

Perspectives of Time and Frequency Transfer via Satellite

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Abstract. This paper reviews key characteristics and requirements for Two-Way Satellite Time and Frequency Transfer (TWSTFT) links. The outline and perspective of two concepts are described: 1. The classical bend-pipe transponder, without special equipment on board, with the potential of 10^{-17} /day frequency transfer uncertainty; 2. The ACES-MWL (Atomic Clock Ensemble in Space Microwave Link) like active on-board equipment, with the potential down to few 10^{-19} /day, using both high-rate modulation and carrier-phase. An outlook to advanced links is given. The aim of these proposed links is to provide a unique platform for the demanding requirements in the field of time and frequency metrology and to support improved orbit determination and relativistic geodesy for the next decades.

1. Introduction

Two-Way Satellite Time and Frequency Transfer TWSTFT is in regular use since the early 1980s, mostly using a modem, which has originally been developed at the Technical University (TU) in Berlin [1]. During its introduction, its stability and accuracy was roughly 1 to 2 orders of magnitude better than existing clocks, whereas today it lacks performance by few orders compared to modern clocks. This is due to the dramatic improvement of microwave frequency standards and optical clocks over the last decades.

Today, TWSTFT is mainly used to link metrological institutes in US, Asia and Europe in support of the generation of Coordinated Universal Time UTC [2]. It reaches a 10^{-15} uncertainty level [7] with modest modulation rates of 1 to 2.5 MChip/s. Ground station networks use the CDMA (Code Division Multiple Access) properties of Pseudorandom Noise (PN) Codes to exchange signals via a single regional geo-stationary transponder. Each station determines the time-of-arrival of signals from the remote sites. The difference between simultaneous readings of a link provides the wanted clock offset [3]. The main advantage of TWSTFT is still seen in the capability to cover intercontinental distances and being a true alternative to links based on Global Navigation Satellite Systems (GNSS). Although ground optical fibers have a promising perspective both for frequency and time transfer [9], they are still limited to continental distances and only very few optical fiber links between selected institutes are available.

Hardware with improved performance has been developed for the ACES (Atomic Clock Ensemble in Space) mission [10], i.e. the ACES MicroWave Link (MWL) [11]. ACES will embark a cold atom clock (Pharao) and an active hydrogen maser on board the International Space Station (ISS), to be launched in 2017. The on-board clocks are compared to ground using the MWL instrument at performance levels in the 10^{-17} region of frequency uncertainty. The performance improvement has been achieved by carrier phase measurements, with phase continuity from pass to pass. Results of laboratory tests show, that the engineering model meets the ACES mission performance requirements.



This renders the ACES-MWL architecture a candidate for even higher performance missions in the near future. Preliminary link simulations for the proposed STE-QUEST mission [12] suggest, that an uncertainty level of 10^{-18} is within reach for ground-to-space links, while ground-to-ground links are less critical and laboratory measurements show that few 10^{-19} are possible.

There are exciting new microwave technologies [15], which suggest a further growth potential using very high modulation rates in the GChip/s region and Extremely High Frequencies (EHF, 30 GHz to 300 GHz), but still providing tolerance to attenuation caused by fog and clouds [16].

An outlook is given for optical free-space communication links [17], currently explored mainly in space-to-space configuration, but which might become relevant for space-to-ground applications as well. The latter is limited to favorable weather conditions, however.

2. Historical Background

2.1. Basic Principles of Remote Time and Frequency Transfer

TWSTFT [3] is based on the principles of coherent communication, which was - at the time of development - well known from pioneering work at JPL in the frame of deep space links [4]. Two simultaneous emissions in bi-directional configuration allow suppression of most link-induced errors. Systems developed so far are MITREX [1] (1977), SATRE [5] (1990), PRARE [6] (1983, for geodetic applications) and the ACES-MWL [11] (2003). In brackets, year of start of development.

The overall performance of such systems is primarily determined by the noise characteristics of the delay-lock tracking loops (DLL), which are used to re-construct the phase of the modulation of the received signal by correlation with a locally generated replica of the received PN signal. In the short-term, i.e. for integration times up to approximately 100 s, thermally-induced white phase noise dominates, averaging well with time. In the medium-term to 1000s, flicker phase noise is limiting, which is best overcome with high modulation rates. In the long-term above 1000s, environmental effects, in particular temperature, impact the performance, which require a well-engineered design of all elements involved.

