Simulating Gravitational Redshift Test Using the European Laser Timing (ELT) Experiment on the ACES Mission

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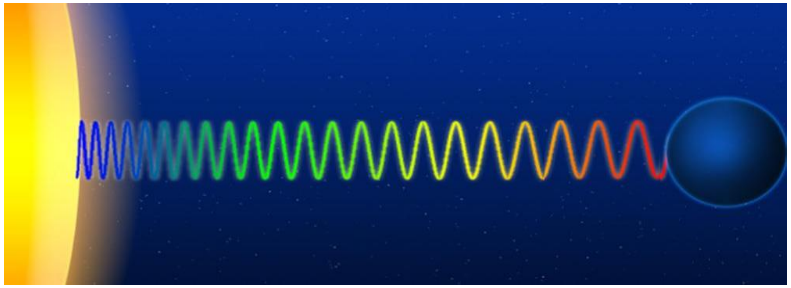
Contents

1. Introduction

▪ Gravitational redshift (GRS)

In this study, GRS is relative time shift between two clocks due to the gravitational field of a body as adapted from Will (2014).

$$\underbrace{\boxed{\Delta\tau_m}}_{\text{Measure}} = \Delta\tau_0 + \boldsymbol{\alpha} \underbrace{\boxed{\int_{\text{path}} \left(\frac{\Delta U_{GR}}{c^2}\right) dt}}_{\text{Theoretical}} \tag{1}$$



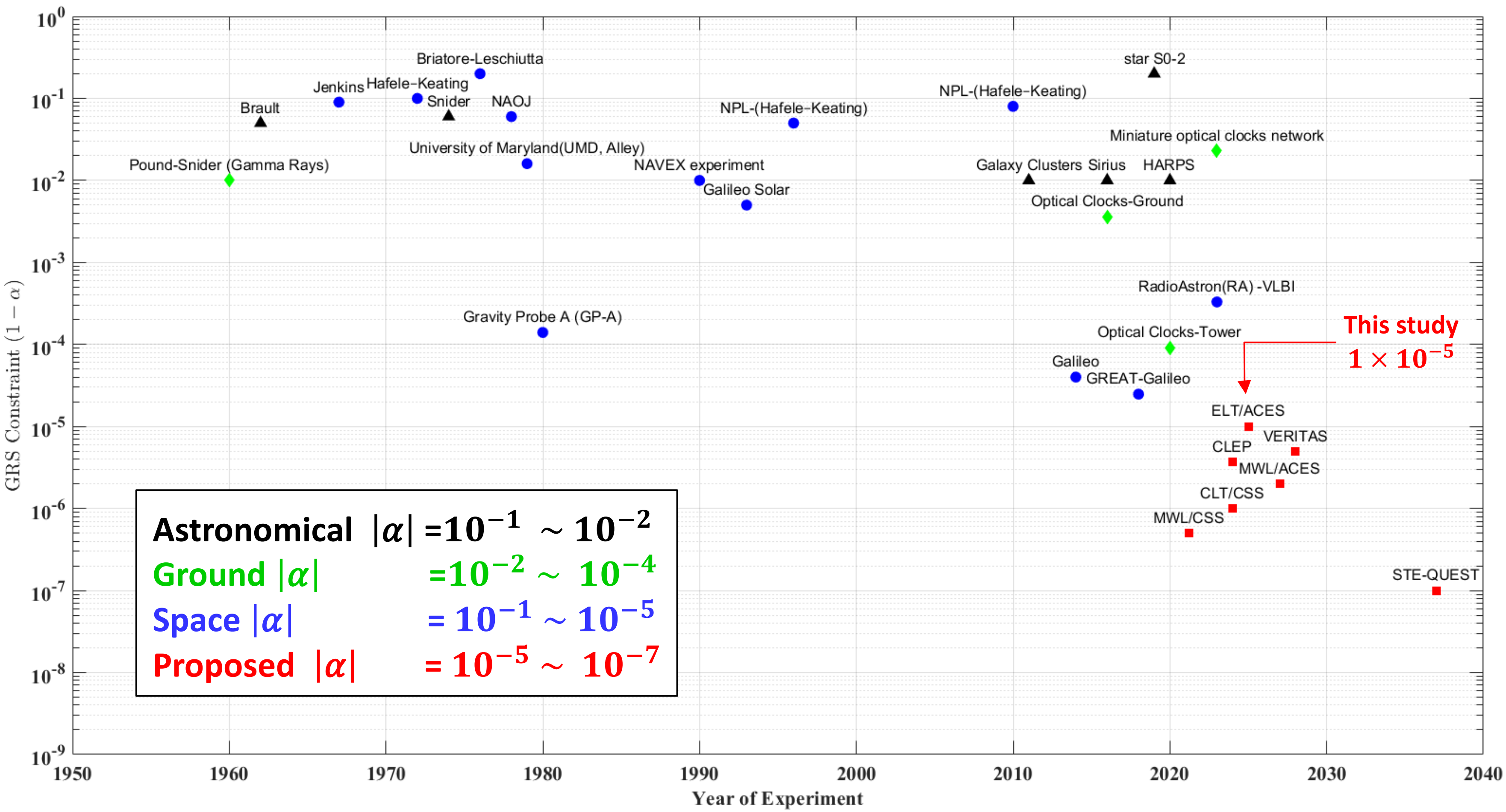
Gravitational redshift
https://en.wikipedia.org/wiki/Gravitational_redshift

