New technologies for laser time transfer and their possible application in the Galileo programme

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ABSTRACT

We are presenting the new instrument, new technology available and new measurement technique proposal for the Galileo programme – optical detector for the laser time transfer. Combining the laser pulse emission times, propagation delays and satellite arrival times the ground to space clock comparison may be accomplished. The timing precision of the order of 1×10^{-12} seconds and a time transfer accuracy of 50 picoseconds is achievable. This precision and accuracy is at least one order of magnitude better in the optical region than in the radio frequency wavelength region. All the components of the proposed instruments are available in Europe, the ground segment of the proposed project is existing, the measurement techniques and data flow and processing procedures are well established. The implementation of new picosecond timing technologies and the laser time transfer into the Galileo programme will improve the precision and accuracy of the satellite on-board time scale and position prediction with unprecedent precision and accuracy. Both these facts will contribute to the Galileo system overall accuracy and performance and simultaneously will enable new experiments in fundamental physics.

1. OPERATING PRINCIPLE

We are presenting the new instrument, new technology available and new measurement technique: optical detector for the laser time transfer ground to space with un-precedent precision and accuracy. The idea of laser time transfer itself is not a new one [1, 2], however, the recent achievements in picosecond lasers, photon detectors, timing technology and the availability of on-board hydrogen maser frequency reference open new perspectives for applications. The project goal is the high accuracy comparison of time scales between the ground station and space clock located on the Earth orbiting satellite. The project is a spin-off of the existing projects of laser ranging to artificial Earth satellites [3]. In satellite laser ranging, the satellite equipped with optical retro-reflectors is ranged using short laser pulses. A short and powerful laser pulse is transmitted toward a satellite and part of the energy is reflected by the retro-reflector on-board the satellite back to the ground. The operating principle is as follows, see Fig. 1.

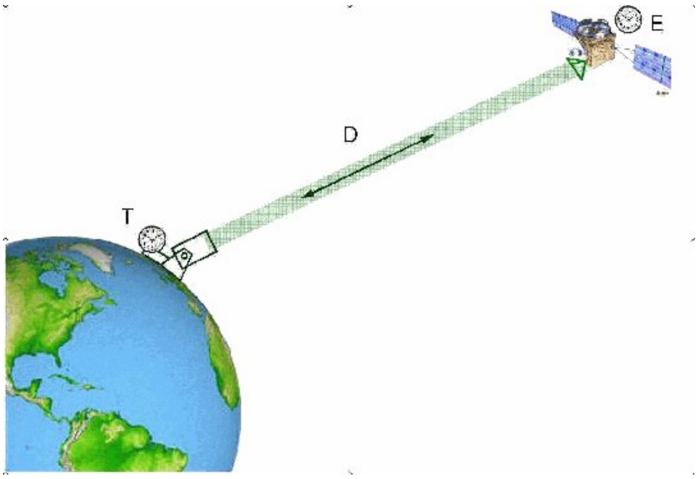

Fig. 1. The principle of ground to space clock synchronization by means of laser pulses. The satellite range ***D*** is measured by laser ranging technique, the laser emittion time ***T*** is recorded wrt ground clock, the arrival time of the laser pulse to the satellite ***E*** is recorded by on-board clock.

The reflected optical pulse is detected at the ground station and the pulse propagation time is evaluated. The range ***D*** is determined on the basis of the measured laser pulse propagation time toward the target satellite and back again. The epoch of transmission of laser pulse ***T*** is monitored with respect to the local clock for each laser pulse emission. For the Laser Time Transfer experiment the existing satellite laser ranging ground stations will be used. The satellite will be equipped with retro-reflectors to enable the laser ranging and, additionally, with an optical detector which detects and time tags the arrival of laser pulse at the satellite. The satellite range ***D*** is measured by laser ranging to the on-board retro-reflectors and the arrival time of the laser pulse to the satellite ***E*** is recorded by on board clock and the recorded time tags are transmitted to ground via satellite telemetry channel. Combining the laser pulse emission times, propagation and instrumental delays and satellite arrival times, the space clock and the station clock may be compared.

