Searching for Dark Matter using Navigation Satellites

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Abstract

Earth mass is a parameter that plays a role in how satellites and probes are navigated and thus impacts how any observations collected by those spacecraft are registered, or positioned. It also impacts the function of the Global Positioning System (GPS). In this project we describe how GPS and several similar, new navigation satellite systems can be used to create a precise estimate of Earth's mass. Our ultimate goal is to determine if the Earth mass is fluctuating–the possible signature of a dark matter halo orbiting the Earth.

We present how the orbit period is precisely derived from publicly available satellite navigation data. Using these data we can observe Earth mass by calculating where each satellite is to the centimeter level, and its orbital period to the nanosecond level. We eliminate the impact of solar pressure and drag on the observation process by chosing the orbit period associated with crossing the Equatorial plane. We describe the analytic orbital theories that further correct the observations based on Earth's irregular shape.

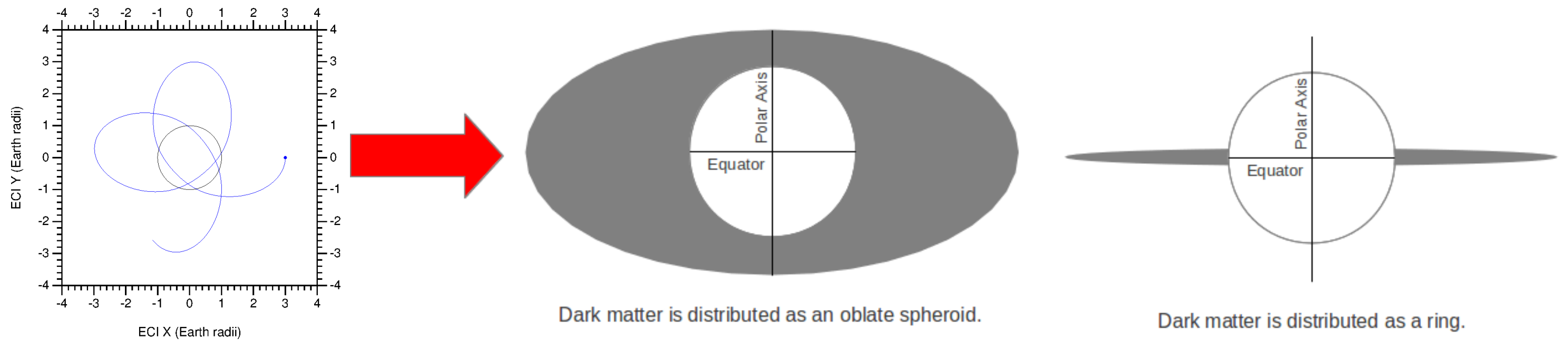
The Earth mass observations are presented and discussed. The solutions agree to the standard accepted value established by the International Astronomical Union in 2009, but shows a slight excess, constrained between .005 to .008 percent. The high precision associated with the process is analyzed. Two major systematic errors—lunisolar gravity and special relativity—are bounded below the mass excess estimate.

Introduction

Interplanetary spacecraft that pass by the Earth are subject to changes in velocity not predicted by Earth's known gravity model, an effect called the Flyby Anomaly. This anomaly has been attributed to the presence of dark matter near the Earth, as dark matter has been used to explain the excess velocity of stars and globular clusters. While other explanation have been presented regarding the Flyby Anomaly, none have been promoted beyond hypothesis by a repeatable experiment or campaign of observations. The underlying mechanism should be universal to all spacecraft. In this study we examine if the dark matter hypothesis has a perceptible impact on spacecraft with the most well-known trajectories, navigation satellites, such as the Global Positioning System (GPS).

