URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Theory and technology of Space Metrology

Wangqianjuan *,Liu Min
Beijing Orient Institute of Measurement & Test (BOIMT), Beijing, China, 100086, wangqianjuan@cast514.com

Abstract

Space Metrology is the measurement science conducting technical and management activities to realize the uniformity of measurement units and to ensure the reliability and accuracy of measurement value in extraterrestrial space. Research in Space Metrology aims to meet to needs of on-site calibration for long-life spacecraft and extraterrestrial base such as the Mars base or the lunar base. Integrating Theory of General Relativity into Metrology, research on the theory of metrology in 4-dimensional spacetime is proposed here. This paper provides an overview of the effect of Relativity on definition of SI units and ongoing technical researches in the engineering field.

1. Introduction

As the Chinese Standard defined, “Metrology conducts measurement to realize the uniformity of measurement units and to ensure the reliability and accuracy of measurement value” [1]. Xu Siwei put forward a new concept of Space Metrology, extending the concept metrology from the Earth ground field to the outer space. Xu defined Space Metrology as the measurement science conducting technical and management activities to realize the uniformity of measurement units and to ensure the reliability and accuracy of measurement value in extraterrestrial space[2].

Space metrology integrates Theory of General Relativity into Metrology, putting forward new definition for base units in the outer space. Utilizing technologies of remote calibration and intrinsic standard in space, periodic calibration could be conducted in space.

2. THEORY of SPACE METROLOGY BASE ON GENERAL RELATIVITY

2.1 Relativistic Effect

2.1.1. Relative velocity effect

Special Relativity (SR) mainly study inertial motion only in inertial coordinates. Principles are put forward in this theory including that light has constant speed, light is isotropic, the speed of light has no relevance with the movement of its source, and etc. Relative velocity effect is one of the many. In a nutshell, the clock ticks slower and the ruler measures shorter while moving. On the earth ground, metrology is conducted in coordinates within the same spacetime. All the calibration conducted on the earth ground has the same coordinate since they are relatively static to the earth ground. While in space, the coordinate is no longer the same and the effect of relative velocity should be considered. Measurement and calibration values need to be adjusted by means of relativity formula in different coordinates.

2.1.2. Gravitational Red Shift effect

General Relativity (GR) applies to both inertial and non-inertial coordinates. It gives the assumption that a curved 4-Dimensional spacetime may exist where the coordinates would curve due to gravitational effect. In a curved 4-Dimensional spacetime, the attraction of mass between different objects does no longer produce gravitational force but instead make space and time curve. Based on this assumption, all satellites and celestial bodies would make inertial motion orbiting around their curved 4-Dimensional spacetime geodesic.

As light moves along the geodesic, it becomes curved in the gravitational field. The stronger the gravitational force is in 3-D spacetime, the larger the curvature is in 4-D spacetime. And vice versa. The curvature influence the ticking speed of clocks. Clocks in spacetime with a larger curvature ticks slower than those in spacetime with a smaller curvature. And this is the so-called “Gravitational Red Shift”[3].

Not only gravitational force but also non-inertial movement, such as acceleration or rotation, can curve spacetime. At present, metrology is conducted in local area with little curvature, the relativistic effect could be ignored. Gravitational Red Shift effect makes relative deviation of ticking speed up to a level of 1.08E-12 at the North or the South pole of Earth at an altitude of 10km [4].Clocks on satellite and on the earth ground are placed in difference gravitational field, and they have different ticking speed. Clocks on GPS satellite with orbit radius of 26562km change -7.1μs/day due to relative velocity effect, and 45.7μs/day due to Gravitational Red Shift effect. In total, the change is 38.6μs/day[5,6].

The speed of the clock depends on the definition of time scale: the SI unit of “Second”. The synchronization of time value in spacetime with different curvature could only be realized as long as the definition of SI unit of "Second" is rectified. The rectification should make clear statement of proper time being used in local area and coordination time being used in wide area.

2.1.3. Sagnac Effect

The Sagnac Effect [7] is a phenomenon encountered in interferometry in a non-inertial frame of reference.A beam of light is split and the two beams are made to follow the same path but in opposite directions. The Sagnac Effect in non-inertial frame of reference could be transformed to the relative velocity effect in inertial frame of reference.

