Geopotential determination using space frequency signal transmission between ground station and space station

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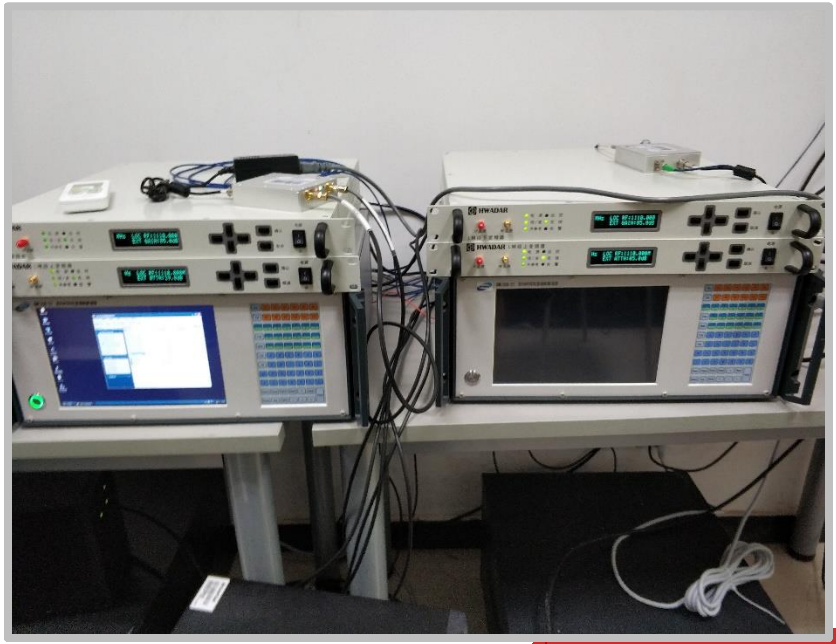
Two time-frequency labs.