Structure of Dark Matter Near the Earth

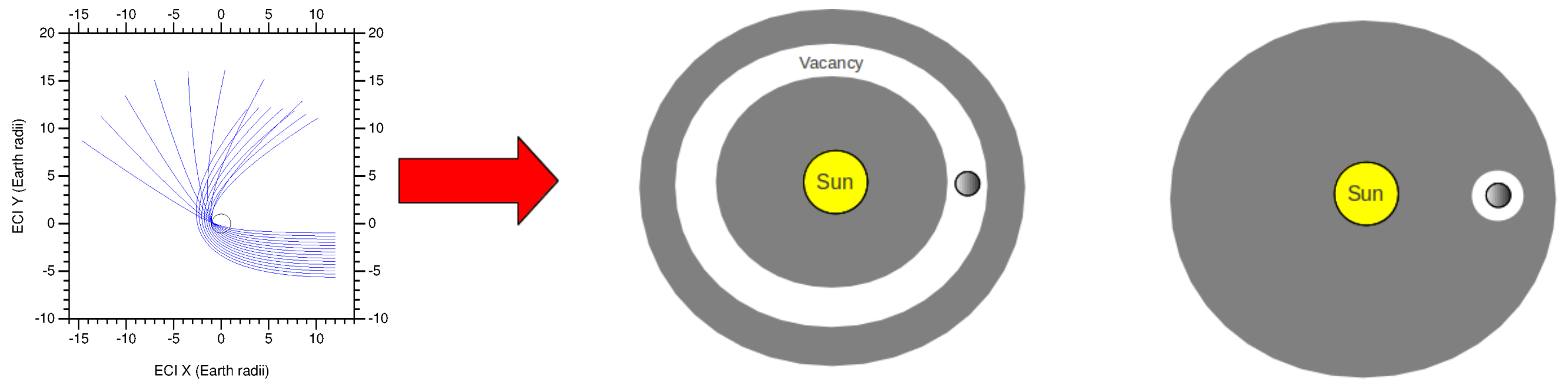
The classic two body problem defines the force on a body of mass m orbiting the Earth of mass m_e as $F = -\frac{Gm_e m}{r^2}$. Assuming the Earth has a spherically symmetric density then the resulting orbit is a conic section of eccentricity e and semi-major axis a. A dark matter particle outside the surface of the Earth will follow the conic section trajectory. However, dark matter does not impact normal, baryonic matter. If the particle enters the Earth, its trajectory is defined by a linear force $F = -\frac{Gmm_e r}{r_e^3}$ where r_e is the radius of the Earth and the Earth is assumed to have uniform density. Trajectories that enter the Earth are rotated or precessed dramatically.



Dark matter is distributed as an oblate spheroid.

Dark matter is distributed as a ring.

This mode of precessing establishes the mechanism to form a halo that surrounds the Earth. That halo could degenerate to a ring.



Dark matter may not be bound by the Earth, but the Sun. The Earth would provide a perturbing force, causing a nearby vacancy. The vacancy could be local to the Earth or take the form of ring evacuated by Earth along Earth's orbit with dynamics akin to those of a shepherd moon.

Halo Perturbation on Elliptic Orbits

In this study we modeled the distribution of dark matter about the Earth as a halo. Consequently, the mass that attracts a satellite should increase as the its distance increases. The apparent value of the gravitational parameter μ should increase with r or a. Given the relationship between period T, μ and a as

$$T^2 = \frac{4\pi^2 a^3}{\mu}$$

We can predict the precision to which Earth's mass m_e can be estimated.

$$\frac{\delta m_e}{m_e} = \frac{12\pi^2}{Gm_e}\frac{a^2}{T^2}\delta a + \frac{\delta T}{T}$$

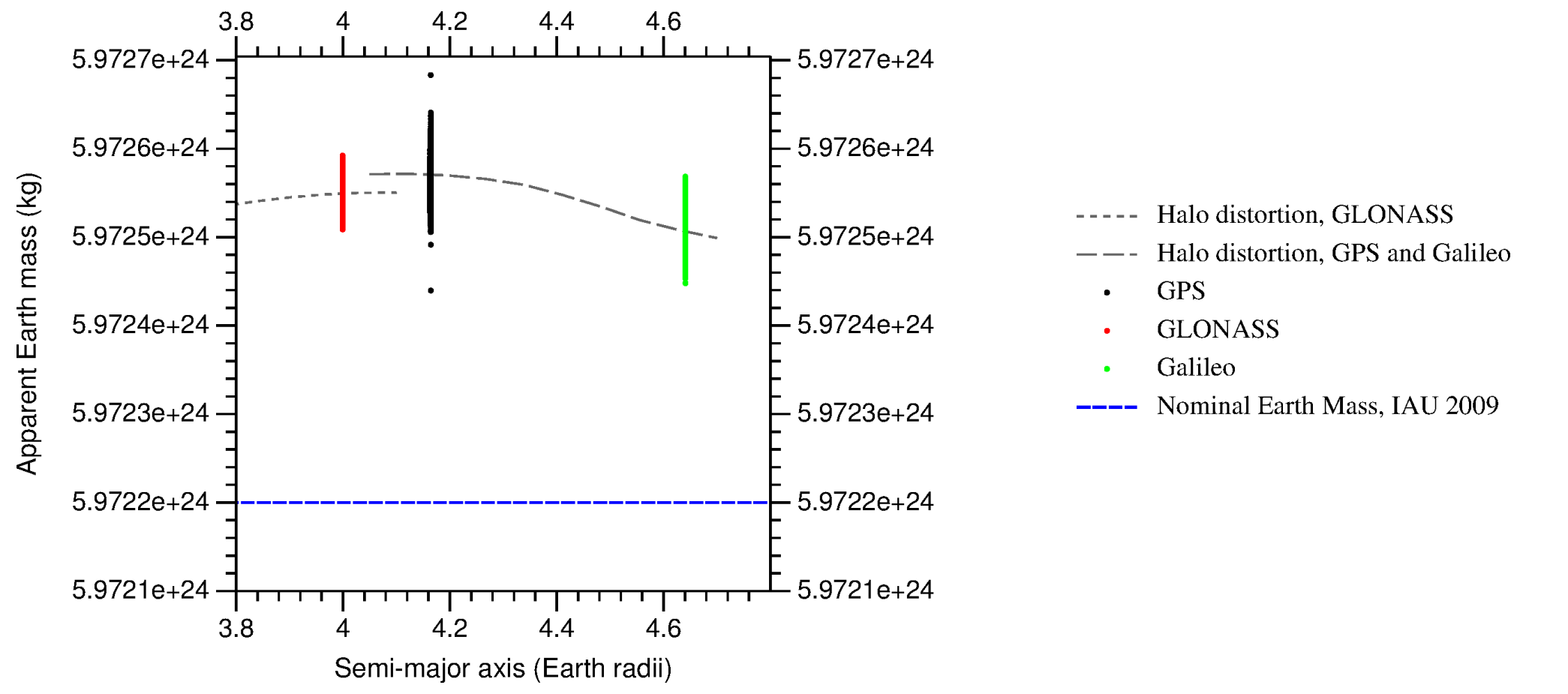
The Earth's oblateness perturbs the orbit rate as well. This correction is provided by Kaula (1966).