The Satellite Laser Ranging (SLR) technique has been well developed in recent years, ranging and epoch timing precision of the order of 1×10^{-11} seconds may be achieved. The range is related to time interval via the speed of light; one millimeter range corresponds to 6.7 picoseconds of two way propagation time.

The accuracy of the ground to space signal propagation delay is extremely difficult to quantify. Typically the consistency of results acquired using different techniques and/or the results of multiple frequency experiments are used to estimate the propagation delay accuracy. The accuracy of the laser ranging measurements is limited mainly by the atmospheric propagation delay model. Its accuracy is high; the absolute error is expected to be well below 4×10^{-11} seconds [3]. This accuracy is more than one order of magnitude better in the optical region than in the radio frequency region, which is expected to be in the order of 1×10^{-9} seconds [4]. Fortunately, the absolute error in the atmospheric correction is completely compensated in a one way laser time transfer when combined with satellite laser ranging at the same time. The absolute propagation delays associated with the optical timing chain may be calibrated down to the level of several tens of picoseconds. This enables to carry out the laser time transfer ground to space with the precision of units of picoseconds and with the accuracy of 50 ps.

2. EXISTING LASER TIME TRANSFER MISSIONS

2.1. Laser Time Transfer (LTT)

The very first laser time transfer ground to space was carried out using the LASSO experiment in the nineties [1]. However, the laser, optical detection and timing technology available were limiting both the precision and data yield at that time. The first LTT in picosecond time domain was completed on board of the Compass M1 satellite launched April 14, 2007. The satellite is a part of the Chinese global navigation system. Its orbit height is about 21,000 kilometres.

Extremely simple and rugged design of the optical receiver has been used [5]. It relies completely on single photon approach, only. This approach permits to minimize the systematic errors due to the optical signal intensity fluctuation and to minimize the on-board hardware complexity at the same time. The existing global satellite laser ranging network provides the typical signal intensity of units of photons per detection chip in one laser shot at the satellite orbit. This enabled to omit the use of collecting optics in receiver design and to use directly a photon counting K14 detection chip of active area diameter of 25 micrometers with attached band-pass filter only.

The ruggedness of the detector is superb, it permits to point the optical receiver directly onto the Sun without the risk of device damage, no Sun protection shutter is needed. The radiation damage of the detectors has been tested; the radiation-limited lifetime in space should exceed 10 years without significant parameter degradation.

The first ground to space time scales synchronization by laser pulses was accomplished from the SLR station located in Changchun, Jilin province, China. The limiting factor in this experiment was an extremely high optical background exceeding 50 million photons per second hitting the receiver and a limited data downlink capacity available. The example of the ground to space time scales comparison result is plotted in Fig. 2 [6].

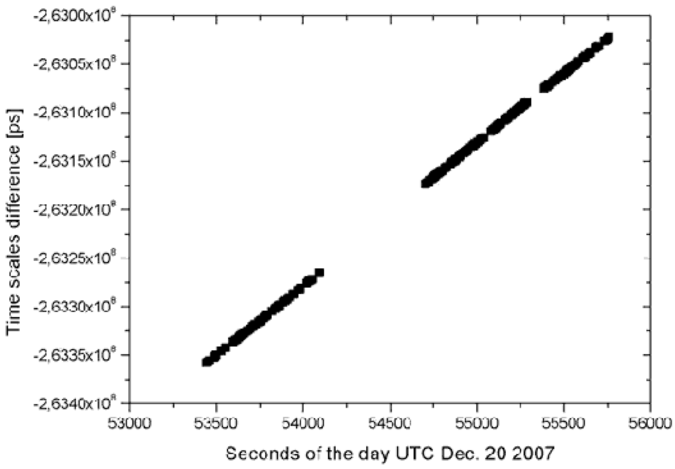

Fig. 2. Example of the ground (H maser) to space (Rb standard) time scales comparison, LTT Compass M1 satellite.