2.2. Key concepts of current hardware implementations

Some key concepts have been developed already in the 1980s at TU Berlin, including

- Use of PN coded signals for ambiguity resolution in favor of tone-based ranging systems;
- Binary Phase Shift Keying (BPSK) modulation with fully suppressed carrier for best efficiency;
- Use of truncated maximum-length PN codes to fit into a decade system for 1pps generation;
- Use of non-coherent DLL to become independent from potential carrier instabilities, including those from Doppler and from superposed data modulation;
- Use of a PN phase shift modulation to add 1pps markers without need for carrier recovery;

These key elements are still present in actual designs, while most performance improvements have been achieved since MITREX by increasing the modulation bandwidth, by using modern wide-band electronics with high intrinsic delay stability and by coherent carrier recovery and demodulation. The latter allows for precise Doppler measurements and data transmission.

2.3. Standard Two-Way Satellite Time and Frequency Transfer (TWSTFT) and Ranging

TWSTFT is based on simultaneous bi-directional exchange of signals through geostationary communication satellites, using Ku- and X-band frequencies. There is no special equipment on board. Most links are via commercial satellites, for which transponder bandwidth has to be paid for. For cost reasons, low bandwidth signals at 1 MChip/s modulation are used in the metrological networks for links between US and Europe and within Europe, the Asia to Europe links operate at a more favorable 2.5 MChip/s rate. These links contribute to the generation of UTC by the BIPM with regularly scheduled operations [8].

At chip rates of roughly 250 MChip/s, TWSTFT has the potential of 10^{-17} / day frequency transfer uncertainty and a systematic time transfer uncertainty of well below 1 ns. However, due to cost reasons, such links would be limited to dedicated experiments.

A good example for higher precision is ranging operation at 20 MChip/s, which exhibits 2 cm ranging noise via geo-stationary satellites at C/No of 43 dBHz, even when the transponder is loaded with regular TV-signals and the ranging signal is 30 dB below main traffic in CDMA mode. For ranging, the round-trip signal delay is measured, where the link delay does not cancel as in the bi-directional case (see Fig 1.)

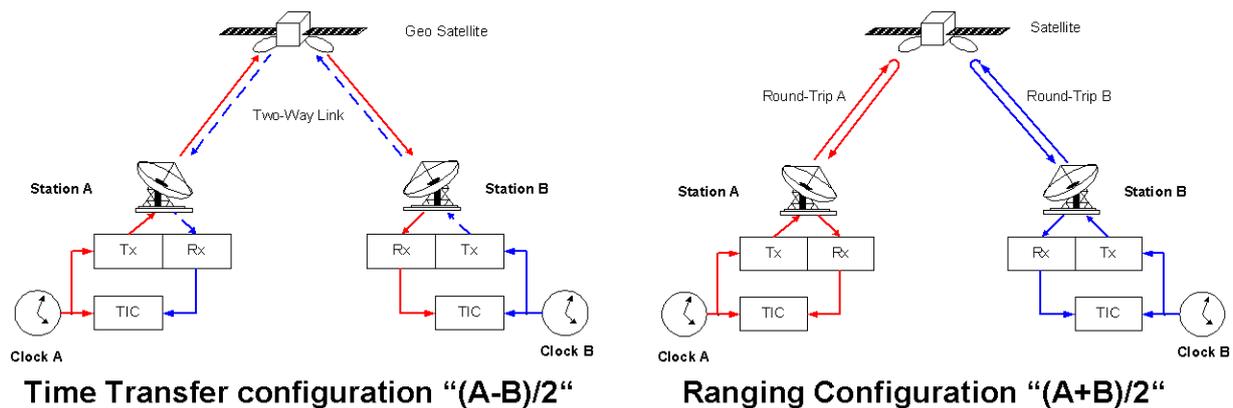


Figure 1. Bi-directional time and frequency transfer (left) and satellite ranging (right)

It is interesting to note, that ranging and TWSTFT can be performed simultaneously and with identical equipment. This allows the combination of ranging for geodesy and time transfer for metrology.

