

Geopotential Determination Between Ultra-Stable Distant Clocks Based on Two-Way Space Laser Time Transfer Links

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01 Introduction.

02 Methodology.

03 Experiment of TWLTTL.

04 Discussion.

05 References.

1.1 Relativistic Geodesy

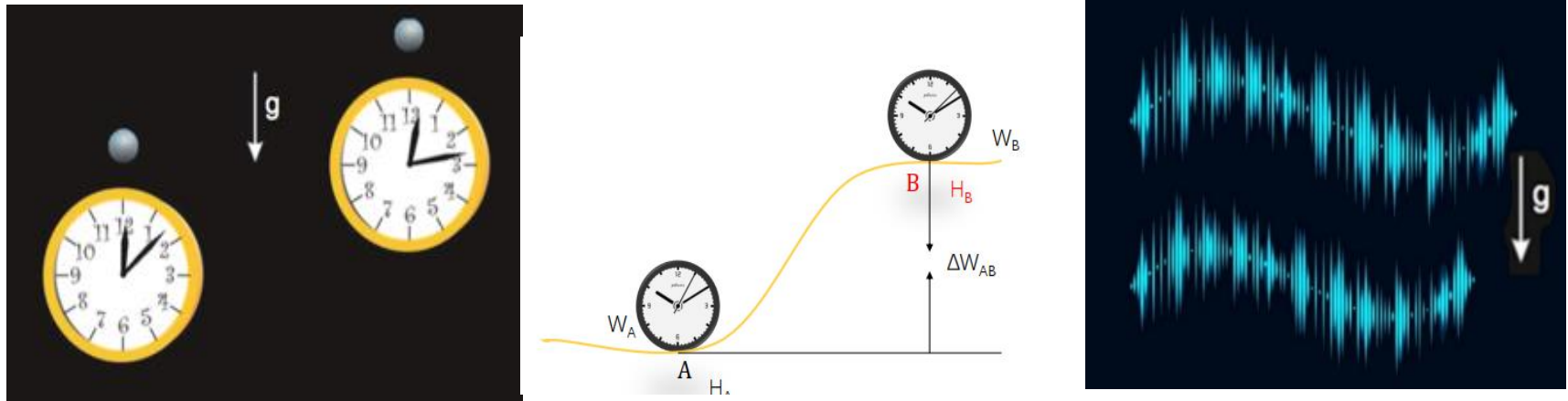


Fig. 1: General Relativity Theory for Determining Geopotential

- **Time comparison:** A clock runs **quicker** at **higher** geopotential position than at **lower** position
- **Frequency comparison:** The vibration frequency of the clock (oscillator) at **higher** geopotential position is **larger** than that at **lower** position.

(Shen et al., 2009)

1.2 Time and Gravity Potential (geopotential)

- **Einstein's Theory:** Precise Clocks Run Faster at Position with Higher Potential

$$\frac{\Delta t_A}{\Delta t_B} = \left[1 - \frac{W_B - W_A}{c^2} \right] \quad (1)$$

- Geopotential Difference

$$\Delta W_{AB} \equiv W_B - W_A = c^2 \left[1 - \frac{\Delta t_B}{\Delta t_A} \right] \quad (2)$$