If Einstein's is correct, coefficient **α = 1**

Several experiments and observations have been conducted to confirm this effect (Pound & Rebka 1960; Hafele & Keating 1972; Vessot et al. 1980; Delva et al., 2018; Cacciapuoti et al, 2020; Shen et al., 2021; 2023).

1. Introduction

▪ GRS Experiments



1. Introduction

▪ Knowledge Gap

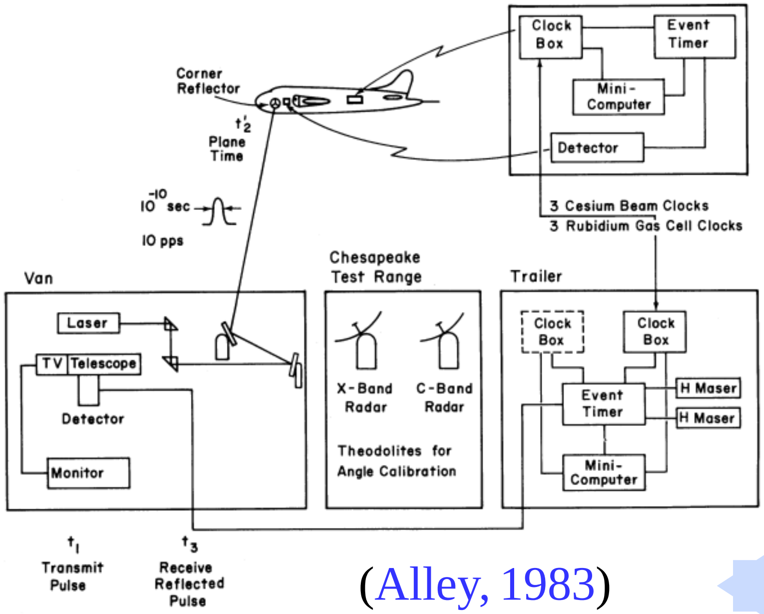
- Many studies on testing GRS using **microwave** time and frequency comparisons exist, but there is a **lack** of research in the **optical** domain.
- First Local Laser GRS Experiment (1975) :Prof. Alley, University of Maryland (UMD), USA

✓ **UMD Experiment: 5** flights (military aircraft), **3** identical ground and space cesium clocks **(stability 2×10^{-14} /day).** Altitude : **8 km**, then **9 km**, and **11 km**.