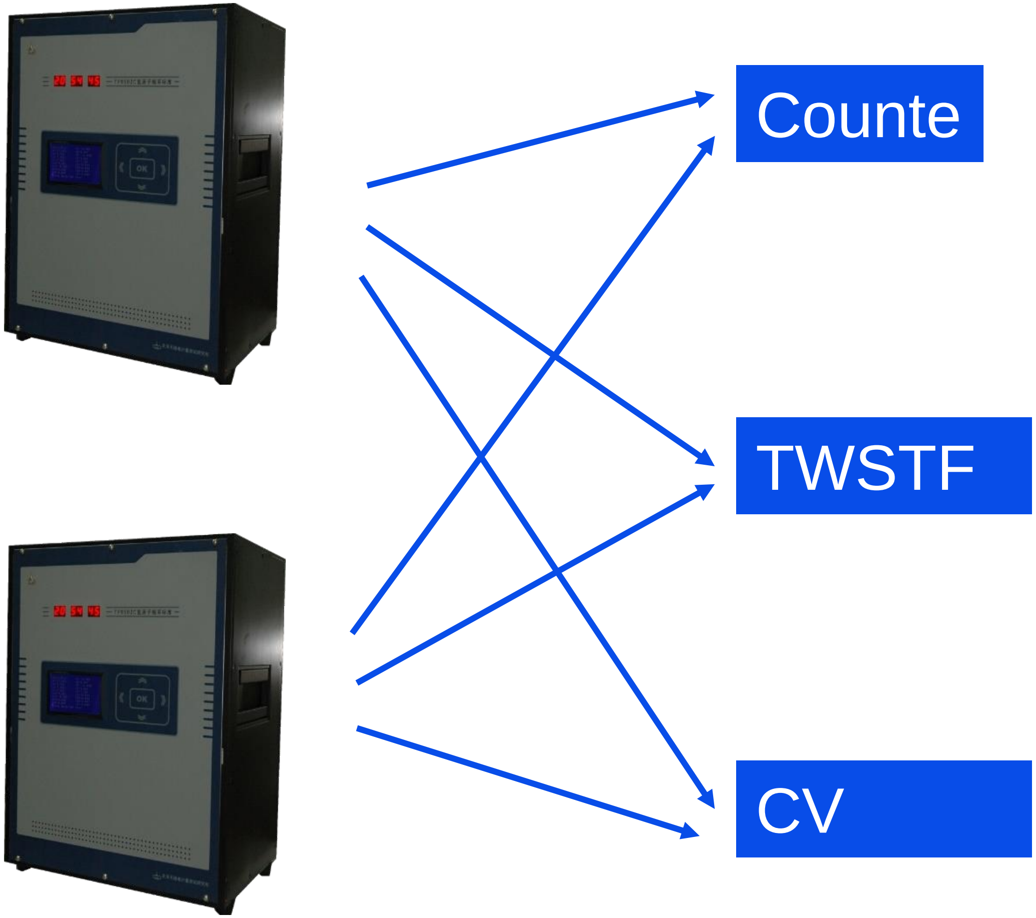
Jiugong time-frequency lab

Wuhan Luojia time-frequency lab

Hydrogen clocks



Equipments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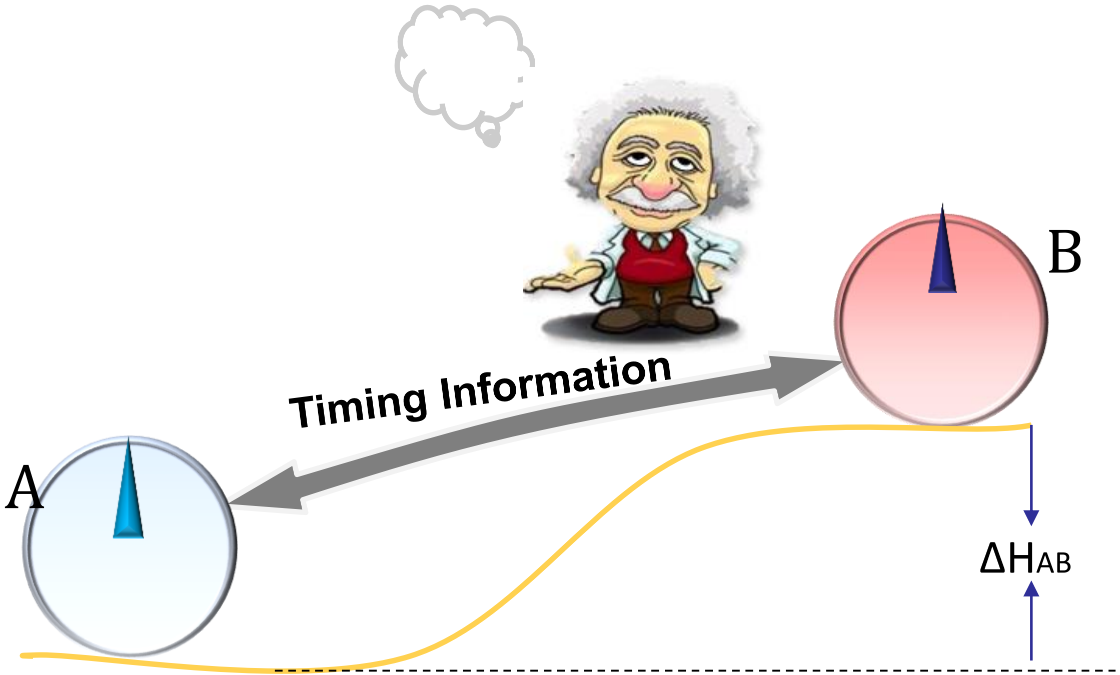
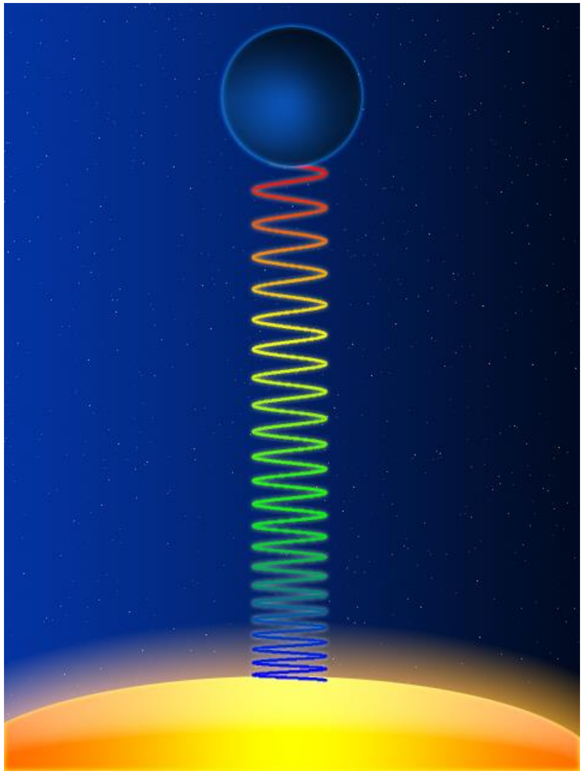
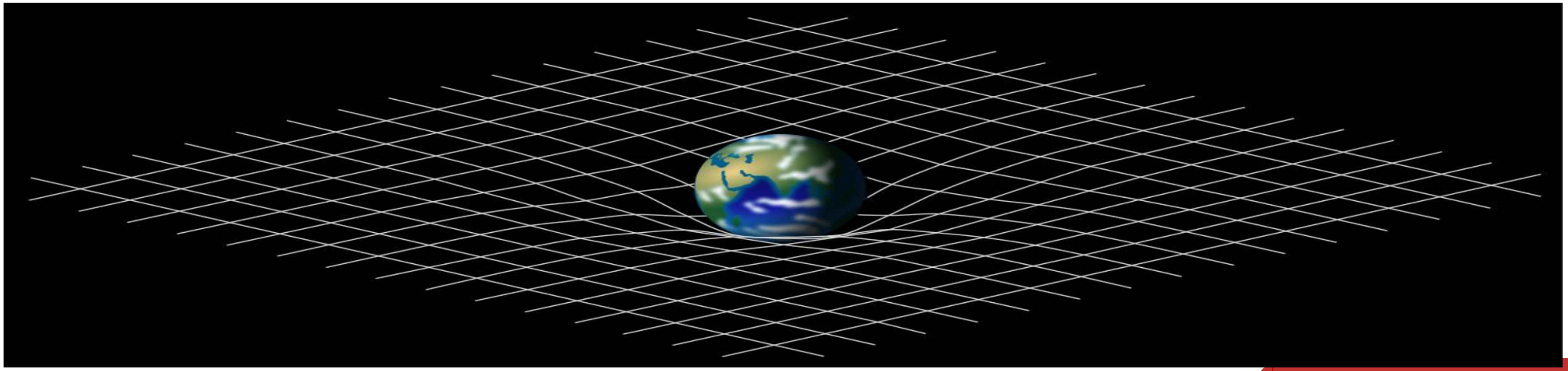
5 Discussion and conclusions

1 Introduction

- General relativity







1 Introduction

- Basic principle: A clock runs quicker at higher geopotential position than at lower position
- Or equivalently: The vibration frequency of the clock (oscillator) at higher geopotential position is larger than that at lower position

1 Introduction

- Clock transportation time comparison (CTTC)

(Bjerhammar 1975, 1985)

Fig1 Test of GRT by clock transportation experiment (Shen et al. 2009)

1 Introduction

- Gravity frequency shift (GFS) (Shen et al. 1993)

$$\Delta f_{PQ} \equiv f' - f$$

$$\Delta W_{PQ} = \frac{\Delta f_{PQ}}{f}$$

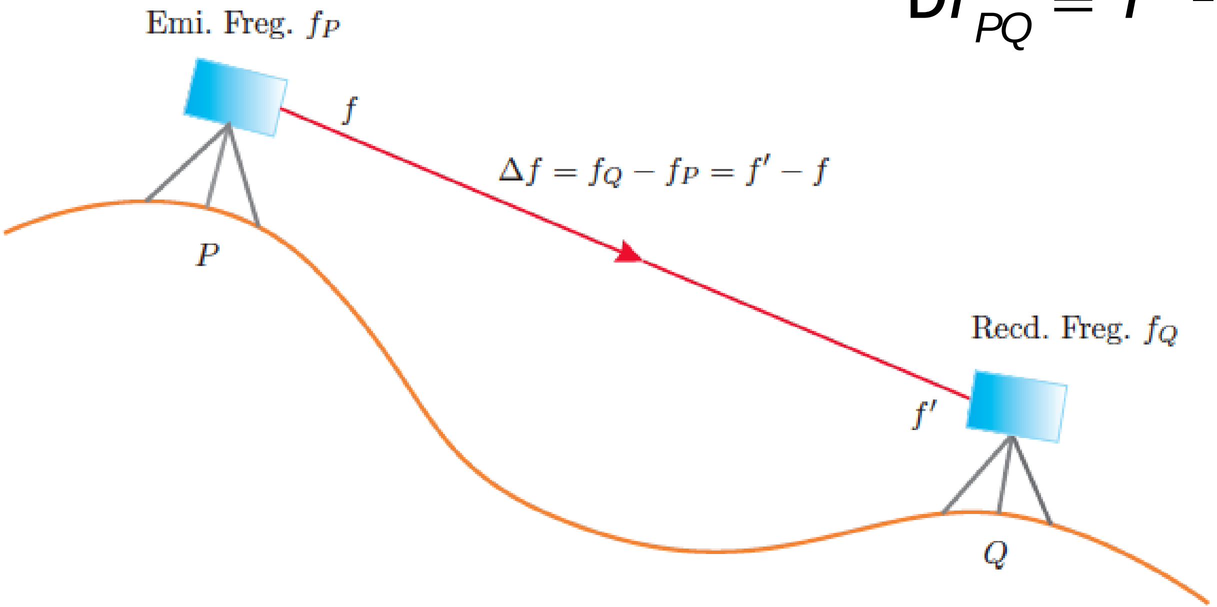


Fig2 A receiver at Q receives signal with frequency f emitted by modified after Shen et al. 2011)

1 Introduction

- Satellite/Spacecraft frequency signal transfer (Shen et al. 1993, 2005)