- Physical height Difference

$$\Delta H_{AB} = \left[\frac{\Delta W_{AB}}{\bar{g}_{AB}} \right] \quad (3)$$

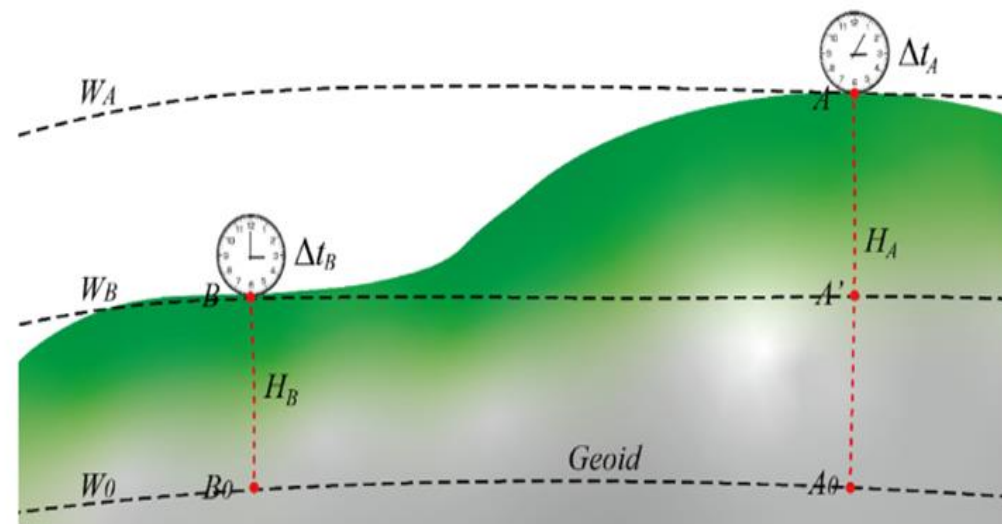


Fig. 2: Clock for geopotential difference (Wu et al., 2020)

- Clock with stability 10^{-18} corresponds to $\Delta W \approx 0.1 \text{ m}^2/\text{s}^2$, and about $\approx 1 \text{ cm}$ in physical heights