The horizontal axis represents the UTC time in seconds of December 20, 2007 and the vertical axis is the measured time scales difference in picoseconds. Fitting the data by the third order polynomial the data spread of 260 picoseconds was achieved. The resulting time scales synchronization precision is better than 20 picoseconds, the frequency difference between the ground and space frequency standards may be determined with an uncertainty of 3×10^{-14} within 2000 seconds [2].

2.2. Time Transfer by Laser Link (T2L2)

The T2L2 was prepared jointly by Centre National d'Études Spatiales (CNES) and l'Observatoire de la Côte d'Azur (OCA), France [7] and launched on board of Jason-2 satellite to the orbit at the height of 1330 km in June 2008. Due to the lower orbit altitude in comparison to LTT, much higher optical signal densities are available at the satellite. The multi-photon detection based on the K14 detection chip was used. It enables higher single shot precision of the on board optical pulses registration and completely asynchronous operation of the ground segment stations. The T2L2 is operational in space since 2008, according to the first results published [8] the time stability measured between space and ground is 7 ps in 30 seconds. This value is limited by the stability of the T2L2 on-board oscillator quality. It is expected, the T2L2 will provide absolute time transfer at ground with an accuracy of 100 ps. However, the detection time walk and the on-board oscillator quality remain a critical issue.

3. NEW TECHNOLOGIES FOR LASER TIME TRANSFER

3.1. Optical detector technology

Considering the Galileo satellites orbit height in the range of 21,000 km and the ground segment parameters, the photon counting optical detectors on board are required. The Chinese LTT concept proved the feasibility of such operation. The research and development of the photon counting detector for the European Space Agency space mission European Laser Timing, Advanced Clock Ensemble in Space (ELT-ACES) resulted in the new photon counting detector with unique features [9]. The detector package is based on the mature detection chip K14 operated in an active quenching and gating circuit, see Fig. 3.

Fig. 3. The laboratory sample of the photon counting detector package for the ELT mission, version 3.0 installed in the temperature control box. The active quenching and gating circuit is based on fast PECL circuits, the K14 detection chip (right).

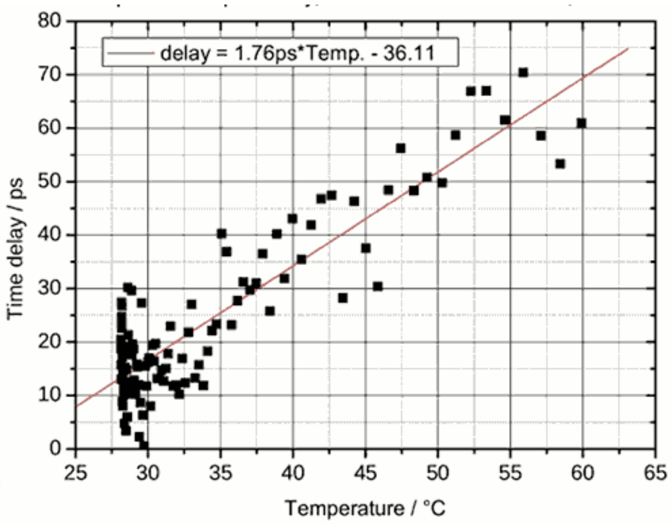

Fig. 4. The temperature stability of the detection, the drift corresponding to 1.76 ps/K may be seen, it will guarantee the delay stability of 10 ps over a temperature interval of 5 K expecting in operation conditions.

The new scheme of the detector control circuit was developed and tested. It enables the operation of the entire detector package in a broad temperature range exceeding −55 to +60°C. It provides timing resolution better than 25 ps in one measurement and good temperature stability of the detection delay: typically 1.76 ps/K, see Fig. 4.

At high satellite orbits the photon counting receivers are affected by a strong background light caused by solar photons back-scattered from the Earth and its atmosphere. At Galileo orbit the background photon count might be as high as 50 Mcounts/s. The new photon counting detector was tested in the presence of high background flux of thermal photons of >100 Mcounts/s. The photon detection delay and timing resolution do not change by more than 2 ps over an entire dynamical range of background flux.