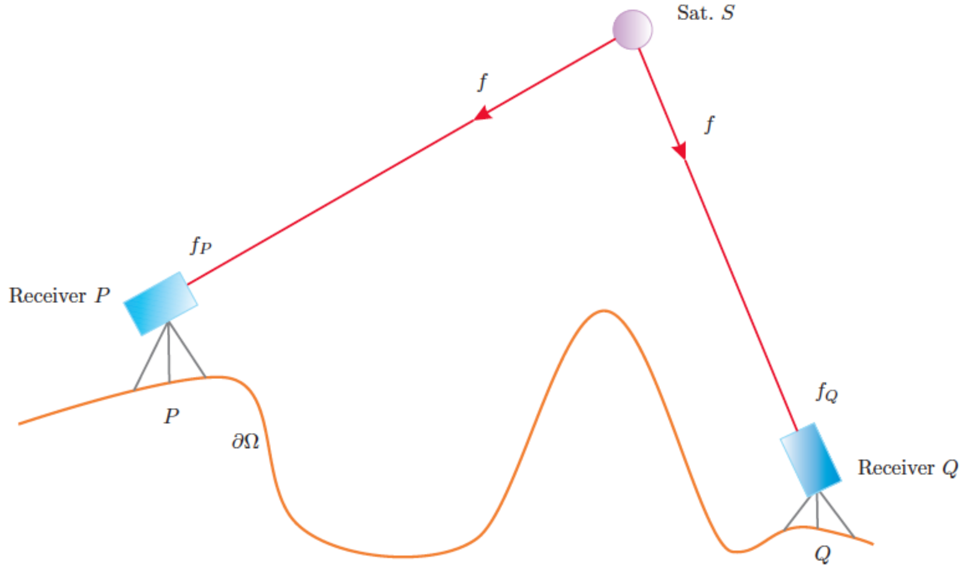
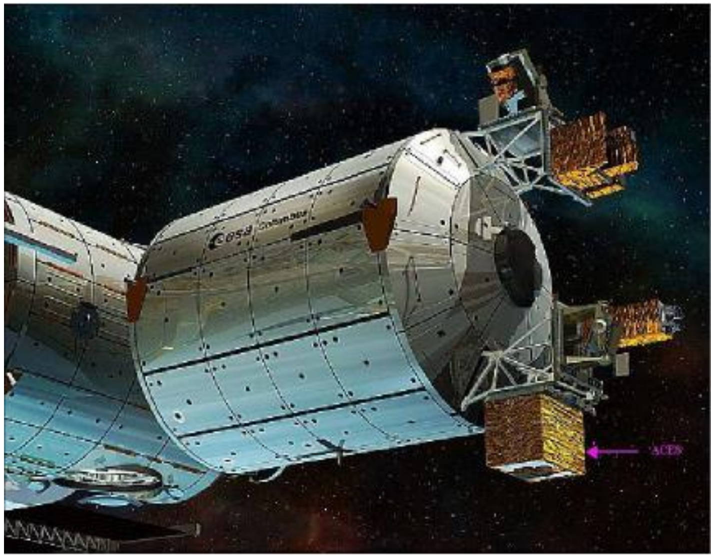


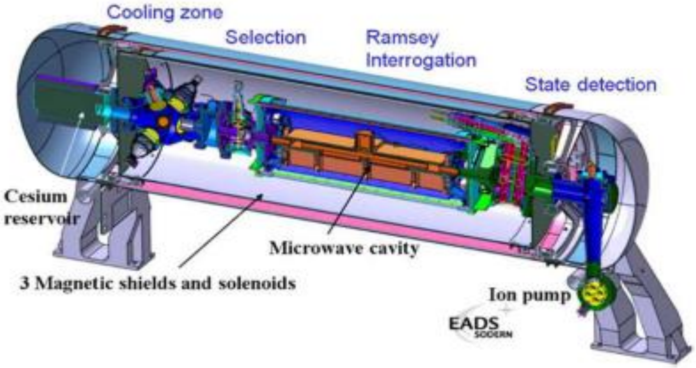
Fig 3 Receivers at P and Q receive simultaneously satellite signals. Geopotential difference between P and Q is determined based on frequency shift between P and Q (modified after Shen et al. 2011)

1 Introduction

The development of Space Station

- “Salyut” (1971~1991)
- “Mir” (1986~2001)
- “Sky Lab”(1973~1979)
- International Space Station (ISS) (1994
- China space station plan（2010~）





1 Introduction

International Space Station(ISS)

◆Mission I-SOC (Space Optical Clock on ISS)

With a high-stability & high-accuracy clock on board:

- *enable world-wide relativistic geodesy at* ***1 cm*** *level*
- *enable world-wide atomic time distribution at* $\mathbf{10^{-18}}$ *level*
- *enable world-wide clock comparisons at* 10^{-18} *level*
- *measure Earth's gravitational time dilation at* $\mathbf{2 \times 10^{-7}}$ *level*
- ……

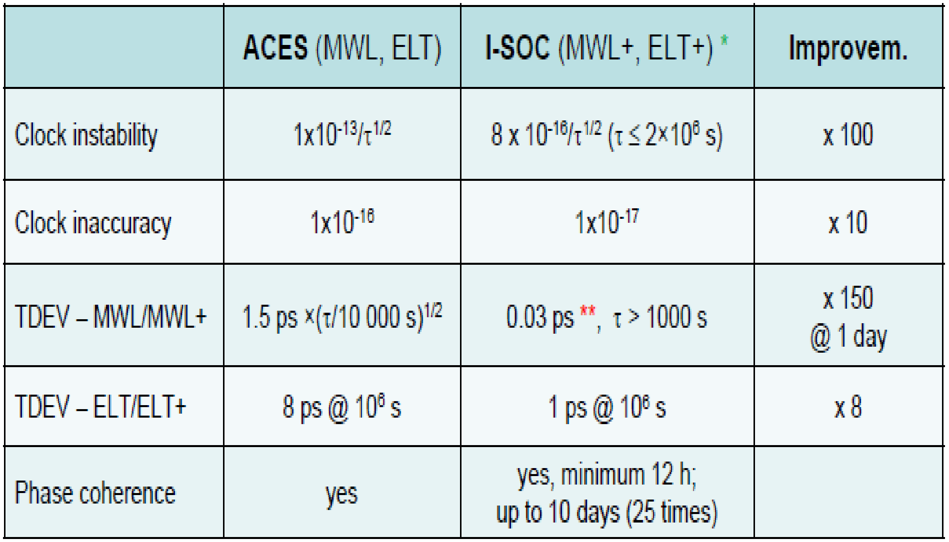
Courtesy of Salomon

1 Introduction

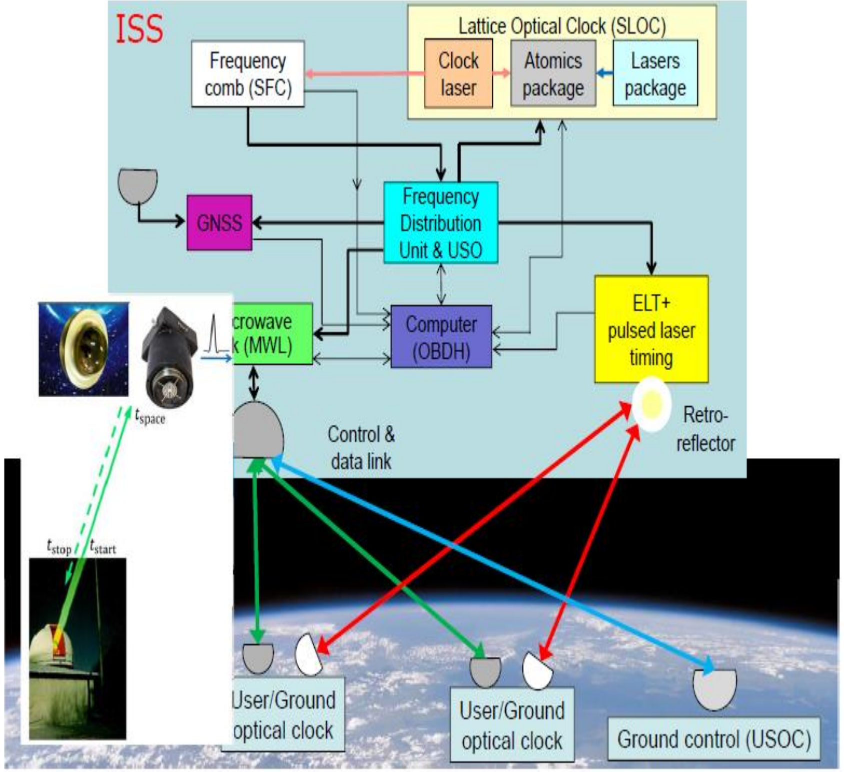
International Space Station(ISS)