The optical fibre gyro and laser gyroscope are just inventions based on Sagnac Effect. They could sense non-inertial motion. Sagnac Effect also exerts on satellite making a deviation of transmission time. Sagnac Effect shows that the path of light or electromagnetic wave is curved in non-inertial frame of reference.

2.1.4. Equivalence Principle of General Relativity

Equivalence Principle of General Relativity claims that " All system of reference are equivalent with respect to the formulation of fundamental laws of physics". Space Metrology also follows this principle. Thus, definition of metrology units should be uniformed in any frame of reference. The comparison of time measurement in different spacetime could be made only by using a uniformed time unit. Global Navigation Satellite System (GNSS) had already set up an independent system for time uniformity, but that differs from the traditional definition of uniformity in metrology[8]. In Space Metrology, it is assumed that the uniformity of time and the uniformity of the SI unit second can't be realized both way in various coordinates and gravitational fields.

2.2Definition of time unit and measurement of time

At the 13th CGPM in 1967and 26th 2018, the SI unit of measure for time was defined as the duration of 9 192 631 770 cycles of radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom[9]. In theory of General Relativity, there are two types of time. "Proper time" is a time measured at local area in SI second. "Coordinate time" is a time measured at a special point in SI second, where the gravitational force is zero, and relative velocity to the origin is zero. With these two concepts of Proper time and Coordinate time, and the formula of General Relativity (1) , time in the wide area could be uniformed.

$$\Delta t = \int_{\tau_0}^{\tau} \left(1 + \frac{U}{c^2} + \frac{V^2}{2c^2} \right) \mathrm{d}\tau \qquad (1)$$

Where: Δt is the duration of Coordinate time in seconds; T is the variable quantity of proper time in seconds;U is the gravitation potential at local area in volts; V is the relative linear velocity to the origin ; c is the constant of light speed.

In figure 1, the TOA of earth is τ1; and the TOA of Mars is τ2. The gravitational potential and relative velocity could be calculated using its own orbit parameters.

By formula (1), we could transform proper time into coordinate time as Earth t_1 and Mars t_2. Taking the Earth and Mars into BRS (barycentric reference system). The Earth's and the Mars's gravitational potential and relative velocity could be calculated inputting its own orbit parameters. Again, by formula (1), Earth t_1 and Mars t_2 could be transformed into new coordinate time of BRS as Earth t_{s1} and for Mars t_{s2}. Finally, we could compare t_{s1} and t_{s2} , thus deciding which one arrives earlier.

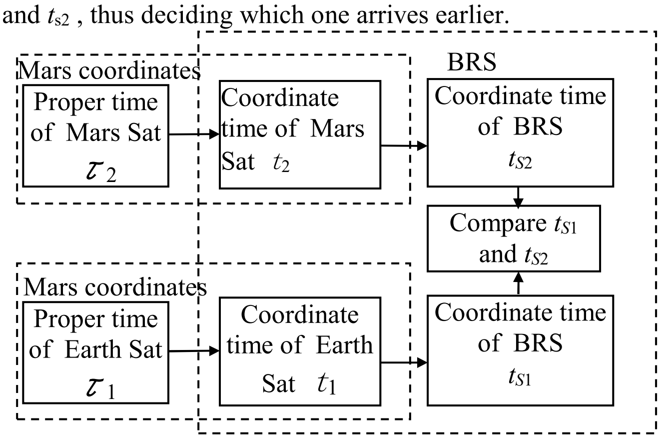

Figure 1. Scheme to compare proper times between different local areas

There are two kinds of frame of reference coordinates on the earth ground. One is non-inertial ECEF(Earth Centred and Earth Fixed) system which rotate with the earth. The other is ECI (Earth Centred Inertial) system which does not rotate with the earth, taking far-away stars as reference coordinate.

Based on these two coordinates, two types of time systems are defined. One is UT (Universal Time) in non-inertial ECEF system whose reference is the average period of the Sun, which divides a day into 24 hours, 86400 seconds. The other is TAI (International Atom Time) in inertial ECI, a fixed time scale as SI second at geoid, whose reference is based on the observing duration of a second around 1950. However, with the earth rotation changing, the time deviation between UT1 and TAI increases. To solve this problem, since Jan. 1st 1972, the international community start to use UTC (the Coordinated Universal Time). In the future, new time keeping systems will be built on many other independent coordinates[10], delivering their standard time from space to other satellite or to the local users. With regards to the relativistic effect, new uniformity of time system will be developed in the whole solar system.