3.2. Sub-picosecond timing technology

A novel time interval measurement method which provides sub-picosecond timing, linearity and stability has been developed and tested [10 – 12]. It is based on a transversal surface acoustic wave (SAW) filter as a time interpolator. A New Picosecond Event Timer (NPET) device based on this new technique has been designed and realized. Measuring the Times of Arrival of the test pulses generated synchronously to the local time base the measurement precision of 1.0 ps was achieved, see Fig. 5.

The timing non-linearity lower than 200 femtoseconds over an entire range [13] and the long term stability in the range of ±20 fs/hour is achieved see Fig. 6.

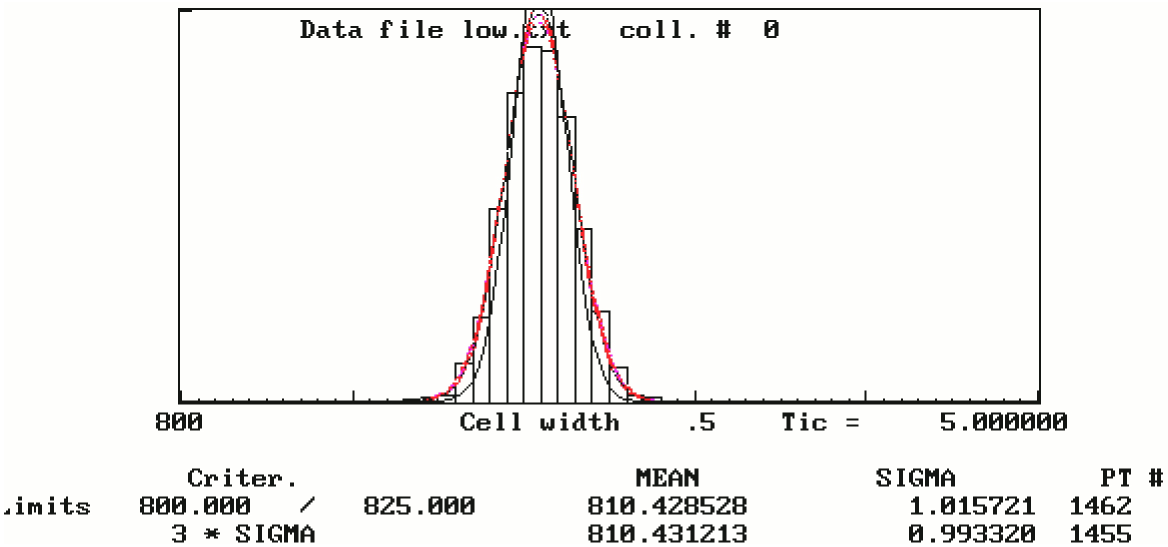

Fig. 5. The histogram of the data spread when recording the times of arrival of the test pulses generated synchronously to the local time base the measurement, the time units are ps, the precision of 1.0 ps was achieved, the data distribution is close to normal.

The timing device temporal stability may be demonstrated in the following experiment: the times of arrival of the test pulses generated synchronously to the local time base were recorded the results are plotted in Fig. 6. It is worth to mention, that all the timing experiments were carried out in standard laboratory environment, without any temperature stabilization, RF shielding etc.

