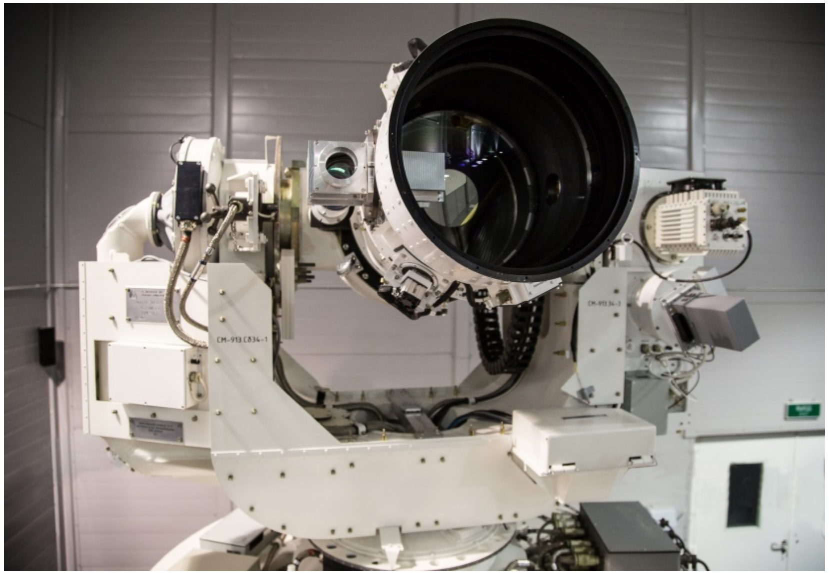
TIME TRANSFER THROUGH GLONASS:

MOTIVATION, GOALS AND TECHNICAL IMPLEMENTATION



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Agenda

1. **Rationale and goals for establishment of a laser time transfer (LTT) system through the GLONASS orbital constellation.**
2. **Concept of time transfer using SLR stations and requirements to additional ground-based time transfer (TT) equipment.**
3. **Comparative accuracy of laser and radio measurements of a divergence between onboard and ground-based time scales.**
4. **Technical implementation of a ground-based TT module in the Tochka station.**
5. **Technical implementation of an onboard TT module in the Glonass-K navigation spacecraft.**

Rationale and goals for establishment of an LTT system through GLONASS

The modern standards provide transfer of time and frequency units with an uneliminated systematic error at a level of $3 \cdot 10^{-16}$ and have a relative instability of frequency and time unit transfer at a level of $5 \cdot 10^{-16}$ per day.

As 2020 approaches, it is expected that there will be created optical primary time & frequency standards with accuracy characteristics at a level of 10^{-16} – 10^{-17}.

Due to that tendency, one of the priority tasks in the Russian instrument making is a respective increase in accuracy of tools to compare the national time scale with the GLONASS system one, as well as with the time scales of other remote time and frequency standards.

The LTT system is currently underway to solve the tasks of increasing the accuracy of time transfer between remote ground-based time and frequency standards and also in order to increase the accuracy of remote estimates of parameters of the onboard clocks, including the divergence between onboard and ground-based time scales, relative error on frequency and relative instability of frequency on the 24h interval.

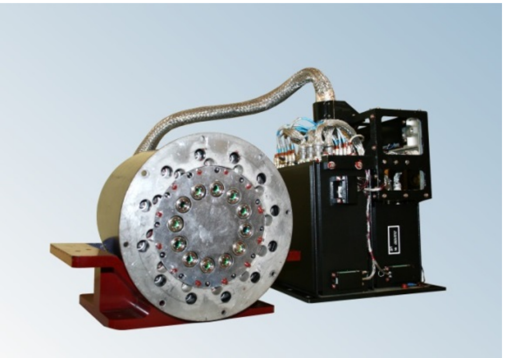
Concept of TT using SLR stations

All of the above-mentioned tasks in the established LTT system are addressed based on regular measurements of divergence between onboard and ground-based time scales.