✓ Combined gravitational and velocity effects

$$\alpha = 1 - (1.3 \pm 1.6) \times 10^{-2}$$

UMD experiment conducted **50 years ago**



(Alley, 1983)

1. Introduction

▪ European Laser Timing (ELT) aboard ACES

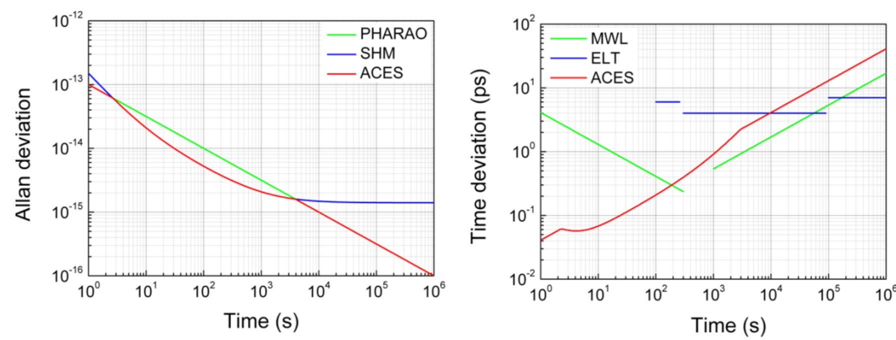
- **On April 21, 2025**, ESA launched the Atomic Clock Ensemble in Space (ACES).
- The ACES ensemble comprises two ultra-precise atomic clocks:

a) **SHM** (Space Hydrogen Maser): Short-term stability.

b) **PHARAO** (Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbite): Long-term accuracy.

- ACES utilizes two links: the **Microwave** Link (MWL), and European Laser Timing (ELT) **optical** link


Left: A SpaceX Falcon 9 rocket carrying ACES. Right: ACES Payload attached to Columbus Laboratory. see https://www.adsadvance.co.uk/new-scientific-experiments-and-supplies-delivered-to-iss.html and https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/ACES_Atomic_Clock_Ensemble_in_Space



Left: Stability of PHARAO, SHM, and ACES clock signal. Right: Stability of time deviation of MWL and ELT (Cacciapuoti and Salomon, 2011)

▪ ELT Space Segment

ACES Time and frequency reference system		Stability
Atomic Clocks	PHARAO	$1.5 \times 10^{-13}/\sqrt{\tau}$
	Hydrogen Maser (SHM)	1×10^{-15}@ 1 day
European Laser Timing (ELT)	Detector	Single, $< 10 \times 10^{-12}$ @ 300 s
	Timer	$< 1 \times 10^{-12}$
	Stability of Laser Time link	1×10^{-12}@ 1 day

2. Methodology

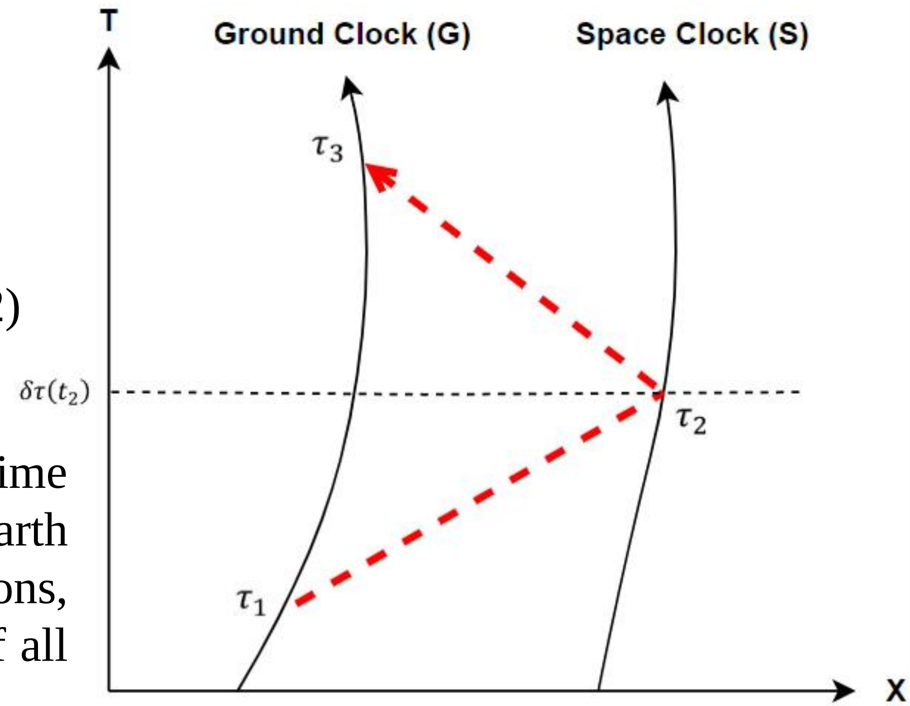
▪ Triple time transfer in the ELT Experiment