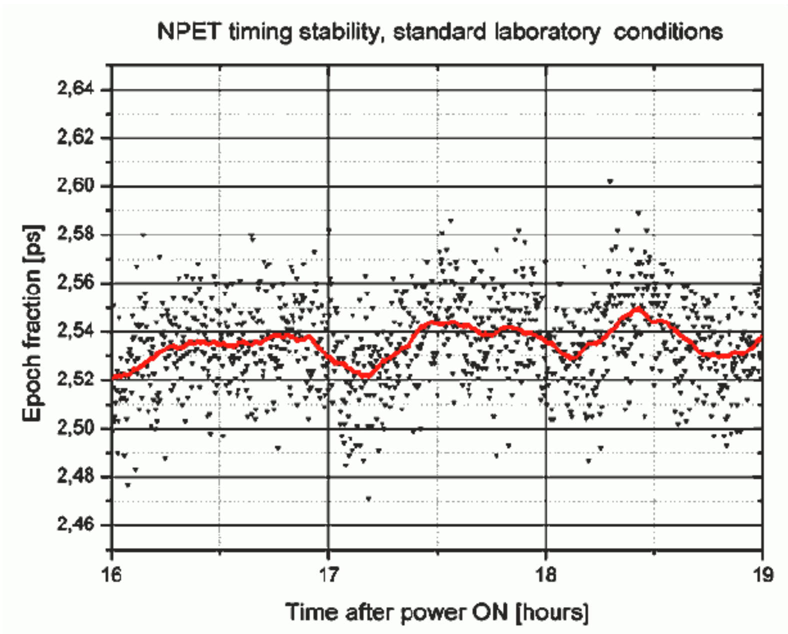

Fig. 6. The times of arrival of the test pulses generated synchronously to the local time base, frequency 763 Hz, average values of 1000 readings are displayed (triangles) together with the moving averages over 100 seconds. The device epoch reading stability of ±10 fs per hour may be seen.

The ultimate timing device temporal stability was demonstrated in the following experiment: the times of arrival of the test pulses generated synchronously to the local time base were recorded the results are plotted in Fig. 7. This experiment was carried out in a temperature well stabilized environment of the observatory of Wettzell, Germany. The excellent value of T_{dev} dropping below 4 fs for the averaging times between 500 and 7000 seconds has been achieved.