3. Active Systems on Satellites

In the case of commercial transponders, the unknown, free-running local oscillator required for signal translation does not allow for unambiguous use of the signal carrier. A 2-way carrier phase (2-WCP) configuration was designed [13], mainly to explore the significantly higher precision available from the carrier, but 2-WCP lacks strict coherency between modulation and carrier. Hence this method is limited to frequency transfer, as it does not allow unambiguous recovery of the carrier phase after signal loss. To add full carrier phase capability with phase continuity after signal loss, active on-board systems have been developed, which use a fixed phase relationship between modulation and carrier.

3.1. PRARE on-board ERS-2 and ACES MWL

The Precise Range and Range Rate Equipment (PRARE) [6] was actually a geodetic instrument based on time-interval metrology. It was intended to combine the best available concepts at that time, including dual band delay measurements and carrier phase data. It was the first ranging system, where the measurement was initiated at the satellite. It operated 12 years successfully on board of ESA's environmental satellite ERS-2 in support of the main radar altimeter instrument, providing high precision orbital data. Round-trip range measurements were in X-band to up to four ground stations simultaneously with CDMA and a PN-code rate of 10 MChip/s. An additional S-band downlink was used to determine the first order ionosphere delay. Ranging noise using modulation was 0.9 cm (corresponding to 54 ps round-trip delay noise) and the velocity noise using carrier Doppler was 0.015 mm/s respectively at 15 s integration intervals. (data courtesy GFZ, Potsdam).

PRARE formed the baseline for the ACES Microwave Link (MWL), which shall be remarkably better than usual GNSS and TWSTFT techniques. Its performance is more than 10 times improved with respect to PRARE and its layout on ground is optimised for bi-directional operation rather than for round trip ranging. Ground stations feature a dedicated design, with antenna radome and well

controlled temperature for the front-end and electronics. The MWL will be installed as part of ACES on the ISS. It uses mainly the bi-directional Ku-band signals, with an auxiliary S-band downlink. Modulation rates are 100 MChip/s in Ku-band and 2.5 MChip/s in S-band (Figure 2, left).

The fully coherent architecture is optimized for unambiguous carrier phase measurements, where the modulation is used mainly for time transfer, synchronisation and carrier cycle identification. Ionospheric delay is accounted for by differential delay in Ku vs S-band and removal of ionospheric variations is by differential carrier phase. Ground tests have demonstrated stability of 2×10^{-16} for the modulation and few parts in 10^{-17} for the carrier at 10000 s integration time (Figure 2, right).