- Ground clock (G) generated laser pulses at emission time τ_1 and transmits them toward space clock (S). Clock S then detects laser pulses at reception time τ_2 and instantaneously reflects them back toward clock G, where they are received at the return time τ_3

- Time offset $\Delta\tau(t)$ between clock S and G :

$$\Delta\tau(t) = \frac{1}{2}(\tau_1 + \tau_3) - \tau_2 + \sum \delta\tau_i(t) \quad (2)$$

- The summation $\sum \delta\tau_i(t)$ represents the time delay corrections, including geometric, Earth rotation, atmospheric, relativistic contributions, systematic bias and offset and calibration of all instrument delays.



Optical triple time transfer link

2. Methodology

▪ Gravitational Redshift Test

According to General Relativity (GR), the proper time τ of a clock is given (Wolf and Petit, 1995):

$$\frac{d\tau}{dt} = 1 - \frac{U}{c^2} - \frac{v^2}{2c^2} + O(c^{-4}) \qquad (3)$$

Integrating with respect to coordinated time can be used to compare clocks G and S in the time domain as (Ruby et al., 2024) :

$$\Delta\tau(t) = \Delta\tau_0 - \int_{t_0}^{t} \frac{(U_S - U_G)}{c^2} dt - \int_{t_0}^{t} \frac{(v_S^2 - v_G^2)}{2c^2} dt \qquad (4)$$

ELT Experiment Eq. (2)

In our study, $$\boldsymbol{\Delta\tau^m = \Delta\tau_0 + \alpha\, \Delta\tau^{GR}} \qquad (5)$$

Measure value

$$\Delta\tau^m = \Delta\tau(t) + \int_{t_0}^{t} \frac{(v_S^2 - v_G^2)}{2c^2} dt \qquad (6)$$

Theoretical value from GR Model

$$\Delta\tau^{GR} = -\int_{t_0}^{t} \frac{(U_S - U_G)}{c^2} dt \qquad (7)$$

3. Testing Gravitational Redshift with ELT

Experimental Setup

- The Wettzell Laser Station is selected as the time and frequency ground station for its precision infrastructure and reliability in timing experiments.
- Simulation data from MJD **60735 to 60741** (March 2025) includes **40 passes (~7 days)**, with **6 per day**, each lasting ~**7 minutes**.

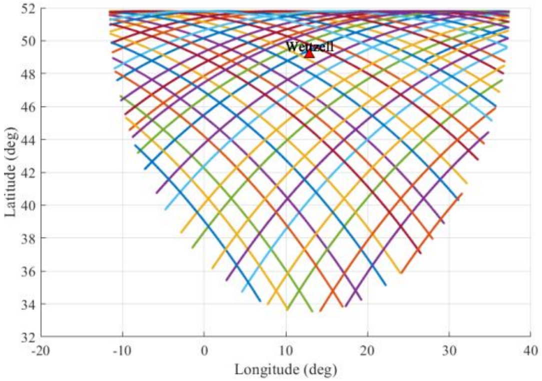
Parameters of Simulation and Optical triple time transfer link

Items	Values of Parameter
Mission Name	International Space Station (ZARYA)
Altitude	370 ~ 460 Km
Orbit inclination	~ 51.6°
Orbit data	TLE file from: https://celestrak.org/
CSS orbit interval	1.0 s
Position/ Velocity accuracy of CSS	0.1 m and $1 \times 10^{-5}\ m/s$
Observation cutoff elevation angle	5° ~ 85°
On-board clock stability	$1.5 \times 10^{-13}/\sqrt{\tau}$
Ground clock stability	$2 \times 10^{-13}/\sqrt{\tau}$
Meteorological data	An ERA5-Based Hourly Global Pressure and Temperature (HGPT) Model
Laser wavelength	532 nm
Gravity field model	EGM2008 for relativistic delay & term $\Delta\tau^{GR}$
Tropospheric model	Mendes and Pavlis (2004)
Time delay function	Blanchet et al. (2000)
Tide correction	ETERNA

Station at Wettzell ,Germany (Master)

https://ilrs.gsfc.nasa.gov/network/stations/active/WETL_general.html

Lat. (deg)	Lon. (deg)	Elevation (m)
49.1444	12.8780	665



Orbit of ISS/ACES during simulations observations (40 passes)