$$T_{corr} = \frac{T}{1 - \frac{3J_2 a_e^2}{4(1-e^2)^{3/2}a^2}(3\cos^2 i - 1)}$$

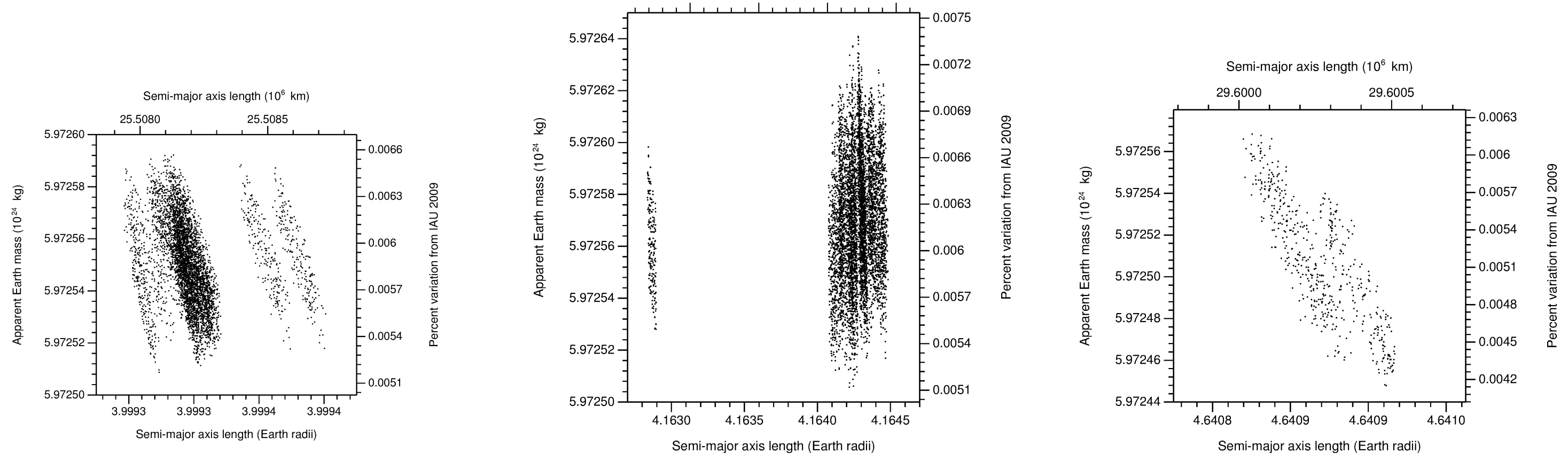
The period is further affected by special relativity, and gravitational forces from the Moon and Sun. These perturbations are not removed in this study but are numerically bounded to less than the observed excess.

