

Atomic Clock-Based Method for Satellite Attitude and Altitude Determination

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Abstract

Time dilation is a measurable change in the passage of time caused by differences in gravitational potential, a key prediction of general relativity. Recent advances in atomic clock precision allow such differences to be detected over small separations relative to that gravitational potential. This capability introduces a new approach to satellite attitude and altitude determination, independent of line-of-sight, optical, or magnetic-field-based sensing. This method could be particularly valuable for planetary landing and navigation missions, including those on the Moon and Mars, where traditional reference systems may be unavailable or unreliable.

Keywords

Atomic Clocks, Satellite Attitude Determination, Time Dilation, Gravitational Navigation, Planetary Exploration

1. Introduction

Satellite attitude determination is important, because it enables precise pointing for instruments and antennas, maintaining communication, GPS timing, power management (from pointing solar panels) and orbital maneuvering and navigation [1].

The current methods for attitude determination are Star Trackers, sun sensors, magnetometers, and gyroscopes. We would like to introduce a new method for attitude determination. That uses the relativity's effect on time moving at different speeds and the distance from the center of a gravitational body.

Due to relativity's importance to global positioning systems, atomic clocks accuracy has been an area of advancement, leading to optical atomic clocks that can perform timekeeping with 19 decimal places of accuracy [2].

Low earth orbit is approximately 200 to 2000 km from the earth's surface or 6600 km to 8400 km from the earth's core [3]. Due to the differences predicted by relativity, high-precision atomic clocks on a satellite should exhibit different times due to differences in velocity, relative altitude, and satellite orientation. Through comparing these different measured times, we can calculate information about the satellites altitude and attitude. Through comparing the values with a ground station, we can calculate velocity.

On satellites, the errors need to be corrected for and have a process for correcting errors created by general and special relativity [4]. As it is a new process and using these atomic clocks for a novel process, it would need new experimentation to validate it in practice.

This difference is measurable and independent of light, a magnetic field, and line of sight. This independence enables use where there is no magnetic field like the Moon or Mars. Or it could enable use where lunar or martian dust has obscured the landing zone.

2. Background

As per general relativity, time is relative to the distance to the center of a mass and is shown by this Gravitational time dilation formula (Weak field approximation) (1):

$$\frac{dT}{dt} = 1 - \frac{2GM}{rc^2} \quad (1)$$

This weak field approximation is a simplification where the gravitational field is weak because we are only going over 1 meter at a time differences that are small. It is based off the Schwarzschild metric [5] (2):

$$\frac{dT}{dt} = \sqrt{1 - \frac{2GM}{rc^2}} \quad (2)$$

which is an exact solution to Einstein's field equations for an object surrounding large slowly rotating masses like Earth, the Moon, and Mars.

The equation for time dilation due to velocity changes describes the change in time dilation due to velocity of the satellite. As satellites travel at orbital velocities the time dilation is a measurable difference as well. This enables a detection of the velocity of the satellite through the time dilation [6] (3):

$$\frac{dT}{dt} = \sqrt{1 - \frac{v^2}{c^2}} \quad (3)$$

This enables speed determination but requires a clock either on the earth's surface or a reference clock with a known velocity and time that can be compared to. This is great for earth orbital missions but on the moon and mars it would require a separate mission to set up the reference clock as it cannot be hosted on the satellite being measured. As the clocks in the same reference frame would read the same value.

3. Attitude Determination

The orientation of the satellite could be determined through taking a time difference between clocks. The benefit of this method is that they use 2 clocks that are the same in regard to velocity and they would be affected by large geological features on the planetary surface, or nearby moons, asteroids, or large space stations the same. Resulting in the ability to remove the “noise” of nearby gravitational fields from affecting the orientation of the satellite.

The atomic clock readings shown in **Figure 1**, show the different orientation that affects the differences in time measured by the atomic clocks. Showing only two clocks for simplicity but the number and placement of clocks could be optimized for the specific use case. More clocks would be needed to measure attitude in other axes.