1. Introduction

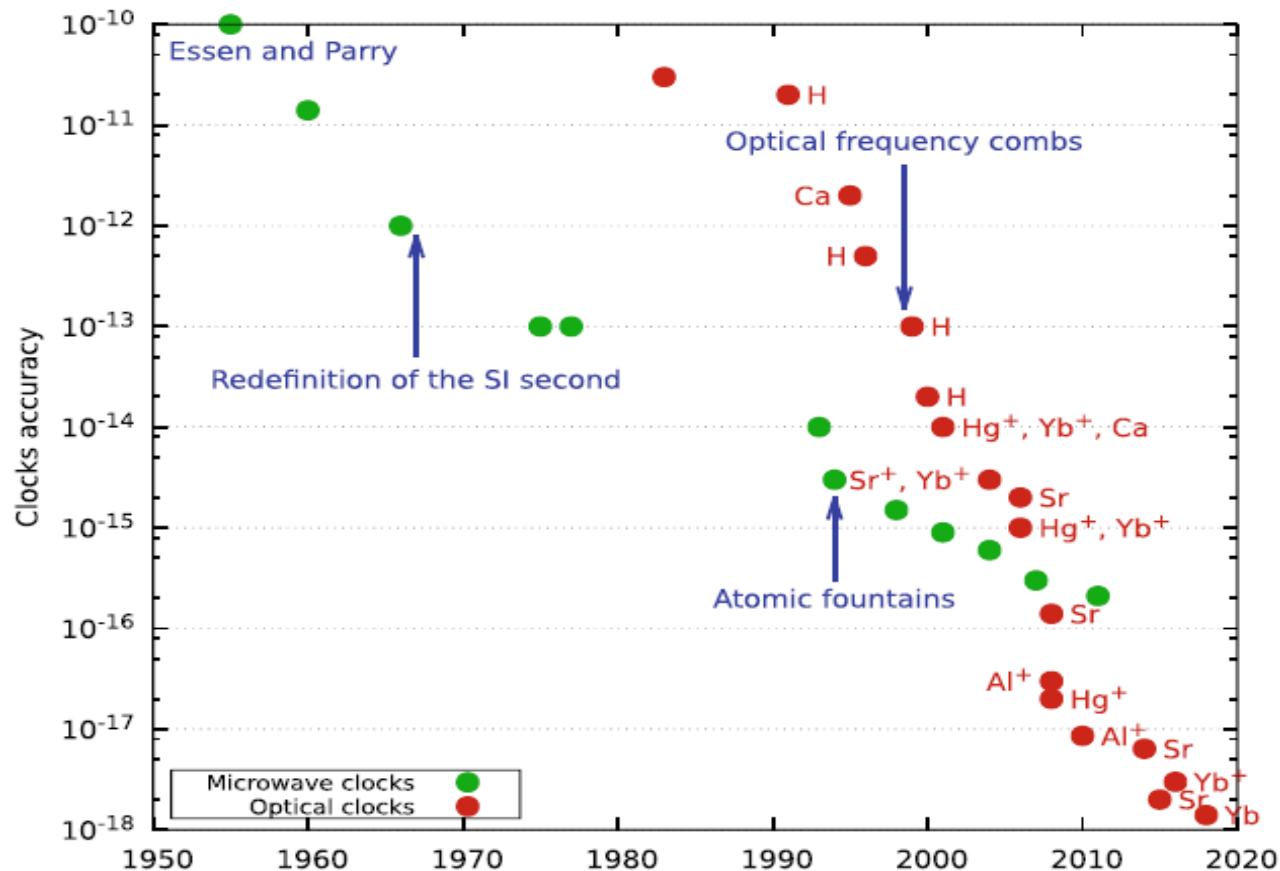


Fig. 3: Accuracy Records for atomic Clocks (Delva et al. 2019)

Challenge: Not only atomic clocks with high stability, but also a reliable time transfer method

1. Introduction

1.4 Current Techniques

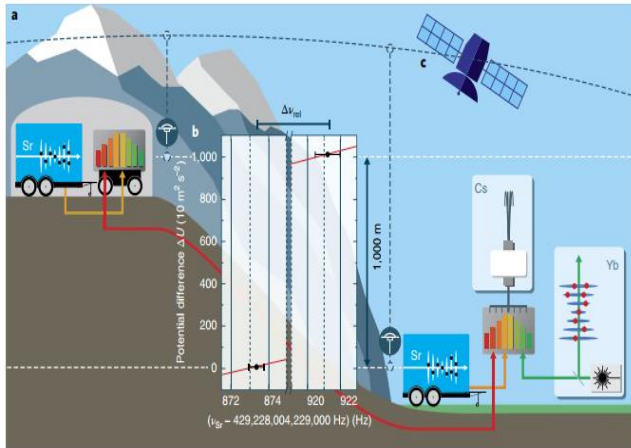


Fig. 4: Clock Transportation (Grotti et al. 2018)

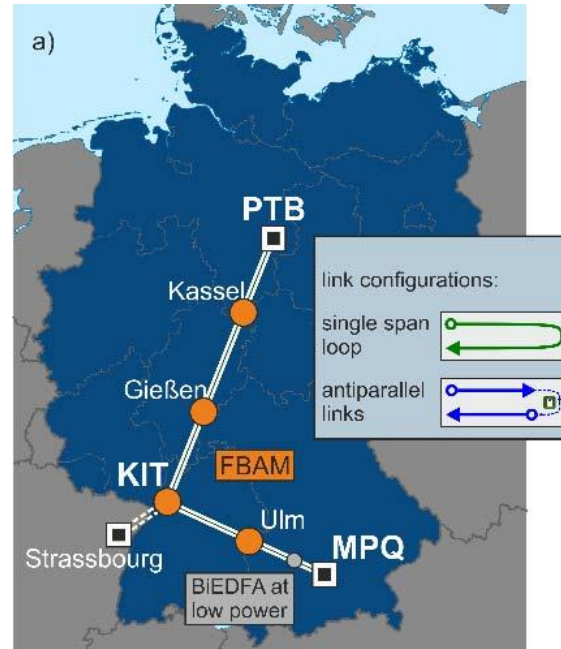


Fig. 5: Optical Fiber Link (A.. Kuhl et al. 2019)

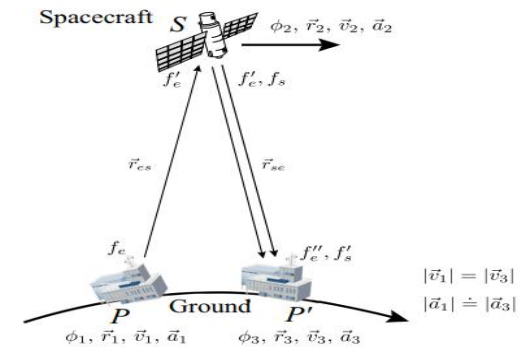


Fig. 6: Satellite Frequency Signal Transmission (SFST) (Shen et al. 2019)

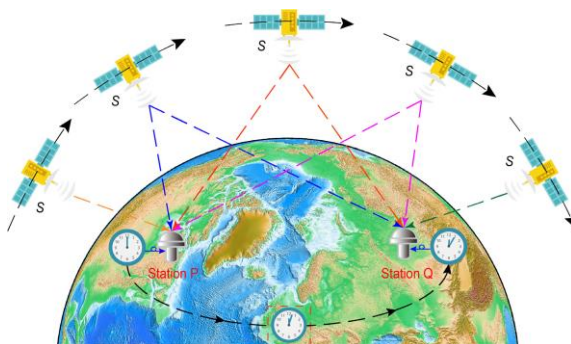


Fig. 7: GNSS PPP Technique (Cai et al. 2020)

What is Gap....?!