- Mission I-SOC (Space Optical Clock on ISS)

ACES (Atomic Clock Ensemble in Space) actual/estimated performance vs. I-SOC requirements (Schiller 2018)



	ACES (MWL, ELT)	**I-SOC** (MWL+, ELT+) *	**Improvem.**
Clock instability	$1\times10^{-13}/\tau^{1/2}$	$8\times10^{-16}/\tau^{1/2}$ ($\tau \leq 2\times10^{6}$ s)	x 100
Clock inaccuracy	1×10^{-16}	1×10^{-17}	x 10
TDEV – MWL/MWL+	1.5 ps $\times(\tau/10\,000\text{ s})^{1/2}$	0.03 ps **, $\tau > 1000$ s	x 150 @ 1 day
TDEV – ELT/ELT+	8 ps @ 10^{6} s	1 ps @ 10^{6} s	x 8
Phase coherence	yes	yes, minimum 12 h; up to 10 days (25 times)	



I-SOC payload: concept (Courtesy of Schiller et al 2018)

1 Introduction

China space station plan

- “Tian Gong” Space Station

- Step 1:(2010~2018)

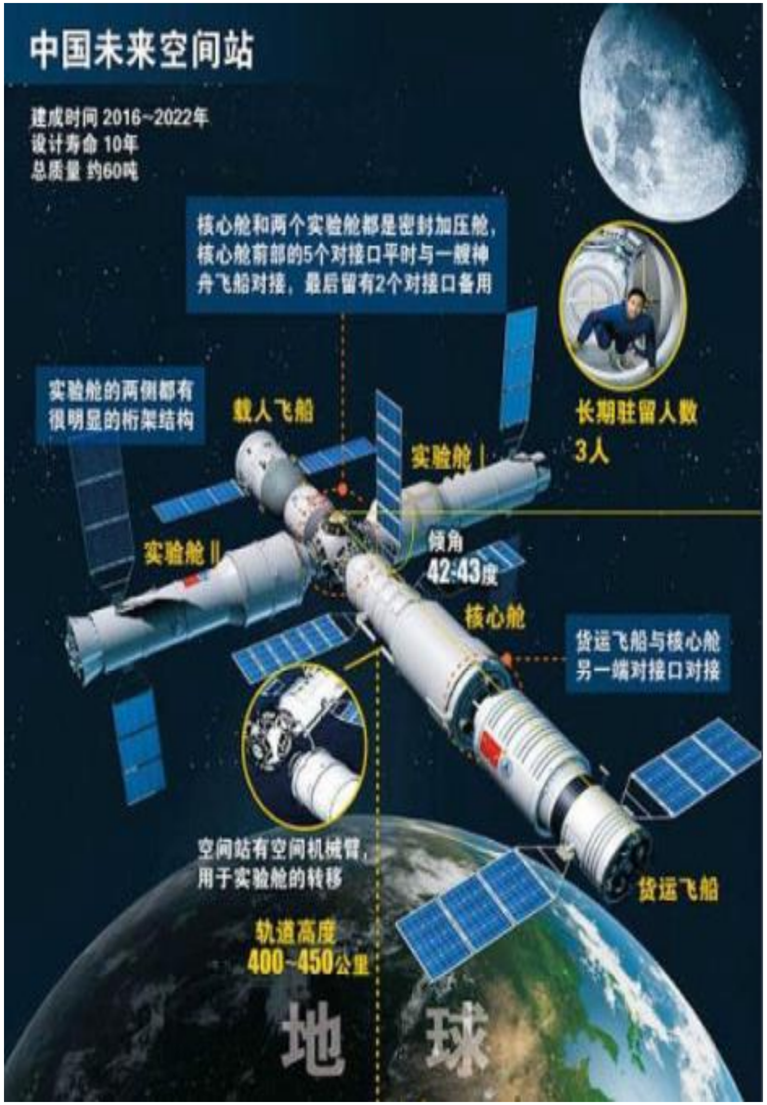
Laboratory stage

- Step 2:(2018~2022)

Space station stage

空间站主要应用方向

☑ 航天医学
☑ 空间生命科学与生物技术
☑ 微重力流体物理与燃烧科学
☑ 空间材料科学
☑ 微重力基础物理
☑ 空间地球科学及应用
☑ 天基信息技术
☑ 航天新技术
☑ 空间应用新技术
☑ 空间环境与空间物理
☑ 航天元器件与部件

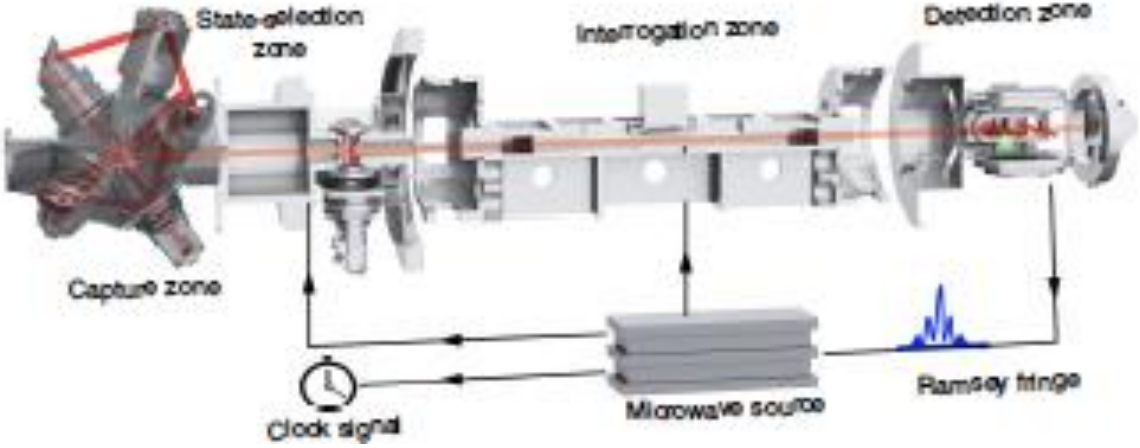


1 Introduction

China space station plan

◆ “Tian Gong II” Space Station

laser-cooled 87Rb atomic clock frequency instability:
1.7 × 10E-16
(Liu et al 2018 Nat. Comm.)



Principle and structure of the space cold atom clock (CAC). The capture zone is a magneto-optical trap (MOT) with a folded beam design. The ring interrogation cavity is used for the microwave field to interrogate the cold atoms. In the detection zone, cold atoms in both hyperfine states are detected. The clock signal is obtained by feeding the error signal to the frequency of microwave source

