Optical frequency transfer via an ultra-stable open-air short link

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Abstract. The 17 m atmospheric link for ultrastable optical frequency transfer is developed. The frequency instability induced by atmospheric fluctuations is reduced by more than 20 times with the help of active compensation system and reaches $2.3 \cdot 10^{-18}$ at $\tau = 250$ s. The link contribution to inaccuracy is reduced by 3 orders of magnitude and equals $1.3 \cdot 10^{-20}$.

1. Introduction
Coherent transfer of frequency and time signals over cities, countries, continents and even between continents, between Earth stations and satellites is rapidly developing area of research and technology. A network of optical clocks connected with links [1] create great opportunities in such fields of science and technology as the formation of national and international time scales, satellite navigation, relativistic geodesy, very-long-baseline interferometry, tests of fundamental theories, search for dark matter. The state-of-the-art frequency standards have reached the level of relative uncertainty and instability of $10^{-18}$ [2, 3]. Transferring signals from these standards without distorting of their characteristics using radio frequency methods is impossible, because the latter cannot provide frequency transfer instability better than $10^{-16}$ [4]. It is possible to reduce the level of the phase noise introduced by the communication link by transferring signals at optical frequencies. The active development of stationary and transportable [5] optical frequency standards shows the necessity of designing both fibre [6] and free-space [7] links for the transfer of highly stable signals.

Atmospheric turbulence can limit both stability and accuracy of a signal transferred through an open-air link. Air refractive index fluctuations introduce perturbations into the signal phase. The spectrum of this noise is described by the Kolmogorov theory of turbulence [8]. According to this theory, the power spectral density $S_\phi(f)$ of phase noise is

$$S_\phi(f) = 0.016 \cdot k^2 \cdot C_n^2 \cdot L \cdot V^{5/3} \cdot f^{-8/3},$$

where $f$ is Fourier frequency, $k$ is the wave number of light, $C_n^2$ is the atmospheric turbulence structure constant, $L$ is the free-space link length, and $V$ is the wind speed.

Apart of phase noise, atmospheric turbulence cause intensity fluctuations called scintillation, beam angle-of-arrival jitter and waviness of the phase front [8, 9]. The last one sets the maximum useful beam aperture called Fried parameter [10]. These effects can limit the link performance, for example the length of obtained continuous data.
Earlier we have developed 5 m in-lab free-space link [11]. In this paper we report on 17 m atmospheric link formed by sending the beam outwards the lab.

**Figure 1.** The principle scheme of experimental setup. AOM – acousto-optic modulator, PD – photodiode, PIA – proportional-integral amplifier, VCO – voltage-controlled oscillator, $\lambda/2$, $\lambda/4$ – half- and quarter-wave phase plates, respectively, RF – radio-frequency, H-maser – passive hydrogen maser, PBS – polarising beam splitter.

2. **Experimental setup**

Figure 1 shows the simplified schematic of our experimental setup. As a light source the Koheras ADJUSTIK fiber laser at 1550 nm (193.4 THz) is used. Totally we use the light power of about 60 mW. The phase noise introduced by the link is detected with autoheterodyning scheme [12] by producing the beatnote signal of the 25 mW of local beam and the 70 $\mu$W of returned beam which has passed the link twice in forth and back directions. For this purpose the beam at the remote receiver side is partially reflected back. This beat signal is called inloop and is detected by the corresponding photodiode (PD Inloop). To create an offset frequency for the beatnote and to compensate the link noise the acousto-optic modulator (AOM) is used. The compensation signal is produced from demodulating the inloop beat signal by 159 MHz signal from stable radio frequency (RF) generator (home-made direct digital synthesizer (DDS)) at digital phase detector and then feeding via the analog proportional-integral amplifier (PIA) into voltage-controlled oscillator (VCO) which in turn drives the AOM. For the full characterization of the link performance especially on the stage of research the detection of the so-called remote beat signal is needed. To create this beat signal we locate the receiver side nearby the rest scheme. The beat note of 5 mW local and 1.5 mW remote beams is detected by the separate photodiode (PD Remote). Frequencies of both of the beat signals (inloop and remote) are measured by high-resolution dead-time-free phase recorder K+K Messtechnik operating in $\Lambda$-mode (phase averaging mode). Note that the phase recorder as well as RF generator should be referenced by common 10 MHz signal from stable RF source. For the characterization of the link performance it is sufficient to use the standard RF generator but for real transfer of an ultrastable frequency the
hydrogen maser should be used. To detect cycle-slip events each of two signals (after proper amplification, down-shifting and filtering) are recorded by pair of independent channels of the phase recorder. At the same time to extract the information of the noise which has been detected and compensated we also record the VCO output signal (correction signal) by two channels of the same K+K recorder. This allows us to observe simultaneously the link noise and the compensation scheme performance. Another possibility is to measure the uncompensated link noise in separate experiment that is with compensation being inactive (AOM is driven by stable RF generator) but in this case the comparison between uncompensated and compensated links is not so clear due to volatile atmospheric conditions. However this kind of experiment is extremely useful to distinguish between noise introduced by feedback loop including interferometric geterodyning scheme and actual link noise.