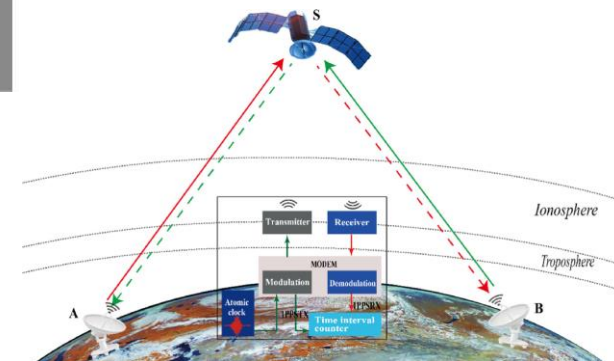


Fig. 8: TWSTFT technique (Wu et al. 2020)

1.5 knowledge Gap

Ground link

01

Clock Transportation Time Comparison (CTTC)

02

Optical Fiber Frequency Transfer (OFFT)

- Transportation
- limited : Ocean & mountainous

Satellite link

03

Satellite Frequency Signal Transmission (SFST)

04

GNSS PPP Technique

05

Two-Way Satellite Time and Frequency Transfer (TWSTFT)

New Tool in Optical Domain

- Tropospheric delay: not sensitive
- Ionospheric delay: less affected

Microwave Domain

Ionospheric & tropospheric effects

06

Two-Way Laser Time Transfer Link (TWLTTL)

1.6 Why → Satellite Laser Ranging (SLR)...?!

- Direct range with **sub-cm accuracy**
- High **accurate space** technique in optical domain

$$R = \frac{1}{2} c \Delta t + \varepsilon \quad (4)$$

- **Model:** Simple, no ambiguities and less detailed compared to GNSS.
- Ionospheric & tropospheric effects are less influenced than microwave links.

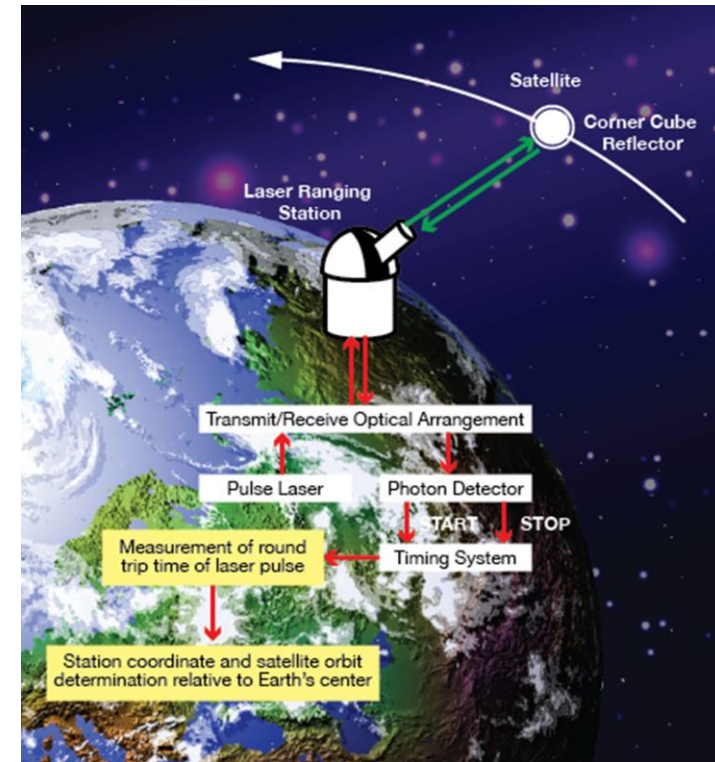


Fig.9 Principle of SLR (Pearlman et al. 2019)