Results

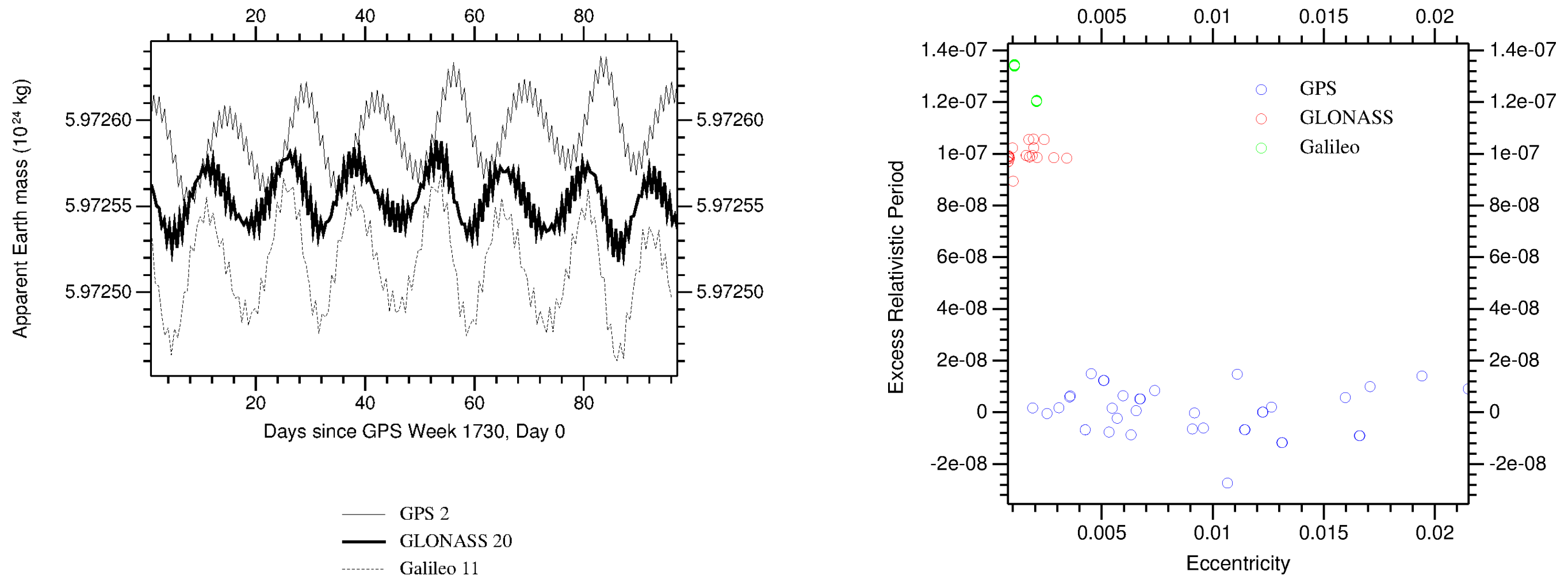
Precise orbits for all functioning and prototype navigation satellites from August 2012 to June 2013 were obtained from the International Global Navigation Satellite Service (IGS): the Global Positioning System (GPS), Russia's GLONASS and Europe's Galileo. For each satellite's complete orbit, a two-body period T is estimated using algorithms from the open source GPS Toolkit.



The observations of m_e are all higher than the 2009 IAU reference. The broad vertical distribution is due to lunisolar perturbation. More detail is shown below for select satellites. The mean of each distribution was used to estimate the size and shape of a possible dark matter halo. The grey line shows the observations the a halo would induce according to a gravity model for an oblate spheroid provided by Hvoždara and Kohút (2011). The halo that fits our observations is essentially a ring about Earth's equator. Its mass is .002% Earth's. It is 191 kilometers thick with a radius of 70,000 km.



Detail. Observations of m_e by GLONASS (left), GPS (center), and Galileo (right).



(Left) Signature of lunar and solar gravity on m_e over time for one satellite in each constellation. (Right) Contributions of special relativity to $\delta T/T$. General relativity contributes less.

Conclusions

We have established a process to estimate Earth mass using navigation satellites. The satellites in each constellation have common semi-major axis and inclination, and consequently provide a similar estimate of Earth mass. The solutions agree to the standard accepted value established by the International Astronomical Union in 2009, with a slight excess, constrained between .005 to .008 percent.

Future Work

This process can be improved by rejecting more known perturbations and by incorporating more navigation satellite systems. Ultimately this process could be used to determine if the dark matter structure near the Earth changes over time. Is there a flux between the Earth and Sun's respective dark matter halos? This could be a contributor to Earth's changing Length of Day (LoD). Alternatively, is the Earth accumulating, or even shedding, dark matter? Our goal is address these fundamental questions.

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