3. Testing Gravitational Redshift with ELT

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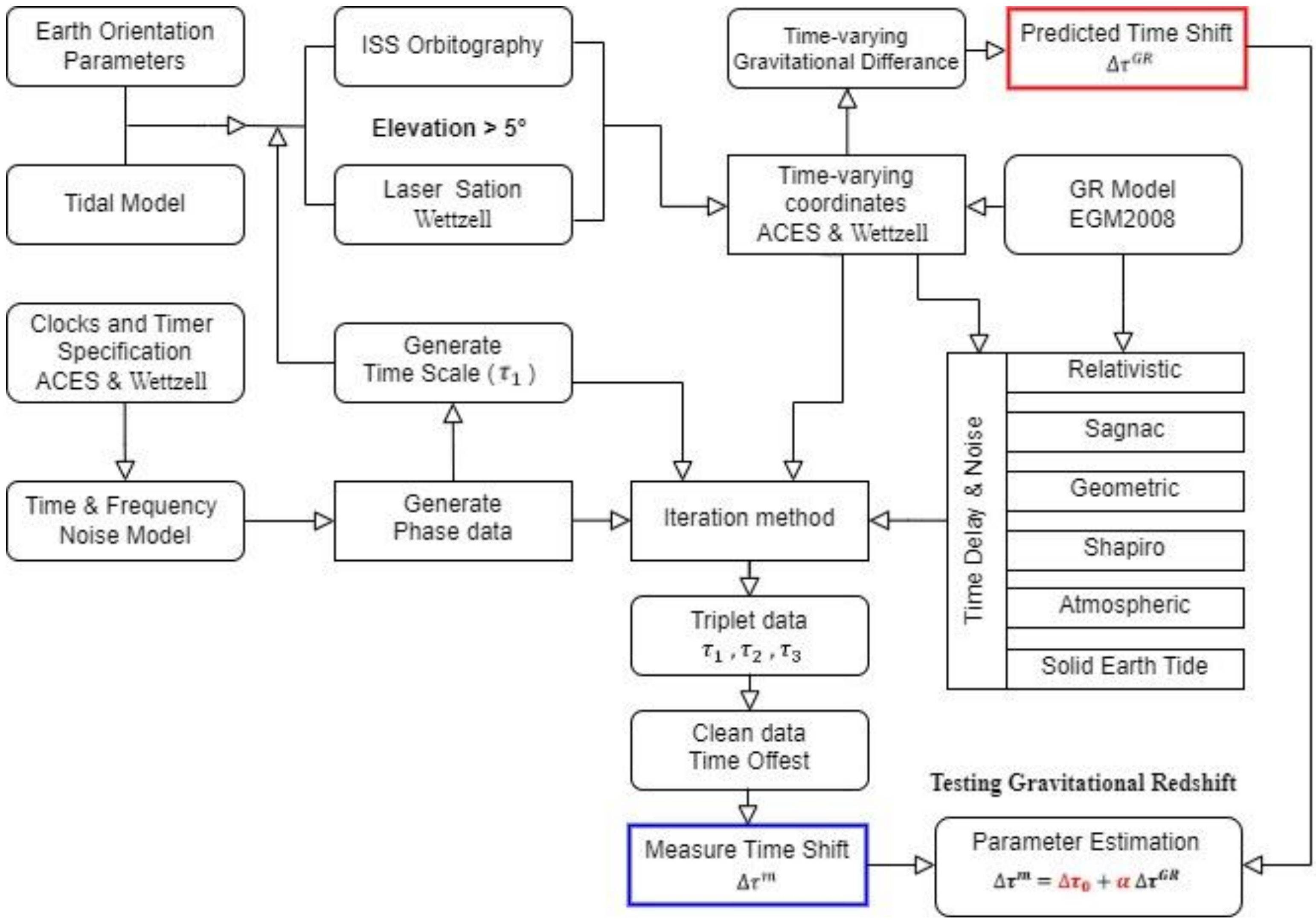
