our horizontal measurement in quiet periods and vertical measurements during standard conditions.

Figure 3 shows the frequency measurements and corresponding power spectral density (PSD) of fractional frequency fluctuations for a 33 min data set taken on July 3 (≈1 h after sunrise) in clear sunny conditions. Similar results are obtained for other days in similar conditions. The lower curve in the PSD graph represents our noise floor, obtained by placing a mirror on the distant arm before injection into the telescope. It is dominated at high Fourier frequency by the white phase noise of our counter, and below 30 Hz by acoustic noise in the laboratory. The upper curve is our measurement over the 5 km return distance through the turbulent atmosphere. The initial data consists of about 2 x10^6 frequency measurements at 1 ms intervals, with a standard deviation of 96 Hz.

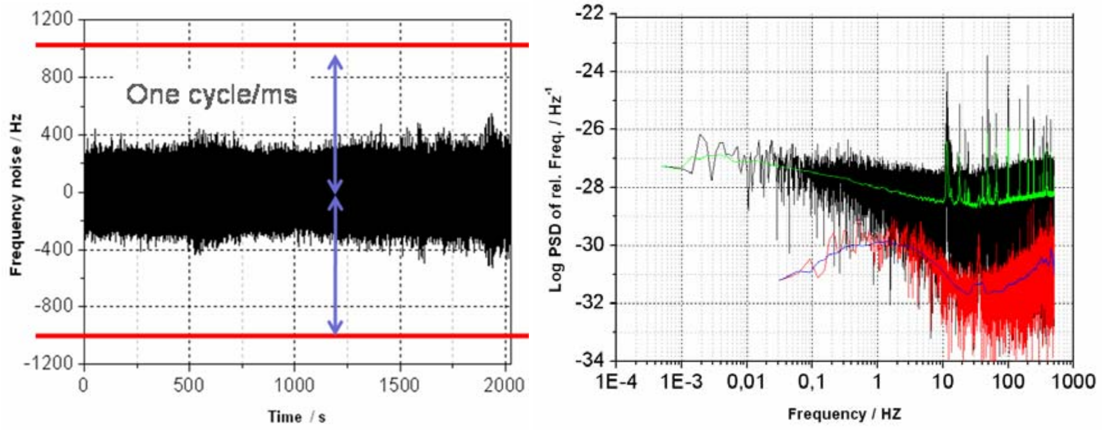

Fig. 3: Frequency measurements (left) of a 33 min data set. At the ms sampling rate a cycle slip corresponds to a 1 kHz step and is clearly detected in the data. Right: corresponding fractional frequency power spectral density of the free-space link (black) and system floor (red), with 500 points moving averages superposed (green/blue).

Optical cycle slips of the phase-locked loop are easily identified, as at our 1 ms sampling they correspond to 1 kHz steps. We removed 66 such points (≈ 3 x10^{-5} of the data) all of which were obvious cycle slips and correlated well with measured signal extinction due to atmospheric scintillation. The PSD of our measurement shows turbulence noise at frequencies below 10 Hz. For this part the PSD is proportional to $f^{-0.3}$, below the expected value from turbulence theory of $f^{-2/3}$ as already mentioned above. Above 10 Hz the PSD exhibits peaks due to mechanical resonances of the telescope and the target with amplitudes around 1 µm, but we also note an underlying increase of the PSD with frequency, due to amplitude to phase noise conversion in our phase locked loop.

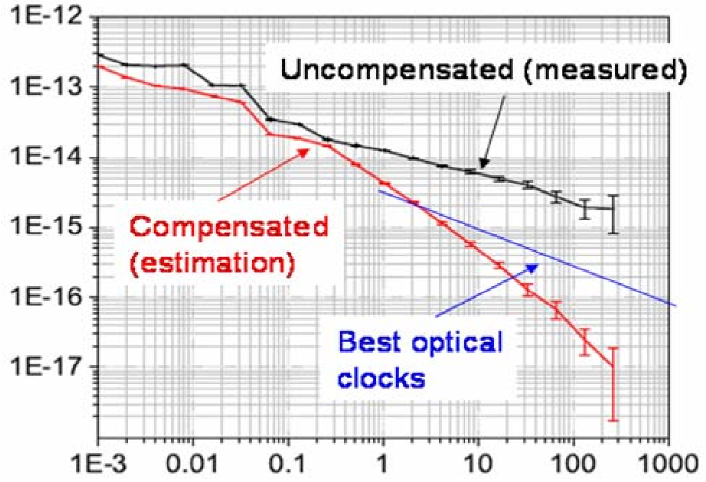

Fig. 4. Fractional frequency stability measured on the ground-ground free space link (black), and estimated for a ground to geostationary satellite clock comparison with two-way noise compensation (red). For comparison the stability of the best present day optical clocks is shown in blue.