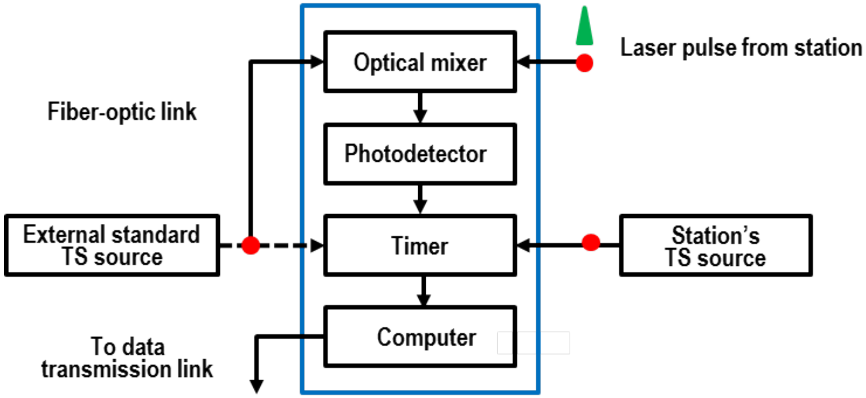
The divergence between the time scales is determined based on the difference between the laser pseudorange and range measurements. In its turn, the pseudorange is determined based on the difference between the moments a laser pulse is emitted in a ground-based time scale and then arrives at a SC in the onboard time scale.

So, in order to operate in mode of measuring the difference between the time scales, an SLR station has to be additionally equipped with a module of measuring the moments of laser pulse emission in the ground-based time scale, while a SC has to have a module of measuring the moments of laser pulse arrival in the onboard time scale.

Onboard TT module



Ground-based TT module



When it comes to the ground-based module, a measurement is taken by an event timer which receives the time tags corresponding to the SLR station laser emitter pulses and also the time tags representing the station time scale and/or the time scale of an external time & frequency standard.

The onboard TT modules which have an error of a single shot measurement of laser pulse arrival moments at a level of 80 ps have already been built and will appear in orbit as the GLONASS constellation grows with the Glonass-K satellites.

Requirements to additional ground-based TT equipment

A required error of single shot measurements of laser pulse emission moments in the ground-based module must not exceed 25 ps – 50 ps.

The energy potential of the station has to provide illumination of the onboard module in the range of 50 photons/mm^2 – 5000 photons/mm^2 at the wavelength of 532 nm. The pulse arrival rate is not limited but to achieve a high accuracy of measurement it is required to have such at a level of no less than 50 Hz.

The onboard TT module implements two modes for laser pulse reception: registration of all arriving pulses and registration of only those pulses which indicate a predetermined consistency in their sequence. The second mode is designed to filtrate the pulses coming to a SC from the stations which only measure the range and operate with the pulse repetition rates of 500 Hz or 1 kHz.

Comparative accuracy of laser and radio measurements of divergence between onboard and ground-based time scales

In general, the measurements of divergence between the time scales can be taken either using navigation signals or using laser pulses coming from SLR stations.

Measurement type	Single shot measurement error (σ)	Measurement error averaged per 30 s (σ)	Standard accuracy estimation error
Pseudorange measurements			
Code measurements	0.6 m (2 ns) at frequency of 1 Hz	~ 0.1 m (0.33 ns)	
Phase measurements	5 mm (16 ps) at frequency of 1 Hz	~ 1.0 mm (3.3 ps)	
Laser measurements	30 mm (100 ps) at freq. of 100-300 Hz	~ 0.5 mm (1.7 ps)	
Measurements of the divergence between the time scales			
Code measurements		0.15 m – 0.3 m (0.5 ns – 1 ns)	$\sim 1 \cdot 10^{-14}$ / day
Phase measurements		15 mm – 30 mm (50 ps – 100 ps)	$\sim 1 \cdot 10^{-15}$ / day
Laser measurements		1 mm – 1.6 mm (3 ps – 5 ps)	$\sim 5 \cdot 10^{-17}$ / day