When the orientation of the clocks is such that the distance to the center of earth is the same, the clocks will read the same time. The time will slowly differentiate as the satellite turns until the maximum time difference with atomic clocks is oriented parallel to the gravitational field.

To put it in another way we can call the direction directly away from the earth’s center of gravity the z-axis. The only measurable difference due to time dilation is the differences between the 2 atomic clocks in the z-axis. In **Figure 1**, the distance shown by A is the only difference that can be measured with atomic clocks. If the satellite is only rotated slightly in relation to the z-axis, there will be only a slight difference in the atomic clocks time difference.

A minimum of 3 clocks would be required to measure the satellite’s orientation in three-dimensional space accurately. This gives one clock per direction x, y, or z resulting in an accurate directional analysis.

The 3 clocks can be orientated in the satellite or spacecraft so that the greatest difference is the z-axis and the plane of the clocks are spread the furthest possible along the x and y axis. So that small angles change the differences in the z-axis are accentuated.

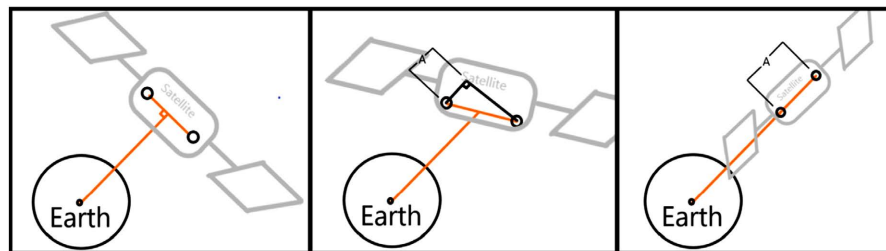


Figure 1. The different orientation of the clocks in relation to Earth’s center of gravity. When the atomic clock’s orientation is perpendicular to gravity there is no difference in time reading. When the atomic clock’s orientation is angled in regard to gravity the difference “A” is the distance that affects the change in time up to the maximum difference in atomic time when the orientation of the clocks is parallel to the pull of gravity.

Major errors in atomic clocks for GPS use are satellite clock bias mostly caused by satellites going at orbital velocities and at orbital distances [7]. For this detec-

tion method to utilize the atomic clocks for attitude and altitude determination there will be some differences between clocks caused by launch and the clocks being in slightly different spatial environments and therefore need to be calibrated before each reading so that the difference caused by velocities, altitudes, rotational speed, nearby large orbital objects, and orbital eccentricity can be removed.

Vibrational frequency of the satellite or spacecraft. The vibrational speed causes changes of relative speed of the different clocks within the satellite. If the vibration affects the satellite as a whole and all clocks being measured, then the clocks would change the readings the same. This would only be caused by the vibrations that only affect the satellite non-uniformly. All vibrations that are below the error tolerance limit can be ignored. Vibrations between 3×10^{-8} hz and 3×10^{-10} hz would interfere with the attitude and altitude determinations as these would cause changes around the target change values of $\times 10^{-17}$ that would change the results of the tests.

Accelerations of the satellite would also result in changes in atomic clock readings within a limit. The accelerations don't modify the readings of the atomic clocks, but the resulting velocity changes the time differences. This includes rotational velocities, so as seen in **Table 1** if the satellite is rotating at 1 m/s the atomic clocks will run 1.11×10^{-17} seconds slower and needs to be accounted for to get an accurate altitude or attitude reading.

Table 1. Time differences caused by changes in velocity.

Velocity (meters/second)	Time difference in seconds
7900	6.94×10^{-10}
1000	1.11×10^{-11}
500	2.78×10^{-12}
10	2.78×10^{-15}
1	1.11×10^{-17}
0.1	1.11×10^{-19}
0.01	1.11×10^{-21}

Another benefit of using clocks as orientation determination tools is that waiting more time can increase the signal strength of the orientation. These time differences are very small changes in the time that compound each second, so the longer the satellite must take a reading the larger the measured difference between the atomic clocks will be. The differences between 2 atomic clocks a meter apart is around which is close to the limit of the high precision atomic clocks. These are differences per second. With a clock that is only accurate to the $\times 10^{-18}$ the difference is close to the limit of its measurement, and it limits the ability to measure below a second difference between two atomic clocks. With this accuracy of the atomic clock the fastest possible time to get a difference between two clocks spaced a meter apart, around the Earth is 0.1 seconds. Which is more than enough time

while the satellite is at orbital distances during regular satellite operation but may provide challenges if speed of getting an orientation result is paramount.