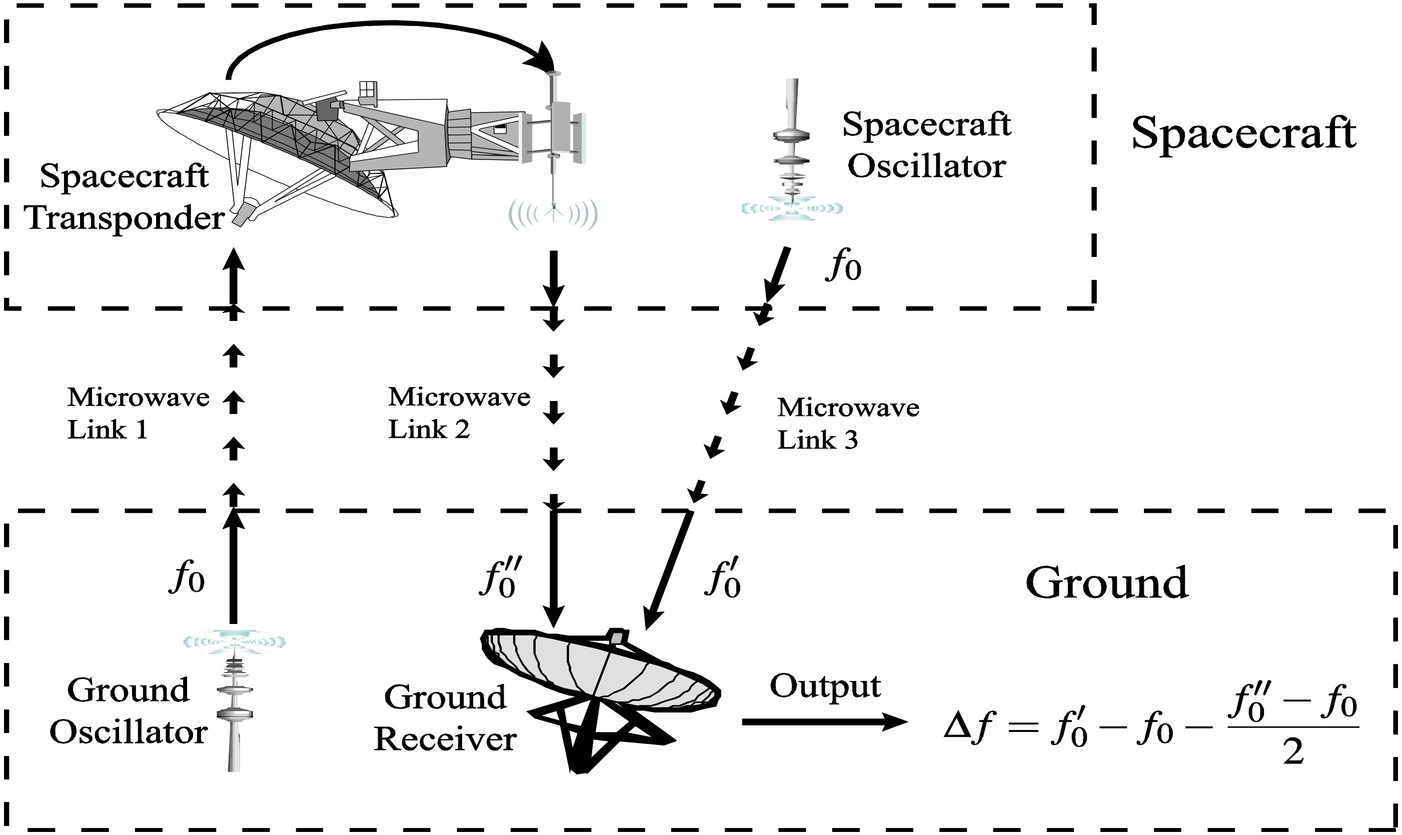
1 Introduction

China space station plan

◆ Launch time (expected): 2022

- Gravitational redshift test with higher accuracy based on various time-frequency comparison techniques
- Test of fine structure constant
- Time signals distribution
- Geopotential determination and world height system unification

2 Space frequency signal transmission



$$\Delta f = f_0' - f_0 - \frac{f_0'' - f_0}{2}$$

Fig 5 The ground oscillator emits a frequency signal f_0 to the spacecraft, then the spacecraft transmits the received signal to ground, and emits a frequency signal f_0 from spacecraft oscillator to the ground at the same time (Shen ZY et al. 2017, modified after Vessot and Levine 1979) .

2 Space frequency signal transmission

- By proper combination of three frequencies, the gravitational potential (GP) difference between satellite and ground is expressed as (Shen ZY et al. 2017):

$$\frac{\Delta\phi_{es}}{c^2} \equiv \frac{\phi_s - \phi_e}{c^2} = \frac{\Delta f}{f_0} - \frac{v_s^2 - v_e^2}{2c^2} - \sum_{i=1}^{4} q^{(i)} \qquad (1)$$

where $\Delta\phi_{es} = \phi_s - \phi_e$ is the GP difference, $\sum_{i=1}^{4} q^{(i)}$ is high order terms (should not be neglected), details are referred to Shen ZY et al. (2017).

- Theoretical precision of Eq.(1) can achieve a relative precision of 10^{-19}

2 Space frequency signal transmission

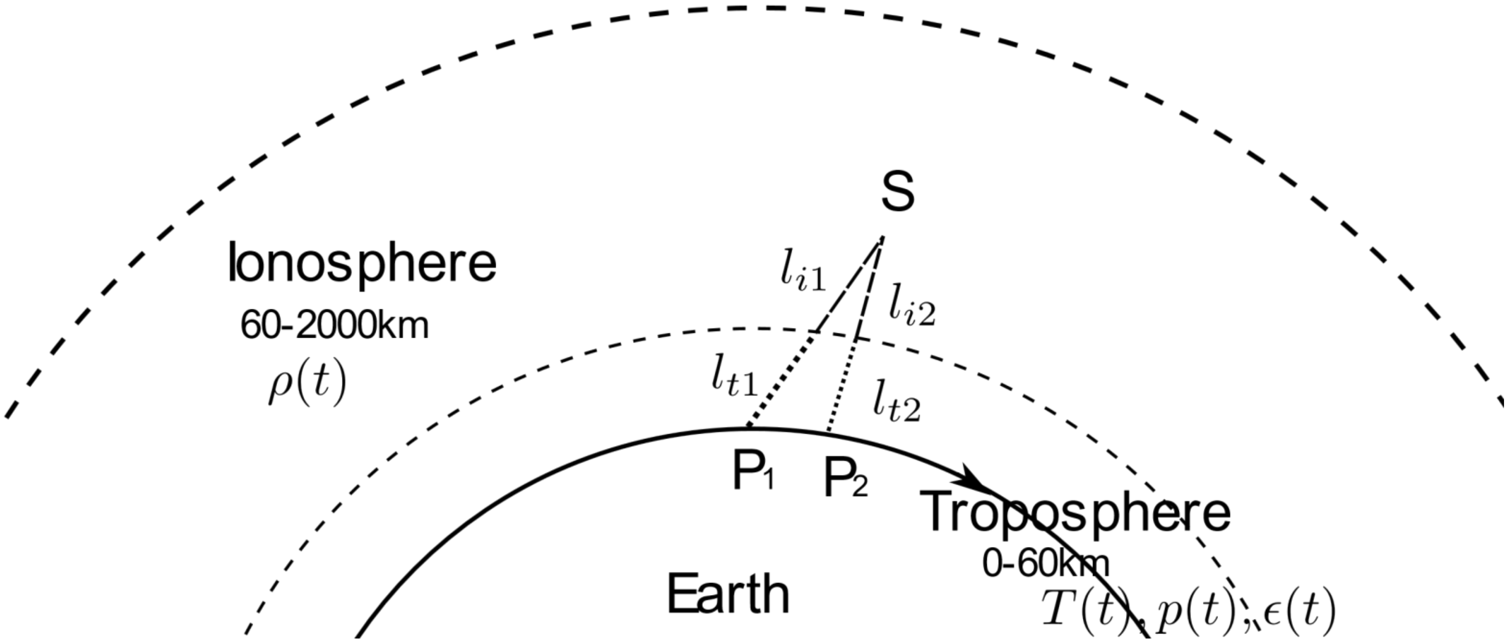


Fig 6 The path difference between uplink and downlink. The oscillator at ground station emits a frequency signal at point *P*1, then the spacecraft (satellite) at *S* receives and transmits the signal toward the ground station. Finally, the receiver at ground station receives the transmitted signal at point *P*2 because of Earth's rotation (modified after Shen ZY et al. 2016)