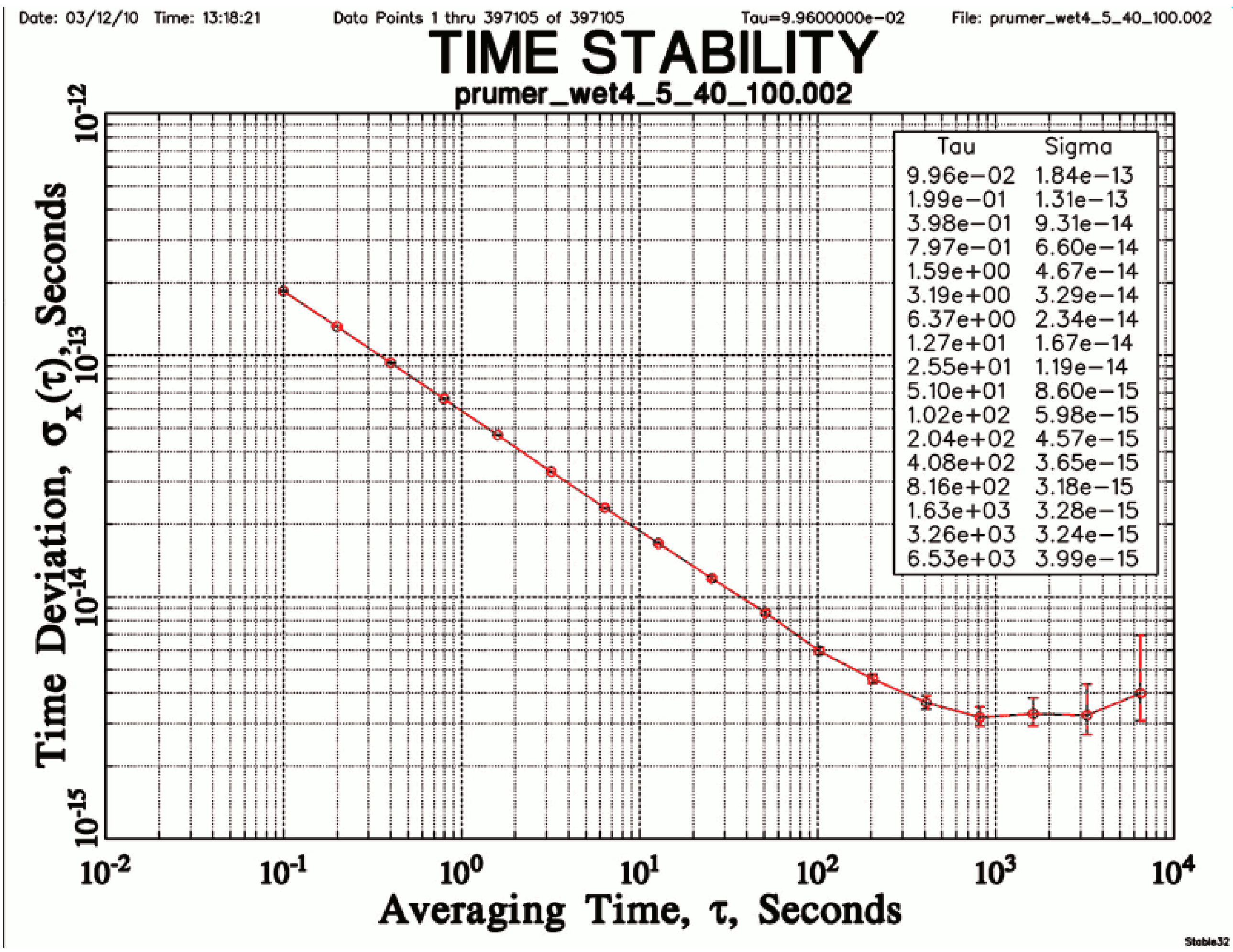

Fig. 7. The timing stability of the device when operated in the thermally stabilized environment. The excellent stability on the level of below 4 fs for the averaging times between 500 and 7000 seconds has been achieved

To summarize – the newly designed timing device provides sub-picosecond timing performance: resolution, long term stability and linearity. The device is self-calibrated – it needs no field adjustment and/or calibration. Its power consumption is well below 20 Watts and mass is below 1 kg. We do expect that its construction might be adjusted for space use.

4. EXPECTED PROBLEMS AND POSSIBLE SOLUTIONS IN LASER TIME TRANSFER

4.1. Optical background noise and detector gating

Considering the laser time transfer optical signal budget: Galileo satellites orbit height (~ 21,000 km), laser ranging station laser energy (in the range of 0.4 to 250 mJ per pulse) and transmitted beam divergence (typically 10 to 20 seconds of arc) the photon counting detection is required on board the satellite. However, the photon counting receiver will detect, among others, rather strong background optical signal coming mostly from photons of solar light scattered by the Earth's atmosphere and by the Earth surface itself. The amount of scattered photons hitting the detector depends mostly on the instant Sun – Earth – satellite configuration. The receiver optical band-pass filter can reduce the amount of background photons. However, its bandwidth is limited by required field of view of the optical receiver. The experience gathered in the Compass M1 mission shows, that the background photon count rate should be in the range of 1 to 30 million counts per second.

To reduce the amount of background counts down to a manageable value the efficient detector gating must be used. This technique was quite well elaborated for the ground based satellite laser ranging systems, which operate at the single photon signal level. The satellite range – the time of arrival ***TA*** of the photon of interest – is a-priori known with certain accuracy of ***DT***. The photon counting receiver is activated "gated on" by ***DT*** time interval earlier prior to ***TA***. Obviously, the efficiency of background photon flux suppression is depending on the accuracy of the a-priory knowledge of the satellite orbit. Fortunately for the GNSS satellite, this accuracy is quite high and it is in the order of several meters. It means that the photon counting detector may be gated as close as 30 – 50 nanoseconds prior to expected arrival of photon of interest. To simplify the experiment organization, it is more practical to gate on the receiver on board in predefined epochs with respect to the on board time scale. The ground stations have to fire their laser transmitters in pre-programmed times selected in such a way, that the optical signal reaches the satellite shortly after the detector was gated on. Although this setup seems to be rather complex, it is manageable. The Chinese LTT experiment proved the feasibility of such operation.