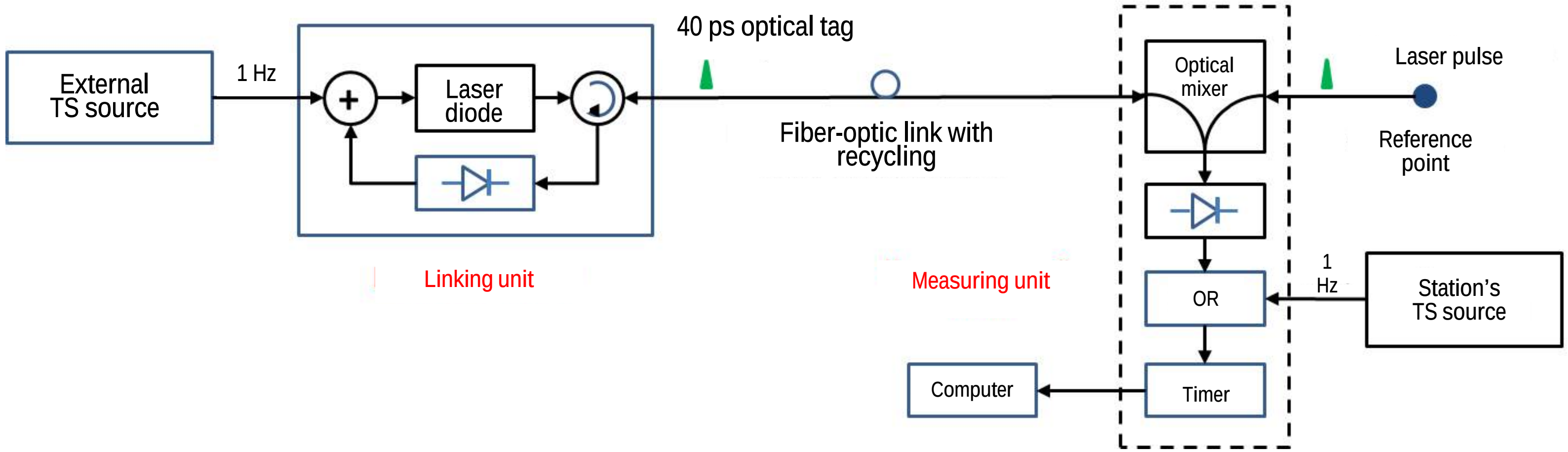
Cumulatively, in case of code measurements the error of estimation of the divergence be-tween the time scales is at a level of 0.5 ns – 1 ns, while in case of phase measurements it is at a level of 50 ps – 100 ps, and in case of laser measurements it is at a level of 3 ps – 5 ps.

Calculated as errors of estimates of characteristics of time & frequency standards, those errors correspond to a level of 10^{-14} per day for code measurements, to a level of 10^{-15} per day for phase measurements, and to a level of $5 \cdot 10^{-17}$ per day for laser measurements.

Technical implementation of a ground-based TT module in the Tochka station

All the Tochka laser stations are equipped with a ground-based TT module by default. The ground-based module consists of a unit for linking to an external time scale source to be placed in the external time source room and a measuring unit to be installed at a laser station.

The linking unit generates laser time tags of 40 ps in length tied to 1 Hz pulses of the external time scale.



The laser time tags go through a fiber-optic line of no greater than 2 km in length and arrive at the input of the optical mixer of the measuring unit. Laser pulses from the station come to the other input of the mixer.

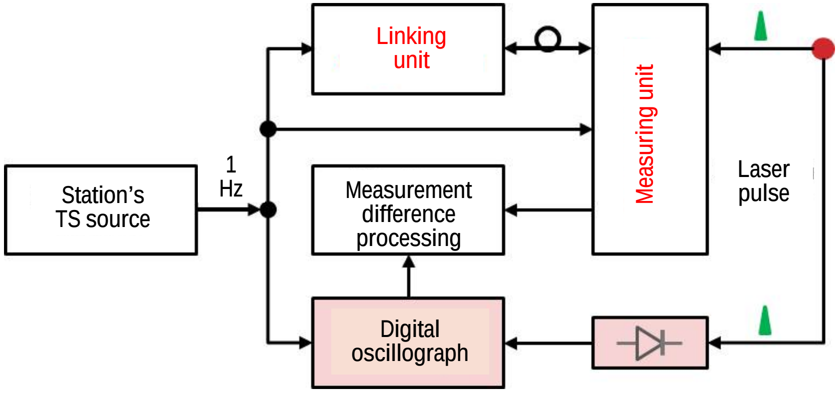
Once detected by the photodiode, the combination of laser pulses is mixed with the 1 Hz time tags of the station time scale source using the OR pattern.

Then the software using the data from the timer and considering calibrated delays in the equipment determines the following things: moments of laser pulse emission in the station's time scale, divergence of the station's time scale in relation to an external one and moments of laser pulse emission in the external time scale.

Estimation of accuracy of measurements taken by the Tochka ground-based TT module

While we're testing this out, the linking unit was placed in the laser station's room and an external time scale was simulated by the station's time scale source, while a fiber-optic line was simulated by a fiber line of delay the length which varied from 80 m to 2 km.