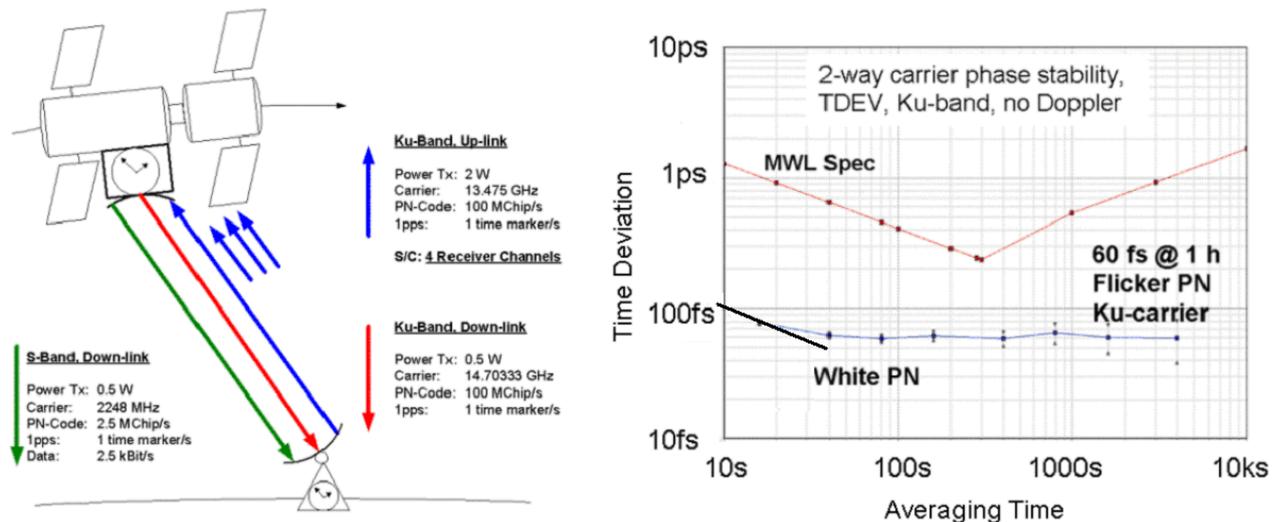


Figure 2. ACES signal characteristic (left) and 2-way laboratory test results compared to specifications.

3.2. MWL design for HEO mission

A new Microwave Link is currently researched for satellite missions on Highly Elliptical Orbits (HEO) with apogee of about 50000 km and perigee of about 900 km, such as the proposed STE-QUEST [12] mission. Intended frequency stability is 10^{-18} at 100000 s averaging time. A systematic frequency uncertainty 5×10^{-19} at 1 week is required for ground-to-ground clock comparisons involving two ground stations. Tentative operation is in Ka-band with modulation at 250 MChip/s and X-band as auxiliary downlink. Key concepts from the ACES-MWL will be re-used, and new components for Ka-band are under development. End-to-end simulations show feasibility to meet these requirements. The major challenges here are potential systematic frequency errors due to relative acceleration between space and ground.

4. A Possible Path to the Future: Laser Communication Terminals (LCT)

Laser communication technology can be regarded as the logical evolution of microwave links. Being bi-directional by design [17] to fulfill strict pointing requirements for the optical beams, they feature very high bit-rate communication and thus positive signal-to-noise ratio. This shows their very promising capabilities, while retaining the bi-directional architecture, at significantly increased signaling rate and an improved link budget. Typical C/No is around 100 dBHz, with BPSK at Gbit/s rates, which results in 4 to 5 orders of magnitude improvement compared to ACES-MWL modulation performance. Even if the optical carrier itself would not be used for metrology, measurements on the modulation alone are very attractive, providing inherent ambiguity removal. Operation under very high Doppler and Doppler-rate has been successfully demonstrated e.g. between two Low Earth Orbiting (LEO) satellites TerraSAR-X and NFIRE, with 5.625 Gbit/s data rates [18].

It is expected, that optical communication link technology will further evolve in the near future, at the same rate as the demand for link capacity is ever increasing. The next step has been achieved for bi-directional links between GEO and LEO satellites at 1.8 Gbit/s data rates [19] and further reductions in complexity and cost are likely for this novel concept.

Current LCT hardware does not yet implement precise time-of-arrival measurements, but the perspective is clearly visible, once such additional capabilities would be incorporated.

Apart from the coherent and continuous LCT designs, pulsed lasers like the ELT (European Laser Timing) [20] as part of ACES payload on the ISS are promising even under light cloudy weather conditions. Their stability performance is not yet considered comparable to continuous links. The limitation is mainly by the available measurement rate. However, pulsed laser links with quasi-instantaneous operation are important means for the calibration of continuous links, both for ranging using the established Satellite Ranging Method (SLR) or for time transfer, using ELT-like configurations. With clocks being synchronized by TWSTFT, one-way laser ranging and time-transfer becomes feasible, which is not limited in distance by on-board laser reflectors.