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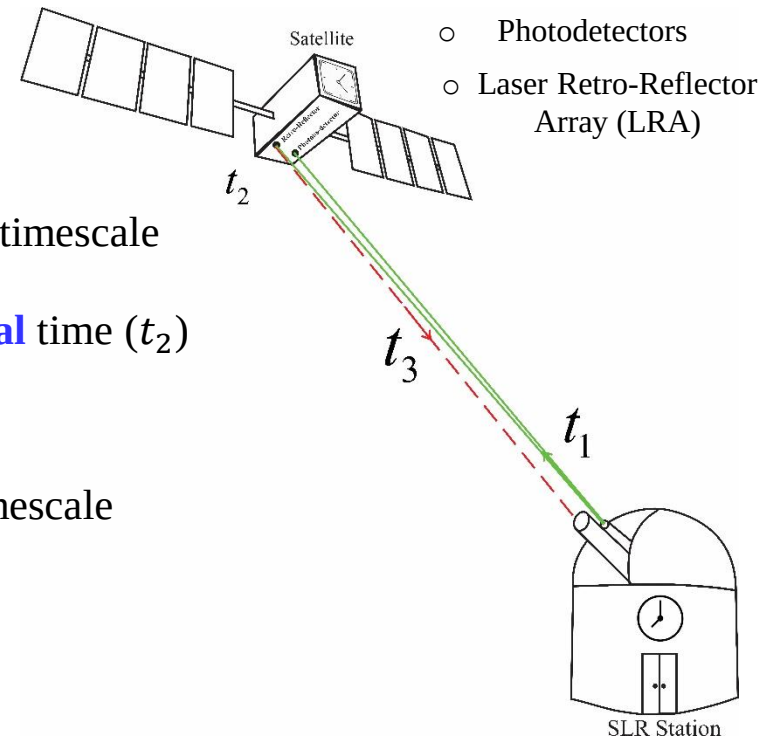
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2.1 Two-Way Space Laser Time Transfer Link

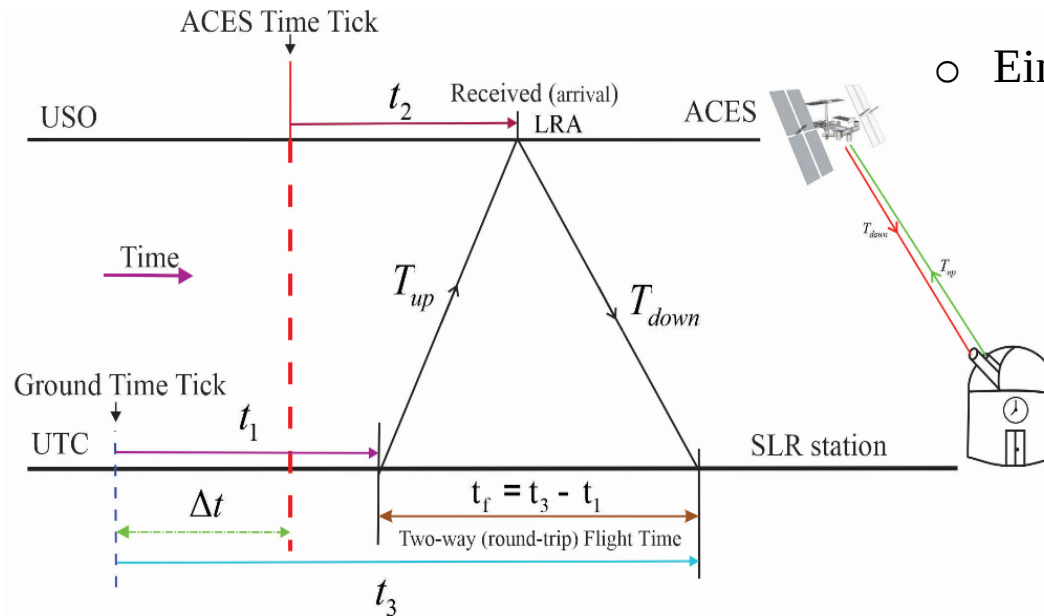
Laser are **Emitted** From **Ground** SLR Station to **Satellite** and then Reflected to **Ground**