To estimate the accuracy of measurement of laser pulse emission moments, we used a control channel containing a broadband photodetector and a digital oscillography with a sampling rate of 40 GHz and an analogue bandwidth of 4 GHz.



Error of measurement of emission moments	In station's TS	In external TS
Random component	< 20 ps	< 25 ps
Systematic component	< 20 ps	< 25 ps

The Tochka ground-based module determines the laser pulse emission moments with an error of no greater than 20 ps in the station's time scale and no greater than 25 ps in the external time scale, respectively.

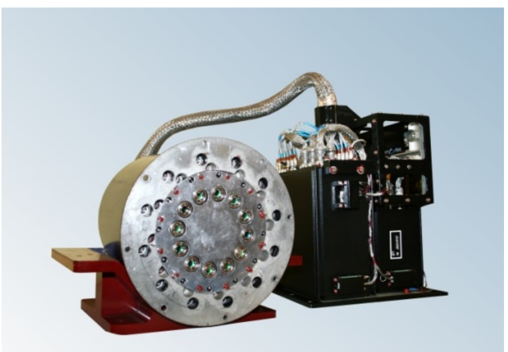
These errors are significantly lower than those from the onboard TT module, that is why the accuracy of TT measurements is in general determined by the onboard module.

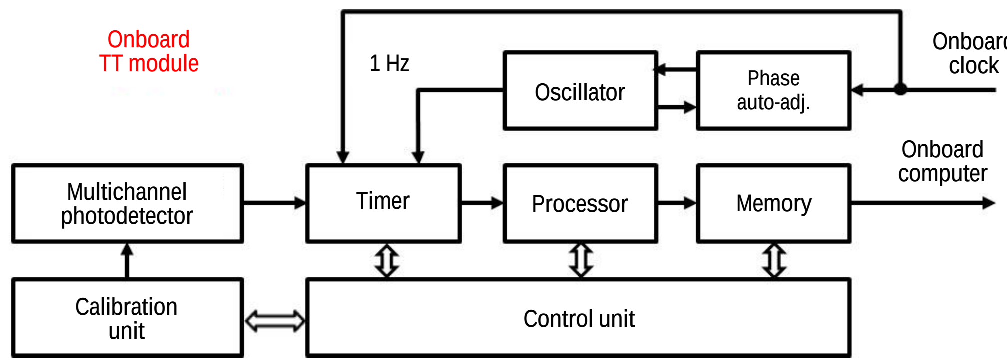
Technical implementation of the onboard TT module as a part of the Glonass-K navigation spacecraft

The onboard modules are designed to log the moments of laser pulse arrival in the onboard clock's time scale. The key components of the module are a multichannel photodetector, a timer, a data processor and a calibration unit.

The PD has 6 channels, the combined field of view of which is 24o and covers the entire visi-ble surface of the Earth. The pulses detected by the PD arrived at the timer, the single measurement error of which does not exceed 50 ps. The combined random error of single shot measurements of the module does not exceed 80 ps.

The measurements are improved by the calibration corrections which consider a laser pulse delay between the onboard retroreflector system's reflecting center and the module's receiving aperture, the module's hardware delay and a delay in the link between the module and the onboard clock. The calibration corrections consider a dependency of delays from the temperature and the intensity of arriving laser pulses.





The systematic error of measurement conditioned by an uncertainty of calibration corrections does not exceed 50 ps within the temperature and intensity operating range. A collected array of measurements is stored in 2Mb memory space which provides measure-ment logging at the 100 Hz rate within 2500 sec.

The module also provides a mode of generating a short data array in which the speed of the real data flow is reduced to 6 Hz which means 125 Kb for the same period. The onboard computer regularly addresses to the module's memory in order to transmit the measurement data to ground-based sites through a radio link.

Summary

1. The accuracy of laser measurement of the divergence between onboard and ground-based time scales is just a few ps on the 30 s averaging interval and exceeds the accuracy of measurement using the GNSS navigation signals for more than an order of magnitude.
2. In order to implement the LTT system through GLONASS, the Glonass-K SC are now equipped with the photodetecting module designed to log the moments of laser pulse arrival in the onboard time scale with a single shot measurement error of about 80 ps.
3. To operate in TT mode, an SLR station must be additionally equipped with the module for measurement of laser pulse emission moments in the ground-based time scale with a single shot measurement error of no greater than 50 ps.
4. The new Tochka stations are equipped with such modules by default, and their single shot measurement error does not exceed 20 ps.

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