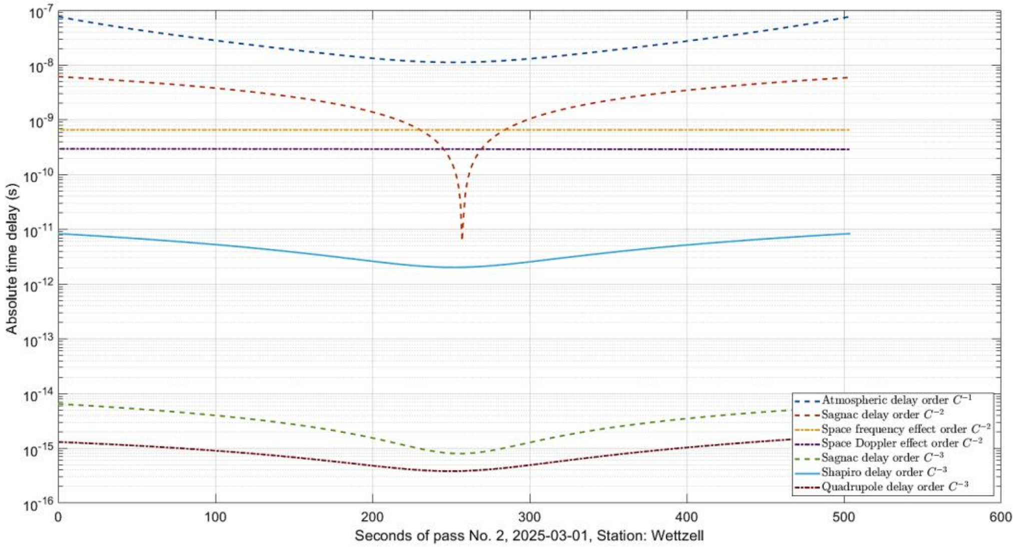
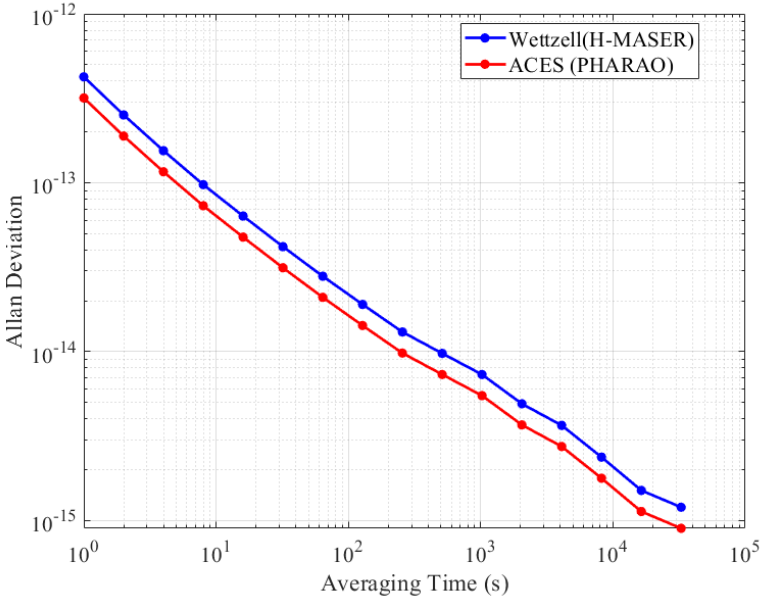
- **Experimental Setup**