2.3Definition of Length unit and measurement of distance

At the 17th CGPM in 1983, the SI unit of measure for length was redefined. "The meter is the length of the path travelled by light in vacuum during a time interval of

1/299 792 458 of a second". Since light speed is a constant, values of time and length are directly correlative.

1)In 4-D spacetime, light is curved in gravitational field or inertial field. Then, How to measure the distance between two points?
Distance in 4-D spacetime could be expressed as below according to the theory of General Relativity:

$$l = \int \sqrt{\left(g_{ik} - \frac{g_{0i} g_{0k}}{g_{00}} \right) \mathrm{d}\, x^i \, \mathrm{d}\, x^k} \qquad (2)$$

Where: l is the distance between two points in 4-D spacetime; x^i, x^k are coordinate axes of 3-D spacetime, superscripts of I and k are not exponent function, (i=1,2,3) and (k=1,2,3) are used to distinguish coordinate axis number; g_{00} is the metric of time coordinate; g_{0i}, g_{0k} are the metric of correlativity of time and space coordinate axes, at g_{0i}=0, space axes x^i is not orthogonal with time axis; g_{ik} is the metric of space coordinate.

2)Distance measurement in local area space must use proper time and light speed constant according to the principle of general relativity. However, in the wide area space, how to choose the proper time or the coordinate time?Assume point A and far-away point B both measure distances between. A and B are in different gravitational fields. They use their own proper time and light to conduct measurement obtaining different results. But if they transform their results from proper time into coordinate time, by formula (1), the adjusted results will be the same.

2.4Others units of physical quantity

Josephson Voltage intrinsic standard builds a correlation between voltage and frequency. Since frequency is affected by relativistic effects, when we use atomic clocks to represent voltage unit, we should choose SI second unit as the proper time.

For definition of temperature, two questions should be considered. Firstly, the definition of plasma temperature. Ions and electrons are moving and colliding with each other by electromagnetic force, which does not comply with the Maxwell gas distribution law, so the average kinetic energy is different with ions or electrons. Two concepts of temperature evolved, the ion's temperature and the electron's temperature. Secondly, the principle of radiation temperature detecting is based on the measurement of electromagnetic frequency. While the frequency is affected by relativistic effects. Therefor, two concepts of temperature evolved, the proper temperature and the coordinate temperature[11].

Einstein's famous formula of $E=mc^2$ tells us that as light speed is a constant, Energy E and mass m are all variable quantities. Energy of matter includes atomic energy, kinetic energy, thermal energy, radiation energy, and so on. All these energy are variables in various spacetime. So does the mass. Therefor, mass is not an intrinsic feature.

3. TECHNOLOGY OF SPACE METROLOGY

3.1. Remote calibration base on Stimulation-Response method

Stimulation-Response method is new calibration technology introduced by space metrology and remote calibration. It applies to on-orbit and on-site calibration for various sensors. This method does not interrupt the sensor's normal operation. During its design, the calibration method had already been considered.

The basic principle of is Stimulation-Response method is imposing an increment value to the original sensor. Then a certain response will be obtained in the original system, by comparing the response value and the ideal expect value, the sensor's transfer function error will be calibrated. A typical Stimulating-Response calibration is to calibrate accelerometer on-orbit of "CE-1" satellite [12]. It uses the remote measurement data before and after satellite's engine control and ground control instruction data to calibrate accelerometer on-obit. In this method, the stimulation is provided by the engine, and the response is obtained through precise measurement including information about the orbit situation.

3.2. Self-calibration by inbuilt standard element

Self-calibration by inbuilt standard element is the technology that installs the calibration standard on independent channels, which are additionally designed to a multichannel system. By measuring the value of calibration standard periodically, the accuracy of the data acquisition function could be obtained. However, this method could only calibrate part of the measurement system, not the whole. In space metrology, calibration standard need to be custom-developed, providing one or several standard with fixed values whose stability outcompete the test system. To study the change patterns of standard element, studies on adaptation of standard element in simulated space environment on the earth ground need to be conducted. The test standard elements could be resistor, capacitance, oscillator, and etc.