Figure 4 shows the Allan deviation of fractional frequency ($\sigma_y(\tau)$) of the same data set. At $\tau < 0.1$ s it is dominated by the sum of the periodic effects due to mechanical vibrations, and at larger τ its slope reflects the noise from atmospheric turbulence ($\propto \tau^{-0.3}$), somewhat different from the expected value from turbulence theory ($\propto \tau^{1/6}$), as already mentioned above and consistent with measurements of [11]. The Allan deviation of our data is about 1.3 $\times10^{-14}$ at $\tau = 1$ s, and reaches 2 $\times10^{-15}$ after about 100 s integration time, which is a remarkable stability for an uncompensated link through the turbulent atmosphere. For instance, it is similar to the uncompensated noise in the best 10^2 km fiber links [7]. Given that, with appropriate two-way compensation schemes, those links show the by far best performance for frequency comparisons over short to medium distances, we believe that if our results are representative of a ground-satellite link, free space coherent optical links have excellent potential for future ground to space and intercontinental clock comparisons. This is discussed more quantitatively below.

Let us assume a two-way free space optical link between a ground station and a geostationary satellite, with heterodyne frequency measurements of the received signal vs. the local signal, on board ($y_s(t_s)$), and on the ground ($y_g(t_g)$). The up and down links will be affected by three main noise sources: satellite motion, ground station motion, and atmospheric turbulence. We further assume that the latter two are characterized by our measured noise as shown above. The two way system is used in such a way that the ”up” signal is received at the satellite at the time of emission of the ”down” signal (to within a few ms), which can easily be implemented during the data analysis when combining the on board and ground measurements. The frequency difference of the ground and on board optical clocks is given by $\Delta y = (y_s(t_s) - y_g(t_g))/2$. In that difference the Doppler effect from satellite motion cancels to a large extent (exactly if the two signals are coincident at the satellite). However, the noise from ground station motion and atmospheric turbulence partially remains as the emission of the ”up” signal is separated from the reception of the ”down” signal by the return travel time $\Delta t \approx 250$ *ms*. We can estimate that residual noise ($y_{res}(t)$), by calculating $y_{res}(t) = (y(t)-y(t+\Delta t))/2$ from our data, and investigate its statistics. The resulting PSD is given by the one in fig. 3 multiplied by a transfer function equal to $(1 - \cos(2\pi f\Delta t))/2$, resulting in a steep decrease at low frequency (≤ 1 Hz). The corresponding Allan deviation of $y_{res}(t)$ is shown in fig. 4. It stays a factor $\approx \sqrt{2}$ (due to the factor 2 in y_{res}) below the measured noise at small τ, but shows a steep decrease starting at $\tau \approx 250$ ms, reaching 1×10^{-17} after about 300 s integration time. Thus, free space optical links hold great promise for future long distance clock comparisons, with the potential of reaching the stability of the best present day optical clocks in less than 100 s.

A limit to the above argument is imposed by signal outages due to atmospheric scintillation and corresponding possible optical cycle slips. These will be uncorrelated between the up and down links, and will therefore fully affect $y_{res}(t)$. In our 33 min data set we observed 66 such signal outages, which implies an average loss of about 0.05 cycles per second. The resulting noise corresponds to an Allan variance of $\sigma_y(\tau) \approx 2 \times10^{-16}/\sqrt{\tau}$ still significantly better than the best present optical clocks and just below the estimated stability shown in Fig. 3. If these cycle slips are not random they cause a frequency bias at worst equal to $\approx 2\times10^{-16}$. This does not affect the clock comparison as long as turbulence is sufficiently low to allow identification and removal of cycle slips (clearly the case in our data, see discussion above and fig. 3), and we expect this to be the case at most astronomical observing sites. Furthermore, signal outages can be mitigated by the use of adaptive optics schemes.

For Doppler ranging using on board corner cubes the residual noise on the satellite Doppler (and thus velocity) is given by $y_{res}(t) = (y(t) + y(t+\Delta t))/2$. The Allan deviation of the corresponding residual distance noise is $\sigma_x(\tau)$ = 28 nm at τ = 1 ms and $\sigma_x(\tau)$ = 1.4 µm at τ = 1 s. Although this corresponds to > 3 orders of magnitude improvement on the present measurement noise in satellite laser ranging, one should bear in mind that, for lower orbits, the long term noise will be dominated by changes of the tropospheric delay as the satellite passes overhead (varying elevation), which can presently only be modeled at the mm level at best.