During satellite operation at orbital velocities the more important factor would be accuracy over speed of reading and saving space. Maintaining the greatest distance between 2 atomic clocks relative to the planetary body is convenient to enable the greatest measurable time variation. With high precision atomic clocks that are accurate to $\times 10^{-18}$. The minimum distance measurable is 0.1 m per second difference between the radii of the atomic clocks to the gravitational center of mass that the satellite is orbiting. With clocks of greater precision, the difference between the atomic clocks radii around the planetary body could be smaller and more precise to the differences per second. Unless more time was spent taking the measurement, if 100 seconds were waited between atomic clock measurements a smaller difference in time dilation would be magnified and you could tell the orientation to a greater degree.

For landing on other planetary bodies, a larger landing craft could be used to have a more accurate attitude determination. Such as SpaceX's starship could have an atomic clock on either end to maximize the difference in the atomic clocks would be per second. Enabling the use of less accurate atomic clocks or using the same high precision atomic clocks and getting usable measurements with less delays for taking measurements. Potentially getting a usable reading once per msec to get an "absolute" orientation in respect to the planetary bodies center of mass.

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Measuring altitudes based on the atomic clock time difference gives a distance to the center of the planetary body. As you can see by looking at the weak field approximation (1) the radius or the planetary body with mass is the measurable distance from the atomic clocks. This gives a result of the mass directly below the spacecraft and toward the planetary surface. It does not measure the distance to the surface of the planetary body. Therefore, this spacecraft or satellite system could only be used as a form of absolute altitude from the center of a planetary body. There could be a hill, crater, and large deposits of high mass minerals could change the reading of altitude of the satellite or spacecraft. Experimentation would be required to see how accurate and sensitive the method would be to topological differences on a planetary surface.

4. Example

To use the example of a satellite around low earth orbit that has two atomic clocks one meter apart.

$$\frac{dT}{dt} = 1 - \frac{2GM}{rc^2} \quad (4)$$

Constants:

Gravitational constant (G) = $6.67430 \times 10^{-11} \text{ m}^3/\text{kg}/\text{s}^2$

Mass of Earth (M) = 5.972×10^{24} kg

Speed of Light (c) = 2.9979×10^8 m/s

Distance to satellite atomic clocks B : 8400 km

Distance to satellite atomic clocks C : 8400.001 km

$$\frac{dT}{dt} = 1 - \frac{2 \times 6.67430 \times 10^{-11} \text{ m}^3/\text{kg}/\text{s}^2 \times 5.972 \times 10^{24} \text{ kg}}{8.4^6 \text{ m} \times 2.9979 \times 10^8 \text{ m}/\text{s}^2} = 1.06 \times 10^{-9} \text{ seconds}$$

$$\frac{dT}{dt} = 1 - \frac{2 \times 6.67430 \times 10^{-11} \text{ m}^3/\text{kg}/\text{s}^2 \times 5.972 \times 10^{24} \text{ kg}}{8.400001^6 \text{ m} \times 2.9979 \times 10^8 \text{ m}/\text{s}^2} = 1.06 \times 10^{-9} \text{ seconds}$$

Difference = 1.06×10^{-9} seconds – 1.09×10^{-9} seconds = 1.26×10^{-16} seconds per second

Giving a value of 1.26×10^{-16} seconds per second around 6600 km and 6.28×10^{-17} seconds per second around 8400 km for the top and bottom of low earth orbit respectively. These are measurable values with current high precision atomic clocks per second.

Due to this being an additive time difference though, waiting more time results in a stronger difference between the two atomic clocks to get better reading.

Time Dilation around Different Planetary Bodies

The slope was able to be calculated for the difference between 2 atomic clocks placed a meter apart due to time dilation for the Earth, Moon, and Mars and graphs were created as seen in the Figures below.