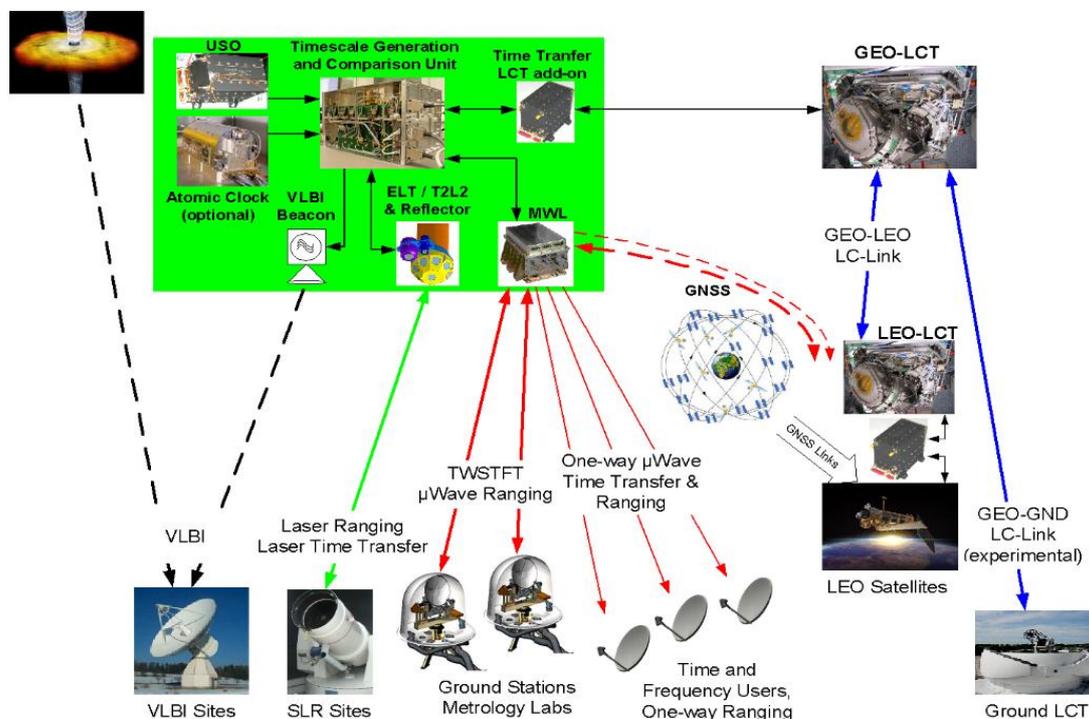


Figure 3. Candidate GETRIS architecture.

5. Geodesy and Time Reference in Space: The GETRIS Concept

The GETRIS concept (Figure 3) has been proposed to fulfill demanding time transfer needs as well as geodetic purposes. It is a geostationary system with sensor co-location on board and on ground. This allows for optimum combination and comparison of different technologies, mainly microwave and optical, both pulsed and continuous. VLBI is used to link terrestrial and celestial reference frames. Optical systems will be used for dedicated experiments and for the delay calibration of microwave links, which serve as everyday workhorse under all-weather conditions. GETRIS aims to detect and solve for systematic errors, which might exist in current geodetic (DORIS [13], GNSS, SLR) and metrological systems. Three spacecrafts would be needed for earth coverage. The planned European Data Relay Satellite System (EDRSS) would be an ideal candidate to host such payload. The application of relativistic geodesy would be feasible regarding observation time and ground coverage.

5.1. Alternative Spacecraft Locations

A recent study performed for ESA showed the feasibility to place a clock at a Lagrange point between Earth and Sun, with link to Earth. Equally well, a package at Lagrange Point L1 between Earth and Moon could provide worldwide coverage with a single spacecraft only. Lagrange orbits are currently discussed as data relay for the exploration of the dark side of the Moon or, more speculative, to assemble missions to Mars.

In contrast to reflective systems, like Lunar Laser Ranging, an active system on board allows for significantly smaller Earth stations, without sacrificing performance, and even one-way operation.

6. Advanced Microwave Links

Links in the EHF region (i.e. 30 to 300 GHz) are deemed to be an excellent alternative to optical space-ground links, still with high tolerance to rain and clouds. The technology for such links is available, developed for high-speed feeder links, terrestrial and space-to-ground [15], [16].