The 17 m long atmospheric link is formed by attaching the corner-cube reflector on a fence 8.5 meters away from the lab window. To avoid huge diffraction divergence the Keplerian type telescope is used to enlarge the beam diameter from 2 mm to approximately 20 mm. For future longer links we plan to use larger beams.

Figure 2. Time dependences of the frequency of inloop (red empty circles) and remote (green filled squares) beat signals and correction signal (blue empty triangles). Phase recorder time window is 100 ms. For clarity, the frequencies are shown with expected mean values being subtracted. The inset shows part of data for inloop and remote since they are not distinguishable in the main graph.

Figure 3. Time dependences of the phase of inloop (red empty circles) and remote (green filled squares) beat signals and correction signal (blue empty triangles). Phase recorder time window is 100 ms. The inset shows part of data for inloop and remote since they are not distinguishable in the main graph.

3. Results and discussion
We have recorded two data sets: short one with 1 ms phase recorder time window and long one with 100 ms time window. Due to scintillation and angle-of-arrival jitter we have managed to obtain data stretch as short as 1500 s for the second data set. Figures 2 and 3 show frequencies and phases dependence on time for inloop and remote beat signals and for correction signal. The expected mean
value is subtracted from frequency data for convenience (159 MHz for inloop and 79.5 MHz for remote and correction signals). It is clearly observable that the detected and compensated noise is much larger than residual frequency and phase fluctuations of remote signal.

Figure 4. Allan deviation vs averaging time for inloop (red empty circles) and remote (green filled squares) beat signals and correction signal (blue empty triangles). Small and large markers correspond to the measurements with phase recorder time windows of 1 ms and 100 ms, respectively. Symbols are connected by lines for eye guidance.

Figure 5. Power spectral density of phase fluctuations vs Fourier frequency for inloop (red dashed-dotted line), remote (green solid line) and correction signal (blue dashed line). Left part of the graph (frequencies less than 5 Hz) and right part (frequencies more than 9 Hz) correspond to the measurements with phase recorder time windows of 100 ms and 1 ms, respectively. Points (are not shown) are connected with lines for eye guidance.

The figure of merit for such kind of systems is its frequency instability, inaccuracy and phase noise which the link imprints into the transferred signal. Fractional frequency instability in terms of Allan deviation [13] is shown in figure 4. The deviation for inloop signal has the slope close to \( \tau^{-1} \) which corresponds to correct operation of the feedback loop. The deviation of the remote signal has bigger values of deviation as well as it has some modulation at small averaging times \( \tau \) and averages slower at \( \tau > 1 \text{ s} \). We guess that partially this is the contribution of nonstabilized fiber tails [14] with total length of 50 cm which outcouple the part of laser radiation for remote beat signal producing (see figure 1). The difference between two measurements is probably caused by different conditions of environment which affects on the fiber (the short data set with 1 ms time window was obtained in the evening whereas the long one with 100 ms is a part of all-night measurement). The Allan deviation of correction signal yields the information about the atmospheric link induced noise. It has almost flat plato for short averaging times and then averages down a bit slower than \( \tau^{-1} \). From this data one can see that noise compensation system allows to decrease fractional instability from \( 5.4 \cdot 10^{-15} \) to \( 1.1 \cdot 10^{-16} \) at \( \tau = 1 \text{ s} \) and from \( 6.2 \cdot 10^{-17} \) to \( 2.3 \cdot 10^{-18} \) at \( \tau = 250 \text{ s} \). Another important value is the difference between real mean frequency and expected one. It shows the link contribution to inaccuracy or uncertainty of
the transferred frequency. In our case it was decreased from 3.6 mHz (for correction signal) to 2.5 μHz (for remote signal) or from 2⋅10^{-17} to 1.3⋅10^{-20} in relative units after 1500 s.

For more detailed analysis of the noise type the power spectral density (PSD) of phase fluctuations is used. Figure 5 shows PSD for inloop, remote and correction signals. The remote signal has resonant peaks in the region of 100-200 Hz which probably correspond to the fiber tails vibrations and can be avoided in future experiments as well as excess noise at low frequencies. In accordance with the Kolmogorov theory the correction signal PSD should has the slope of $f^{-8/3}$ in some part of spectrum whereas in some experiments the deviation from this law is observed, for example in [8] the slope is $f^{-2.3}$. The region 1.5 Hz-4 Hz is close to $f^{-2.4}$ dependence but due to lack of data is requires further investigation.

Our recent plans are to eliminate the impact of measuring scheme, e.g. fiber tails, on the result, implement active beam position control with the help of the mirror with 2D galvo system, enlarge the link length up to 500 m and use unmanned aerial vehicle as a model of moving receiver.

4. Conclusion

We have demonstrated the system of active phase noise compensation for 17 m atmospheric link. The obtained instability of $2.3\cdot10^{-18}$ at 250 s and inaccuracy of $1.3\cdot10^{-20}$ show the potential applicability of the link in clock comparison experiments however the longer data sets are needed. By using the femtosecond frequency comb it is possible to compare frequency standards with very different frequencies.

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