For the Earth (**Figure 2**), Moon (**Figure 3**), and Mars (**Figure 4**) the rate of time dilation change is around 10^{-17} per meter with some variation and with existing high precision atomic clocks this time difference is measurable at orbital distances. It is important to note that this slope is the rate the 2 clock differences change with altitude and not a measure of the differences between the two atomic clocks. For example around earth the difference between 2 atomic clocks a meter apart at a distance of 6600 km from the earth center or 200 km from the earth’s surface is 1.02×10^{-16} seconds per second and if the whole satellite moved 1 meter away from the surface of the earth the difference would 7.95×10^{-17} seconds less of a difference between the 2 clocks. This also enables altitude determination by comparing the differences between the 2 clocks compared to the difference expected at that altitude.

This novel approach enables the determination of an “absolute” altitude relative to the planetary center for the spacecraft around different planetary bodies. In this case the absolute altitude means the distance of the spacecraft or satellite relative to the center of mass for the planetary body, not how close the spacecraft is to the surface. As the three would be variations due to large caves, mountains, dense minerals or materials under the planetary surface.

As seen in **Table 2**, the measurable time differences with clocks 1 meter apart at the surface of the different planetary bodies are quite small due to gravity. The Earth, Moon and Mars are all measurable but on the asteroid 99,942 Apophis the time differences are so small that they would require measurements over minutes or hours to get a reading that was usable for altitude or attitude.

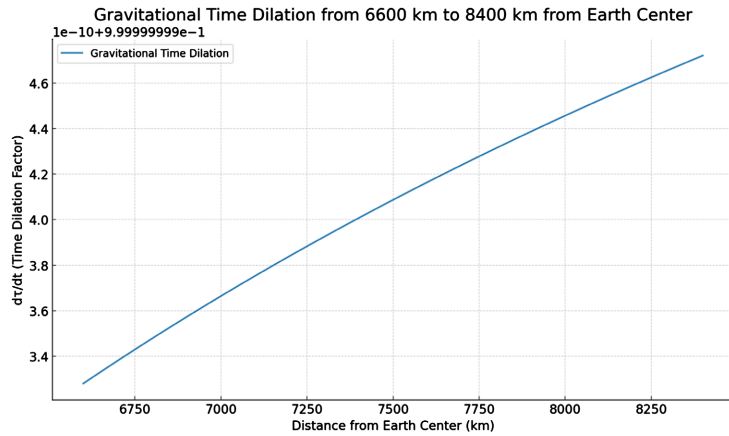


Figure 2. Time dilation gradual change between 2 atomic clocks 1 meter apart around earth as the altitude increases at low earth orbital distances. The slope is 7.95×10^{-17} seconds per meter.

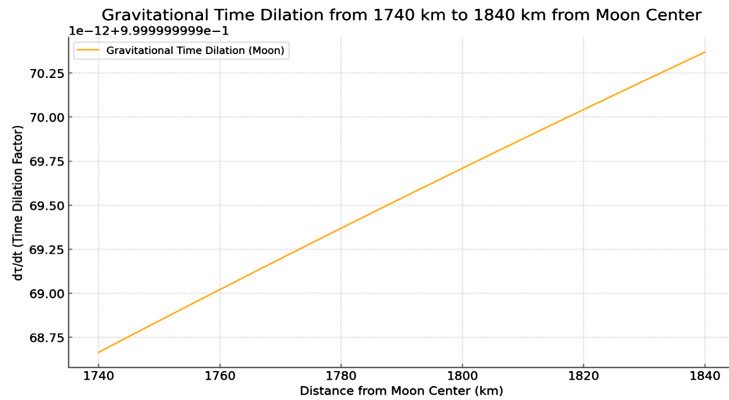


Figure 3. Time dilation gradual change between 2 atomic clocks 1 meter apart around the moon as the altitude increases from the surface to a common satellite orbital distance of 100 km from the surface. The slope is 1.7×10^{-17} seconds per meter.