2 Space frequency signal transmission

- When various corrections and influences are taken into consideration, Eq.(1) is modified as following equation:

$$\frac{\Delta\phi_{es}}{c^2} \equiv \frac{\phi_s - \phi_e}{c^2} = \frac{\Delta f}{f_0} - \frac{v_s^2 - v_e^2}{2c^2} - \sum_{i=1}^{4} q^{(i)} + \Lambda f + \delta f \qquad (2)$$

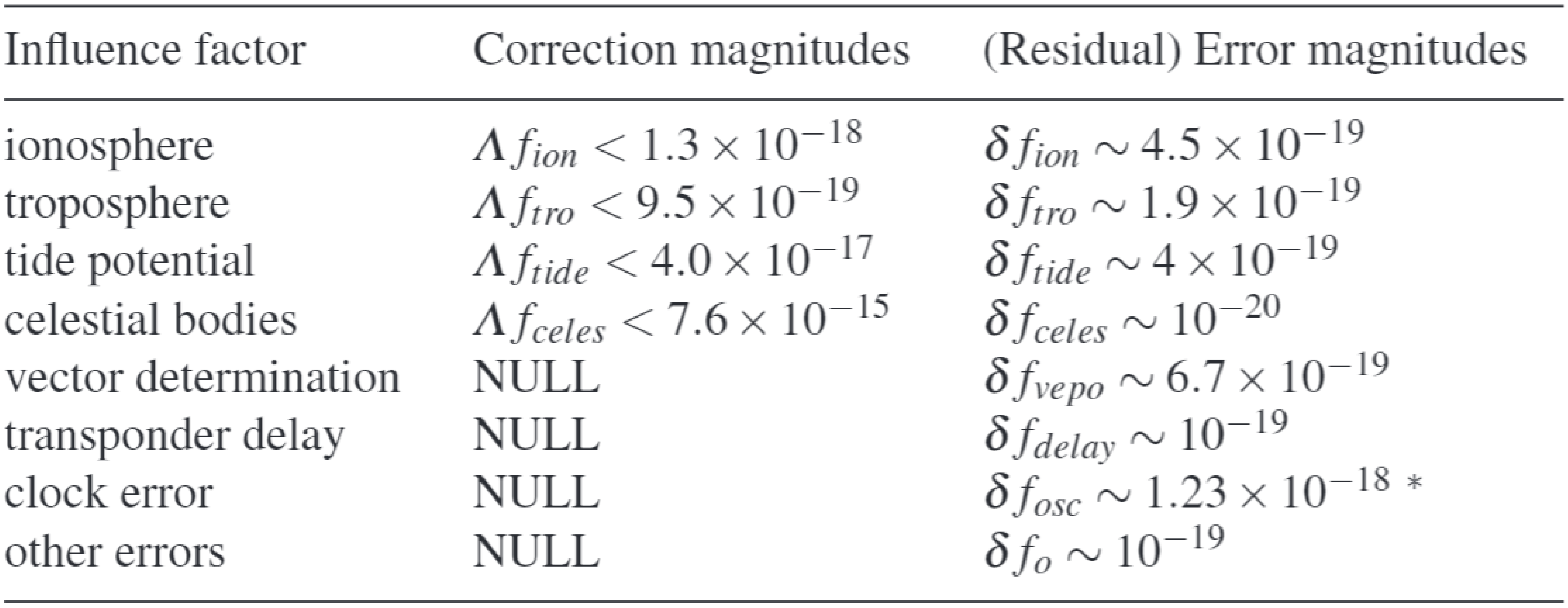
where Λf is the sum of all correction terms, δf is the sum of all error terms.

2 Space frequency signal transmission

- The correction terms Λf include:
  - Ionosphere correction
  - Troposphere correction
  - Tidal correction
  - Celestial bodies' GP correction
- The magnitude of correction terms and error terms are list in Table 1 (modified from Shen ZY et al 2017):

2 Space frequency signal transmission

Table 1 Error magnitudes of different error sources in determining GP difference between a Space Station and a ground station (modified from Shen ZY et al. 2017)



Influence factor	Correction magnitudes	(Residual) Error magnitudes
ionosphere	$\Lambda f_{ion} < 1.3 \times 10^{-18}$	$\delta f_{ion} \sim 4.5 \times 10^{-19}$
troposphere	$\Lambda f_{tro} < 9.5 \times 10^{-19}$	$\delta f_{tro} \sim 1.9 \times 10^{-19}$
tide potential	$\Lambda f_{tide} < 4.0 \times 10^{-17}$	$\delta f_{tide} \sim 4 \times 10^{-19}$
celestial bodies	$\Lambda f_{celes} < 7.6 \times 10^{-15}$	$\delta f_{celes} \sim 10^{-20}$
vector determination	NULL	$\delta f_{vepo} \sim 6.7 \times 10^{-19}$
transponder delay	NULL	$\delta f_{delay} \sim 10^{-19}$
clock error	NULL	$\delta f_{osc} \sim 1.23 \times 10^{-18}$ *
other errors	NULL	$\delta f_{o} \sim 10^{-19}$

3 Geopotential determination via Space Station

- The Chinese Space Station (CSS) **will be launched in 2022**
- The orbit height is about 400~450 km, and inclination is about 42~43°
- It contains various experiments cabins, including one that consists of **precise atom and optic clocks** and relevant instruments

3 Geopotential determination via Space Station

Geopotential difference between two ground stations using SFST via Space Station

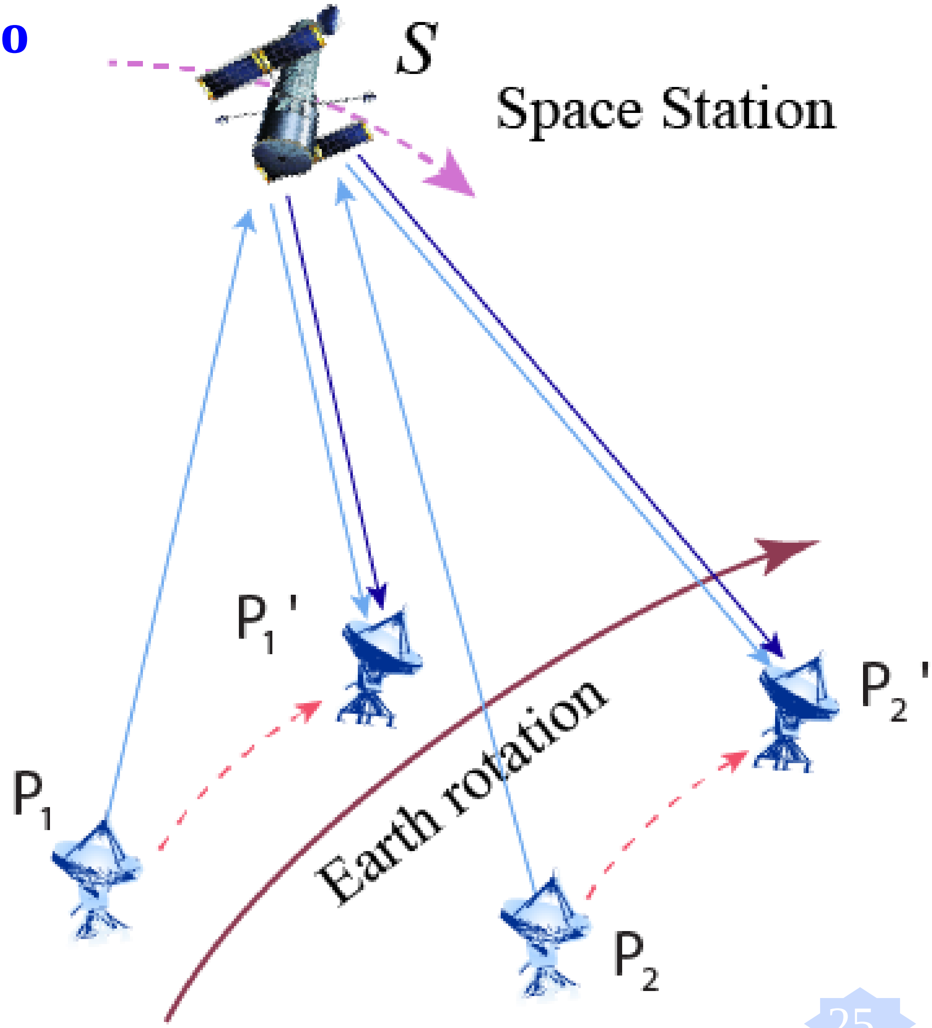


Fig 7: Links of frequency signals among a spacecraft and two ground stations. The space station S receives frequency signals from two ground station P_1 and P_2 simultaneously, then transmits the signals back to ground stations. The ground stations receives the transmitted frequency signals at P'_1 and P'_2 because of Earth rotation.