- SLR station records **emission** time (t_1) with ground timescale
- On board a satellite, an active package records **arrival** time (t_2) with space timescale.
- SLR station records **return** time (t_3) with ground timescale
- 2-way (round-trip) time of flight (t_f) = $t_3 - t_1$



This event (t_1, t_2, t_3) is called a **Triplet**

2.2 Two-Way Ground to Space Laser Time Transfer Link



○ Einstein Synchronization

Fig. 10: Principle of Two-Way Ground to Space Laser Time Transfer Link

$$\Delta t = \frac{1}{2} (t_1 + t_3) - t_2 + \varepsilon \quad (5)$$

$$\varepsilon = (\delta_{Atmospheric} + \delta_{Shapiro} + \delta_{Sagnac} + \delta_{Relativity} + \delta_{system}) \quad (6)$$

The shapiro delay and atmospheric effect are canceled to the picosecond level, where T_{up} and T_{down} are close enough. Therefore, only the sagnac delay and relativistic frequency shift need to be considered.

2.3 Two-Way Ground to Ground Laser Time Transfer Link

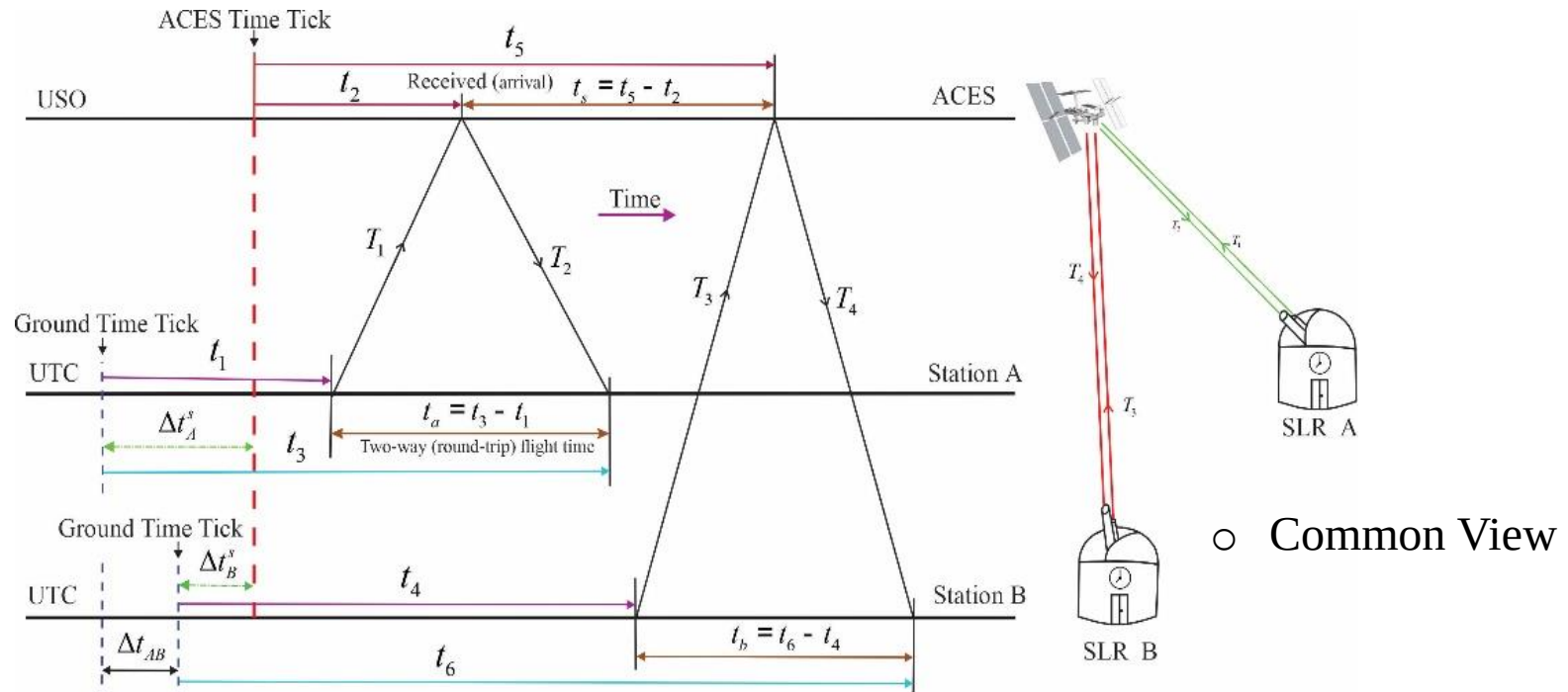


Fig. 11: Two-Way Ground to Ground Laser Time Transfer Link

$$\Delta t_{AB} = \Delta t_A^S - \Delta t_B^S \quad (7)$$

(Serene 1981)