For intercontinental ground – ground frequency comparison the principle of the two way link can be used via a relay satellite (taken to be geostationary in this example). The general principle is shown in figure 5. The clocks are linked to astronomical observing sites via local fiber links. The fibers are used to lock a local laser at the telescope to the distant clock signal. The satellite is equipped with an onboard laser (2 W power), two small telescopes (10 cm aperture) and two heterodyne detection systems that measure the frequency difference between the on board laser and the incoming signals from the respective ground stations. The on board laser signal is also emitted towards the ground stations where the frequency between the respective ground lasers and the satellite signal is measured using local heterodyne detection systems. The on board and ground measurements are combined in post-analysis providing noise compensation for each satellite-ground link (as described above) and the ground clock frequency difference.

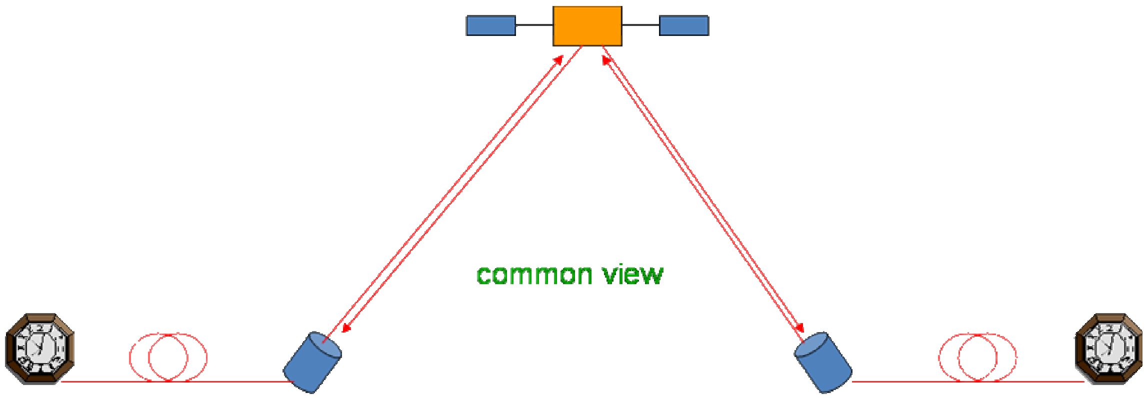

Fig. 5: Principle of the set-up for intercontinental ground – ground comparisons using a relay satellite

Using 10 cm on board telescopes and 40 cm ground telescopes (requiring no, or only very simple tip-tilt adaptive optics) the received power (1 W emission) on board and on the ground is between 10 nW and 1 µW, depending on pointing performance (assumed here to be about 10^{-5} rad (2”)), which is amply sufficient for the heterodyne detection. To ensure that the noise of the on board laser is negligible in the comparison strict common views are required. This can be implemented in post-analysis when combining the on board and ground measurements. If we assume an unstabilized typical Nd:YAG laser on board the geostationary satellite and we want to reach a performance at the level shown by the red curve on figure 4, the common views need to be simultaneous at the microsecond level, ie. the onboard and ground time scales used to time tag the measurements need to be synchronized at that level. This can be easily achieved by microwave techniques (GNSS receiver on board) or iteratively, using the laser link itself. Also, the orbit of the satellite needs to be known with an uncertainty of about 300 m, again possible by GNSS techniques or using the laser link itself. Both these requirements can be strongly relaxed if the on board laser is stabilized to a cavity, a delay fiber, or an atomic or molecular transition. Therefore long distance clock comparisons using free space optical techniques seem promising and feasible using a relatively modest and technologically unchallenging on board package.

CONCLUSION

In conclusion, we have demonstrated operation of a free space coherent optical link through the turbulent atmosphere. Based on our results we estimate that such links promise large improvements in long distance clock comparisons and satellite ranging. We are at present working towards extending our experiment to a ground-space link using existing low orbit satellites equipped with corner cube reflectors. The main challenges in doing so are the large induced Doppler shift of our signal (±12 GHz), the low expected return power < 1 pW, and the longer signal travel time which requires frequency stabilization of our laser. The results of those experiments expected over the next years will make the present estimates on the possible performance of free space coherent optical links more robust and realistic.

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