4 Simulating experiments

As a simulation example, here we only show how to determine the geopotential difference between CSS and a ground station

- We choose a ground station at Wuhan, China, whose geodetic coordinate is (114.35°, 30.53°, 50.0m)
- Suppose the average orbit altitude of the China Space Station (CSS) is 400 km, period is about 1.5 h

4 Simulating experiments

- When CSS flies over the Wuhan ground station (WGS), we choose proper observing time period, which is about 5 min-length “observations”
- One day we obtain 10 min-length “observations”, because of Earth’s rotation

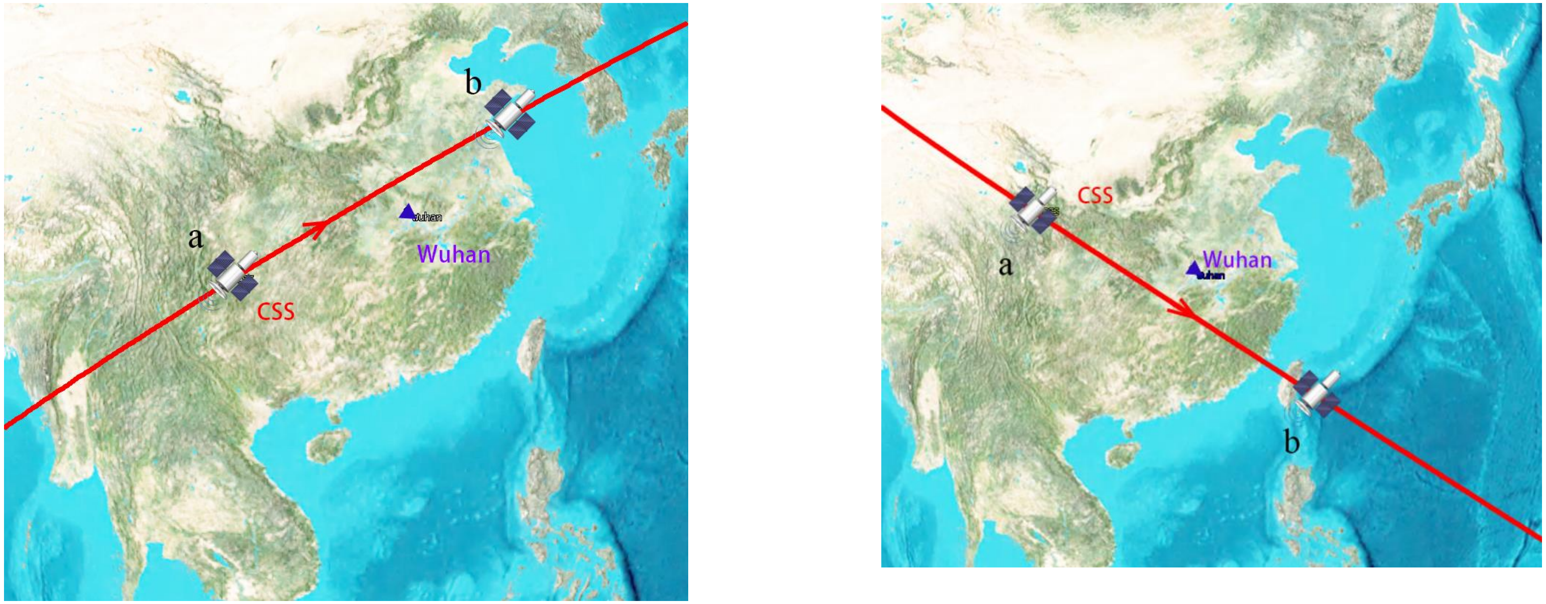


Fig 8: because of the fast movement of low orbit spacecraft, time duration for an experiment section is about 5 min, when the CSS flight from a to b (for example)

4 Simulating experiments

- The angle between observation sight and zenith is below 60° during the experiment time
- Suppose the experiment lasts for 3 days (30 min in total)

- The orbit data and ground position are regarded as true value, and we use EGM2008 model to calculate the geopotential values at ground station and Space Station at different times. These geopotential values are also regarded as true values.

4 Simulating experiments

- After adding noises, we get a new set of ”observations” which are used to estimate the value of interest. Then we calculate the geopotential difference $\varphi_s - \varphi_e$ at time t_i.

- By comparing the estimated (average) value and the true value at time t_i (i=1,2,...,N), we expect to evaluate the SFST method.

4 Simulating experiments

Table 2 Relevant parameters used in simulation experiments

Parameters	**Values**
Orbit data	Satellite Tool Kit
Ground Station	Wuhan (114:32° E, 30:52° W, 50 m)
Observation duration/day	10.0 min
Experiment time	3 days (30 min in total)
Measurement interval	1.0 second
Spacecraft position errors (Zhang et al 2006)	< 10 mm
Spacecraft velocity errors	< 0.01 mm/s
tide correction residual error	$< 4\times10^{-19}$
Celestial bodies correction residual error	$< 10^{-20}$
Other errors	$< 10^{-18}$
Gravitational potential error of Ground Stations	$\approx 0.1\ m^2/s^{-2}$