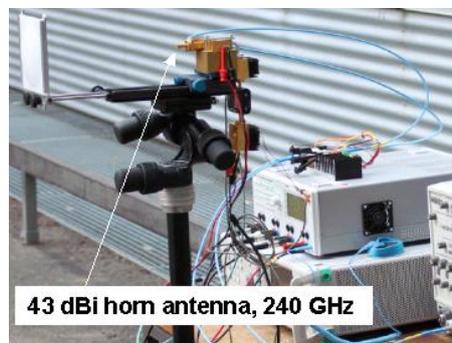


Figure 4. High gain horn antenna at 240 GHz [15]

Figure 4 shows the set-up of a propagation experiment between Aalen television tower (Germany) and a 15 km remote location using 240 GHz and with data rates of several GBit/s. The experiment has shown that the link will also work in extreme weather conditions like rain and heavy fog. Although the atmospheric attenuation increases dramatically with increased frequency [22], several “radio windows” are available, where attenuation is relatively low. With GBit/s data rates, carrier cycle identification becomes feasible also in the EHF region.

		Ground to GEO			Ground to Lagrange Point (Moon)		
		50	70	200	50	70	200
Frequency	GHz						
Modulation	MChip/s	250	500	2000	500	500	2000
Transmitter power	W	3	3	3	6	6	6
Satellite antenna diameter	cm	2.6	1.8	0.6	18	13	4
Ground antenna diameter	m	1.2	1.2	3.0	0.73	0.63	0.73
Receiver C/N_0	dBHz	50	50	48	49	47	49
Code jitter @ 1s	ps	18	9	3	10	12	2.6
Carrier jitter @ 1s	fs	14	10	5	17	14	4

Table 1. Link budget for EHF links to GEO and to an Earth-Moon Lagrange point

Table 1 shows example link budgets for EHF links between Geostationary Orbit (GEO) and ground at 50, 70 and 200 GHz. The atmospheric attenuation is estimated considering ITU recommendations

[22]. The satellite antenna provides full Earth coverage. The noise (jitter) on the carrier is at fs level, thus the links have the potential to reach 10^{-19} frequency uncertainty within 1 day, ground-to-ground.

Table 1 contains link budgets for the Earth-Moon Lagrange point L1 as well. These links reach similar performance levels with twice the RF power.

The links shown in Table 1 are particularly suited for time transfer in support of the generation of UTC. Key is the available bandwidth in the EHF range, which allows for chip rates in excess of 100 MChip/s. The DLL tracking loops used in current projects like PRARE (10 MChip/s) and ACES-MWL (100 MChip/s) can be adapted to the chip rates shown and allow for an unambiguous transmission of time signals, with long-term stability, i.e. weeks and months, at the ps level. Calibrated links between UTC laboratories at the 10 ps level become feasible using a transportable TWSTFT station [21].

7. Conclusion

This contribution tries to conclude on the most promising way forward for time and frequency transfer via satellite, mainly in support of a worldwide network to link clocks for the generation of UTC over inter-continental distances and to match current clock performance with room for growth. Operational links still operate at less than optimal conditions for cost reasons. The advanced link designed for the ACES mission introduces new concepts, in particular full carrier coherency and thermally stabilized ground equipment. It requires an active element on-board, in contrast to traditional bend-pipe commercial transponders.

The only way towards better performance is the use of higher frequencies, both for modulation and for the carrier. The need for ever-increasing communication bandwidth goes into the same direction, with promising results both in microwave and optical link technology.

While optical links appear to be the logical choice for best bandwidth and highest carrier frequency, the full coherency between modulation and carrier is not as obvious as in the microwave region, but more severe, weather dependency limits their use to few favorable locations. On the other hand, EHF technology is likely to overcome weather problem at similar data rates, and significant advances readily appear [15]. Drawing on the experience with ACES-MWL, carrier cycle identification even at EHF frequencies is feasible.

Hence, it is suggested to go the microwave way for the next generation of an operational system. Continuous laser technologies are certainly attractive for specialized missions and space-to-space links. Pulsed lasers are still the foundation for calibration purposes, both for timing and ranging.

Regarding orbits, LEO and HEO show significant disadvantages for an operational system, due to limited visibility and due to extreme Doppler shifts. It is thus recommended to use benign orbits, like GEO or, even more promising, at Lagrange point L1 between Earth and Moon. Link budgets show modest instrument requirements. Concepts with synergies between geodetic and metrological applications are proposed, which would make such systems attractive for a number of communities.

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