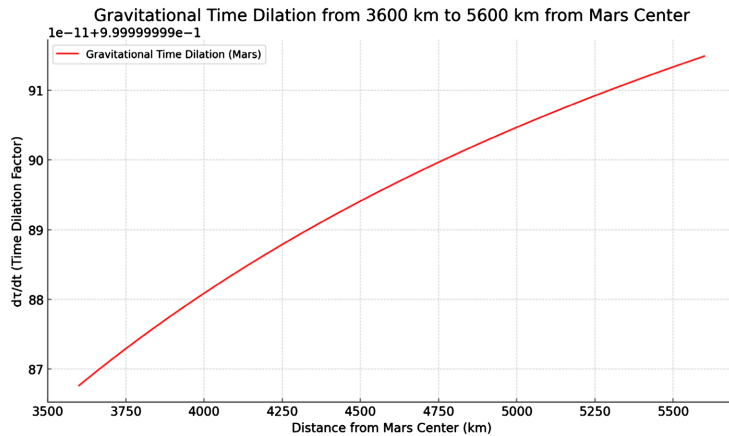


Figure 4. Time dilation gradual change between 2 atomic clocks 1 meter apart around mars as the altitude increases from the orbit of the *Mars Reconnaissance Orbiter (MRO)* [11] lowest orbital distance of 370 km and up 2000 km, that was arbitrarily chosen. The mars rate of time dilation is more of a curve due to the Schwarzschild metric (2) not using the weak field approximation (1). A slope was still fitted to the line with the result of $2.32E-17$ seconds per meter.

Table 2. Time dilation for different planetary bodies at surface level [8]-[10].

Planetary body	Mass (Kg)	Radius	Time difference at surface between 2 clocks 1 meter apart
Earth	5.97×10^{24}	6.38×10^6	2.18×10^{-16}
Moon	7.35×10^{22}	1.74×10^6	3.62×10^{-17}
Mars	6.39×10^{23}	3.39×10^6	8.26×10^{-17}
99942 Apophis	4.00×10^{10}	185	1.73×10^{-21}

5. Conclusions

This method is a theoretical method that has yet to be validated *in-situ*; what has been shown is that highly precise atomic clocks have atomic clock bias that is documented. Showing that the differences caused by gravity and velocity have been measured and currently are a source of error in GPS. Showing that these values can be measured experimentally. Highly precise clock readings can enable attitude determination, and altitude determination on satellites. It requires multiple high precision atomic clocks, and it depends on how far apart they are on the same satellite.

As this method measures the differences between two atomic clocks, waiting more time will result in stronger and more accurate time difference measurements. Taking information over a day would result in a larger difference between the two clocks.

For low earth orbit of around 6600 km the difference in atomic clock reading a meter apart is as high as 1.02×10^{-16} seconds per second. Enabling attitude determination by comparing the differences of atomic clock time one can determine the orientation of the satellite and by comparing the time with a reference time on the earth an approximate altitude can also be determined. At lower altitudes this gives 2 atomic clocks more positional accuracy between different orientations as they can detect small changes in orientation. The strongest orientation signal will be when the vector between the 2 clocks points directly toward the planetary center of mass or along the z-axis. When the vector points in another direction, only the distance of the clocks in relation to the planetary center of mass results in a detectable change. For high precision atomic clocks with accuracy of $\times 10^{-18}$, the detectable limit at low earth orbit is 10 cm difference in distance between the 2 clocks and the planetary center of mass. A more accurate clock would be required to detect smaller changes in satellite orientation in one second time frames or the time between measurements would have to increase. The current record for accuracy for an atomic clock according to the National Institute of Standards and Technology is $\times 10^{-19}$ [12].

Altitude can also be determined around different planetary objects as at different elevations above the center of mass of the object, the difference will change in a measurable way and can be visualized in **Figures 2-4**. Around the Earth, Moon, and Mars, the rate of change with altitude of the difference between the clocks is 7.95×10^{-17} seconds per meter, 1.7×10^{-17} seconds per meter, and 2.32×10^{-17} seconds per meter respectively.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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