4.2. Data transmission / downlink

The gated operation of the photon counting receiver is reducing the downlink data volume. Considering the timing resolution required (order of units of picoseconds) the corresponding data volume is about 45 bits per one measurement. The repetition rate of the satellite laser systems is in the range of 5 Hz to 2000 Hz. The data volume for the measurement itself corresponds to 450 bits/s and 90 kbits/s for the repetition rates of gating of 10 and 2000 Hz respectively. The total volume of data which should be transmitted to the Earth per day might be further drastically reduced by the on board data storage and consequent down linking only the data corresponding to the time slots, when some of the ground stations performed the measurement. This procedure would reduce the total data volume to be transmitted to the Earth significantly much more than 10 times, what would result in <4 Mbits/ day for 10 Hz rate and in <400 Mbits/day for 1 kHz measurement rate.

5. NEW SCIENCE ON GALILEO USING LASER TIME TRANSFER

The new technology achievements listed in previous chapters along with the availability of extremely stable on board time scales open new perspectives for experiments in physics in future Galileo missions.

The ongoing Galileo mission might benefit from several important facts:

- The experiment itself is carried out routinely on board two space missions CompassM1 and Jason-2. The Compass M1 application proved the concept of single photon detection, the Jason-2 proved the capability to provide picosecond timing.
- The European Laser Timing is under preparation for the European Space Agency ACES mission, the future Galileo might rely on its experience and results which are expected to be available in 2013.
- Due to the orbit geometry, the laser time transfer via Galileo orbit would enable time transfer ground to ground via space in a common view configuration over inter-continental distances. This is in contrast to the ELT and Jason-2, which are both flying on low Earth orbits.
- The availability of Hydrogen maser on-board Galileo will remove the key limitation on time transfer ground to ground, which is present in the Jason 2, thus longer averaging times will be available for picosecond precision and accuracy.
- The recent achievements in photon counting detectors for space application will provide picosecond stability of the optical detector including the unprecedent picosecond stability of the detection delay.
- The achievements in sub-picosecond timing will enable to build the timing system which will provide sub--picosecond linearity and stability.
- These values of timing resolution and stability are about one order better in comparison to the detector and timing system operating on board of Compass M1 satellite. Moreover, the data downlink capacity of 450 bits/s or even higher will allow averaging of much larger amount of measured data in comparison to the Compass M1 satellite data downlink capacity which is limited to 40 bits/s allocated for LTT.

A time transfer with picosecond precision and uncertainty of 50 picoseconds is achievable. This precision and in particular the level of accuracy is at least one order of magnitude better in the optical region compared to designs using micro-waves. Hence this technique of time transfer by laser light might be used as a powerful tool to calibrate the ionosphere delays and to improve the existing models of ionosphere signal delays.

The ground to ground laser time transfer via Galileo would significantly contribute to a world wide availability of local time scales synchronization tool with accuracy not achievable by other techniques. It will provide an independent means to calibrate time links between national metrological institutes, which are responsible for the generation and maintenance of national UTC time scales.

The implementation of laser time transfer concept into the Galileo programme will improve the precision and accuracy of the satellite position prediction and will add the capability of comparing / monitoring / deriving corrections for the space clocks.

The laser retro-reflector arrays are expected to be installed on the future Galileo satellites. The implementation of laser time transfer concept into the Galileo programme will require the additional hardware on board the satellite: the optical receiver and the timing unit. This adds about 4 kg of additional mass and less than 25 Watts of power.

6. SUMMARY AND CONCLUSION

The implementation of laser time transfer concept into the Galileo program will improve the precision and accuracy of the satellite position prediction and will enable the ground to space time transfer with unprecedent precision and accuracy. Both these facts will contribute to the Galileo system overall accuracy and performance. In addition, it will provide an independent means to calibrate time links between national metrological institutes, who are responsible for the generation and maintenance of national UTC time scales. Thanks to optical frequencies involved, the laser time transfer will provide an independent and accurate information on signal propagation delays ground to space. Hence, the ionosphere radio delays might be calibrated by an independent technique.

All components of the proposed instruments are available in Europe. They have been used successfully in previous space missions. The ground segment of the proposed project is readily available at several laser sites. Measurement techniques, data flow and processing procedures are well established. Requirements on satellite resources are modest.

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