$$\Delta t_{AB} = \frac{1}{2}(t_a - t_b) + (t_1 - t_4) + t_s + \varepsilon \quad (8)$$

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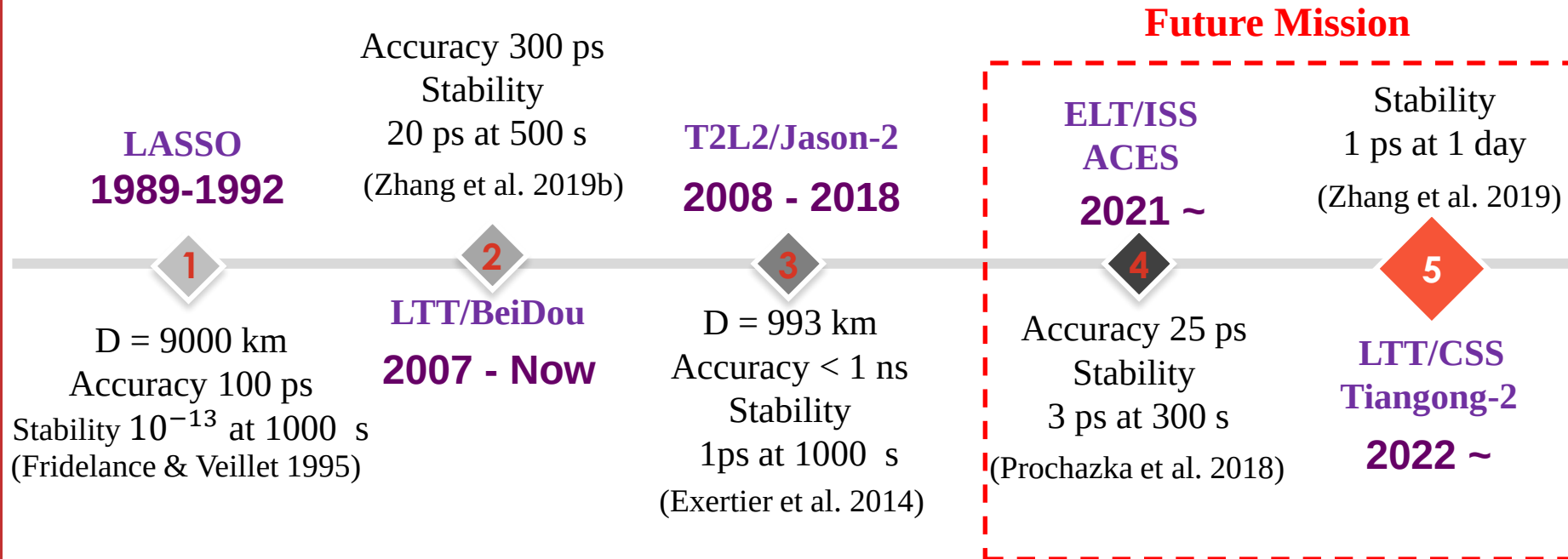
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3. Experiment of TWLTTL

Experiment of Two-Way Laser Time Transfer Links



Challenge: Better Ground Time Equipment, Long-term Stability of Space Clock , New Space Detector and Timing Systems onboard

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- With better ground time equipment, long-term stability of space clock, new space detector and timing systems onboard, the approach proposed in this study for determining the geopotential difference is prospective.
- Two-way Laser Time Transfer (TWLTT) technique via a space station as a bridge could be used to unify the International Height Reference System (IHRIS) based on the worldwide - distributed of SLR stations.