3. Testing Gravitational Redshift with ELT

▪ Simulated one-way time delays and clock stabilities



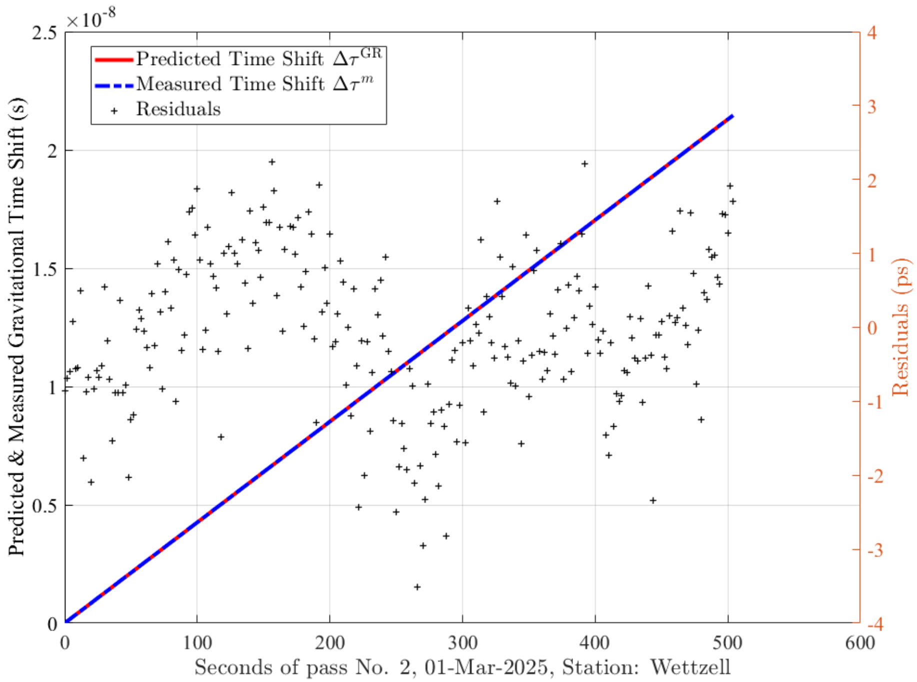


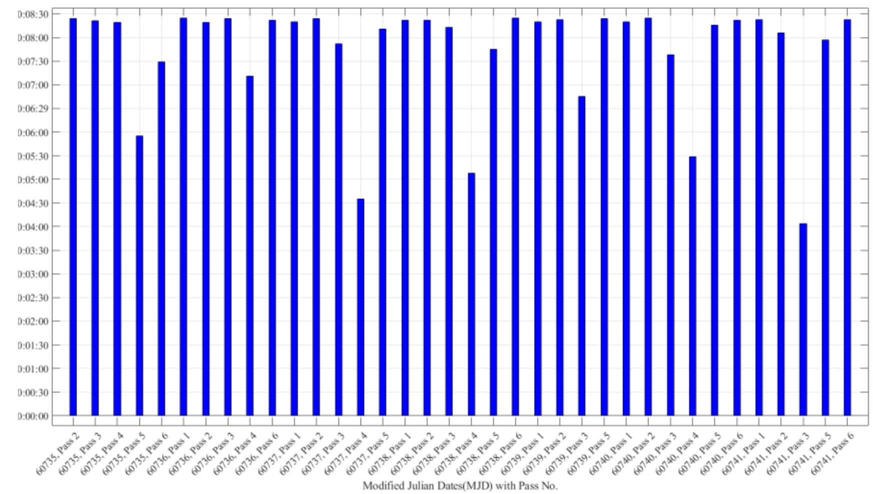
- Different time delay simulation in a one-way laser time link.
- Simulation clocks data for PHARAO/ACES and Wettzell ground Hydrogen Maser clock.

- Other factors, such as system delays, geometric corrections, significantly influence the results, they are not considered in this simulation.