4 Simulating experiments

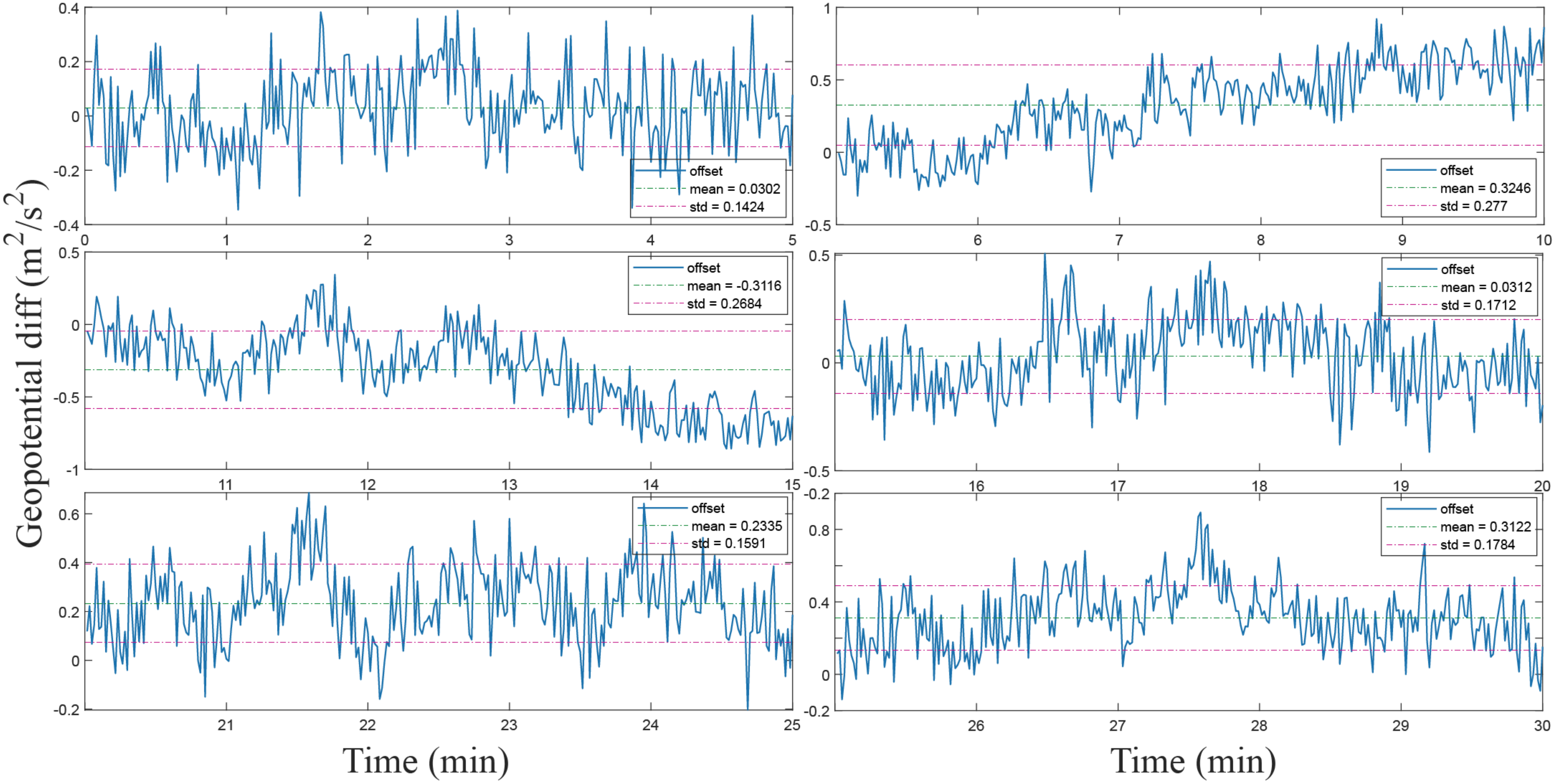


Fig 9 The offset between true values and estimated values of the potential difference between the CSS and the ground station at Wuhan for 6 different periods.

4 Simulating experiments

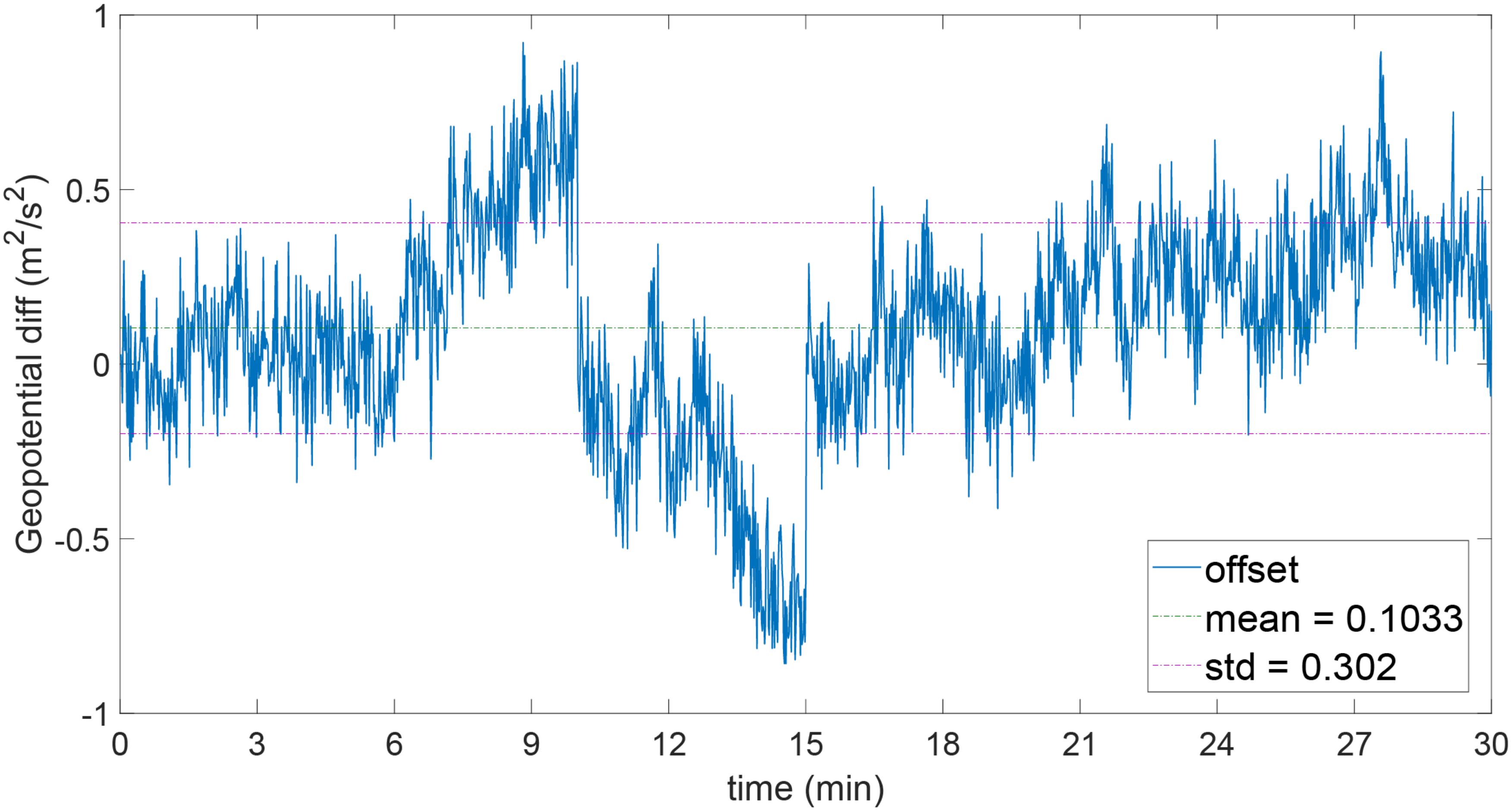


Fig 10 The offset between true values and estimated values of the potential difference between CSS and WGS for total 30 min time

4 Simulating experiments

Table 3 results of the simulation experiments

Time duration	Mean offset (m^2/s^2)	STD (m^2/m^2)
0 ~ 5 min	0.0302	0.1424
5 ~ 10 min	0.3246	0.2770
10 ~ 15 min	-0.3116	0.2684
15 ~ 20 min	0.0312	0.1712
20 ~25 min	0.2335	0.1591
25 ~30 min	0.3122	0.1784
Total (0 ~ 30 min)	**0.1033**	**0.3020** [a]

[a] Note: there are shifts among the results obtained based on different-periods observations.

4 Simulating experiments

- There are **1800 observations** in total, and the mean value of the differences is **0.10 m^2/s^2**, and standard deviation (STD) is **0.30 m^2/s^2**.
- Our simulation experiments show that this approach might be prospective in various applications.

5 Conclusion

- SFST is a promising method to determine geopotential difference between ground station and Space Station
- Via Space Station, it is potential to determine geopotential difference between ground stations separated by sea, **realizing the unification of the world height system**
- This approach may test gravitational redshift effect with **accuracy level two to three-times magnitude higher** than the present accuracy level.

Thanks for your attention!

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