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A.. Kuhl, G. Vishnyakova, T. Waterholter, S. Koke, R. Holzwarth and G. Grosche, "A 1880 km Long Interferometric Optical Fibre Link PTB-MPQ-PTB for Chronometric Levelling with a Transportable Optical Clock," 2019 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC), Munich, Germany, 2019, pp. 1-1, <https://doi.org/10.1109/CLEOE-EQEC.2019.8871628>

Auriol, A. & Tourain, C. (2010), DORIS system: The new age, Adv. Space Res. 46(12), 1484-1496. <https://doi.org/10.1016/j.asr.2010.05.015>

C. Cai, W. -B. Shen, Z. Shen and W. Xu (2020), "Geopotential Determination Based on Precise Point Positioning Time Comparison: A Case Study Using Simulated Observation," in IEEE Access, vol. 8, pp. 204283-204294, 2020, <https://doi.org/10.1109/ACCESS.2020.3036988>

Delva P., Denker H., Lion G. (2019) Chronometric Geodesy: Methods and Applications. In: Puetzfeld D., Lämmerzahl C. (eds) Relativistic Geodesy. Fundamental Theories of Physics, vol 196. Springer, Cham. https://doi.org/10.1007/978-3-030-11500-5_2

Exertier, P., Samain, E., Martin, N., Courde, C., Laas-Bourez, M., Foussard, C., & Guillemot, P. (2014). Time transfer by laser link: data analysis and validation to the ps level. Advances in Space Research, 54(11), 2371-2385. <https://doi.org/10.1016/j.asr.2014.08.015>

Fridelance, P., & Veillet, C. (1995). Operation and data analysis in the LASSO experiment. Metrologia, 32(1), 27. <https://doi.org/10.1088/0026-1394/32/1/003>

Grotti, J., Koller, S., Vogt, S. et al. Geodesy and metrology with a transportable optical clock. Nature Phys 14, 437–441 (2018). <https://doi.org/10.1038/s41567-017-0042-3>

5. References

- Pearlman, M.R., Noll, C.E., Pavlis, E.C. et al. The ILRS: approaching 20 years and planning for the future. *J Geod* 93, 2161–2180 (2019). <https://doi.org/10.1007/s00190-019-01241-1>
- Prochazka I., Blazej J. & Kodet J. (2018). Current status and expected performance of European Laser Timing. In Proceedings of the 21st International Workshop on Laser Ranging, Canberra, Australia, Nov. 5 - 8, 2018.
- Serene, B. E. H. (1981). The Lasso Experiment & Its Operational Organization. *IETE Journal of Research*, 27(10), 422-432. <http://dx.doi.org/10.1080/03772063.1981.11452498>
- Shen, Z., Shen, W.B., Peng, Z. et al. (2019) Formulation of Determining the Gravity Potential Difference Using Ultra-High Precise Clocks via Optical Fiber Frequency Transfer Technique. *J. Earth Sci.* 30, 422–428 (2019), <https://doi.org/10.1007/s12583-018-0834-0>
- Wu, K., Shen, Z., Shen, W. B., Sun, X., Cai, C., & Wu, Y. (2020). A preliminary experiment of determining the geopotential difference using two hydrogen atomic clocks and TWSTFT technique. *Geodesy and Geodynamics*, <https://doi.org/10.1016/j.geog.2020.03.006>
- Wu, K., Shen, Z., Shen, W. B., Sun, X., Cai, C., & Wu, Y. (2020). A preliminary experiment of determining the geopotential difference using two hydrogen atomic clocks and TWSTFT technique. *Geodesy and Geodynamics*, <https://doi.org/10.1016/j.geog.2020.03.006>
- Zhang H., Cheng Z., Long M., Deng H., Meng W., Wu Z., Zhaoa G. & Zhang Z. (2019b). Applications of satellite laser ranging and laser time transfer in BeiDou navigation satellite system. *Optik*, 188, 251-262. <https://doi.org/10.1016/j.ijleo.2019.04.131>
- Zhang, Z., Zhang, H., Wu, Z., & Tang, K. (2019). The developments of ground-satellite Laser Time Transfer in the mission of Chinese Space Station. In *Geophysical Research Abstracts*, Vol. 21, EGU2019-6262, Vienna, Austria, 7–12 April, 2019



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