3. Testing Gravitational Redshift with ELT

- **Simulated testing of gravitational redshift over one pass**





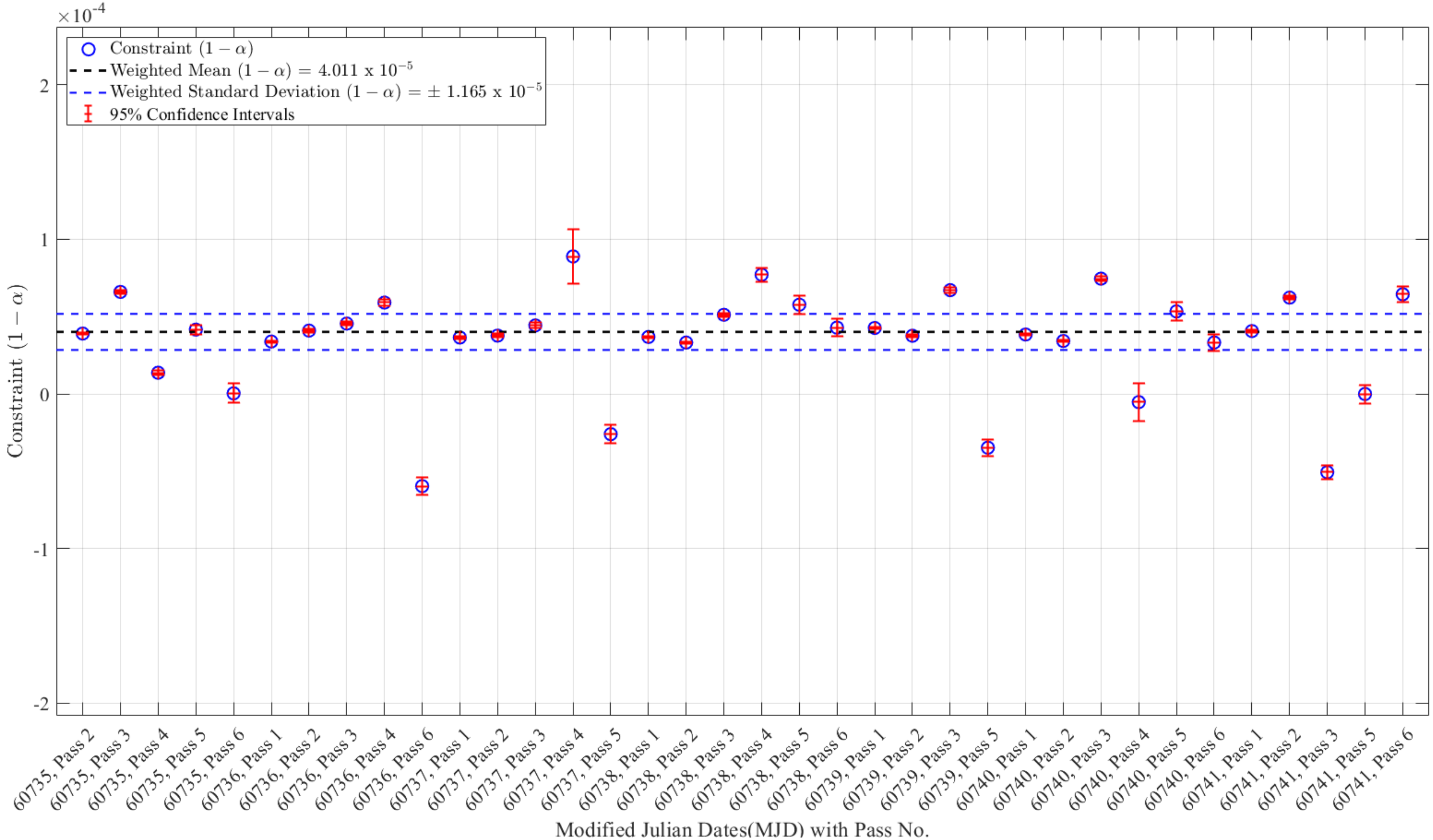
- Simulated pass duration: MJD 60735 to 60741 (one week)

- Simulated, predicted, and measured cumulative time shifts over one pass

- Using single pass, the expected accuracy: $\boldsymbol{\alpha = 1 - (3.9 \pm 0.4) \times 10^{-5}}$ ($\approx$ 8 minutes)
- This confirms that the ELT ability to detect redshift predicted by general relativity

3. Testing Gravitational Redshift with ELT

- **Simulated testing of gravitational redshift at the Wettzell Laser Station**



After removing outliers, the expected accuracy: $\boldsymbol{\alpha = 1 - (4 \pm 1) \times 10^{-5}}$ ≈ 4 hours (36 passes)

4. Conclusion

- The ACES experiment employs a state-of-the-art primary frequency standard using laser-cooled cesium atoms with stabilities of $1.5 \times 10^{-13}/\sqrt{\tau}$ and accuracy 1×10^{-16}, along with a novel single-photon detector offering superior timing stability for European Laser Timing (ELT) experiment .
- The ELT experiment achieves an accuracy of $\sim$ $\mathbf{10^{-5}}$ for testing gravitational redshift (GRS), as validated by simulated observations.
- Using real ELT data, the expected precision of GRS is **3 to 4** orders of magnitude greater than that of the University of Maryland (UMD), USA, experiment conducted **50 years ago**.
- Calibration of both ACES and ground equipment is critical to ensure high-precision GRS measurements and maintain data consistency.

Thanks for your Attention

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