3.3. Space primary standard

Primary standard could not be placed into space directly. They must be portable, light weighted, and energy efficient. Also, before paced into space, primary standards need to go through a long term test in simulated space environment. NASA's terrestrial observation satellite ,"Terra carried Moderate Resolution Imaging Spectroradiometer (MODIS)", had carried a solar diffuser, a solar diffuser stability monitor, a blackbody and a spectoradiometric calibration assembled to conduct on-orbit calibration[13]. When comes to traceability, the basic requirement of standard apparatus, there are the following aspects need to be taken into consideration:

1)Develope primary standards in space. In 1997, European Space Agency (ESA) launched the Space Atom group (ACES) project, sending a cold Atom of caesium 133 clock and a hydrogen atom clock into international space station in 2017. In the future, primary standards such as Josephson voltage standard and Hall resistance quantum standard might be used on extraterrestrial base stations.

2)Utilize radiation of nature celestial bodies to build traceability. The radiation from the sun, the moon, or far-away celestial bodies could provide stable electromagnetic wave and light radiation with a stability of 0.01% [14], which could be used as reference for space radiometer.

3)Utilize the stability of special material to develop standard element. With fasten protection designed and change patterns in simulated space environment obtained, those standard elements could be used as primary standard for the whole life of spacecraft.

4)Use increment method to build traceability. The Stimulating-Response method may not provide the absolute accuracy, but the stimulation source with a known increment signal could build a relative traceability.

4. CONCLUSIONS

Base on the theory of General Relativity, the development of Space Metrology was another milestone in history. Focusing on measurement in 4-D spacetime, the uniformity of SI base unit of proper time in local area and coordinate time in wide area is put forward.

The technologies discussed here are potential feasible technologies in the future. And BOIMT now is conducting research on remote calibration of current sensor based on Stimulating-Response method, and developing standard resistor used in space.

5. References

1. JJF1001-1998 General Term and Definition for Metrology[S] , Chinese Standard, (1998)

2. Xu Siwei, Su Xin-guang, Zhang Shufeng, Liu Biye, Liu Min, Zhang Shaonan, Research On Status and Prospect of Space Metrology Technology[J], *Journal of Astronautic Metrology and Measurement*, 2014,34(5):1-4.

3. Claus Lammerzah, The Einstein Equivalence Principle and the search for New Physics, *Lect. Notes Phys.* 631, 367-400, http:// www.springerlink.com, © Springer-Verlag Berlin Heidelberg 2003, p381.

4. Liu Min, Peng Ming, Liu Biye, Discussion on The Definition of Basic Physical Units in Space Metrology[J], *Journal of Astronautic Metrology and Measurement,* 2017,37(1):1-6.

5. Robert A. Nelson, Relativistic Time Transfer in the Solar System, 2007 Joint with the 21st European Frequency and Time Forum, IEEE international, 1278-1283.

6. Zhang Ke, Xue Shun, Lü Mei-bo, Relativistic Time Transfer and Synchronization in the Vicinity of the Earth[J], *Journal of Electronics & Information Technology,* 2014, 36(8):1992-1998.

7. Matteo Luca Ruggiero, Angelo Tartaglia, A note on the Sagnac effect for matter beams[J], *The European Physical Journal Puls,* (2015)130:90, DOI 10.1140/epjp/i2015-15090-8.

8. Wang Zhengbo, Zhao Lu, Wang ShiGuang, Zhang JianWei, Wang Bo, Wang LiJun, COMPASS time synchronization and dissemination–Toward centimetre position accuracy, *Science China, Physics*, Mechanics and Astronomy, 2014,57,(9):1788-1804.

9. Michael Stock, Richard Davis, Estefania de Mirandes, Martin J T Milton, The revision of the SI – the result of three decades of progress in metrology [J]. *Metrologia*, 56(2019) 022001, (14pp)

10. Liu Min, Shuai Pin, Liu Zhihong, Li Jun, Space Metrology and Pulstar Navigation, [J], *Journal of Astronautic Metrology and Measurement,* 2019,39(1):5-11.

11. Nie La-Mei, [J]， College Physics， 2010， Vol.29,No.8

12. Tang Geshi, Chen Lidan, Liu Yong, Analysis and Implement of Determining the Orbit Maneuver Effect of CE-1 Satellite[J], *Chinese Space Science and Technology,* (2009)6:1-6.

13. X. Xiong, W. Barnes, A Overview of MODIS Radiometric Calibration and Characterization[J], *Advance in Atmospheric Science,* 2006,23(1):69-79

14. David B. Pollock, Alexander Panfilov, Inessa Glazkova, etc, The Space Metrology Progarm, Proc. of SPIE Vol.5570:301-305.