Dark Matter at Our Doorstep: Searching for Dark Matter with GPS

Ben Harris

Mechanical and Aerospace Engineering,
The University of Texas at Arlington

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STL
SATELLITE TECHNOLOGY LABORATORY

The Flyby Anomaly

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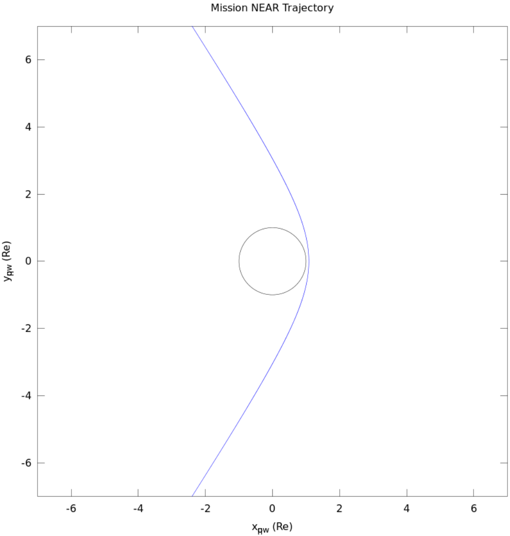
Dark Matter in Astrodynamics

Gravity Assist

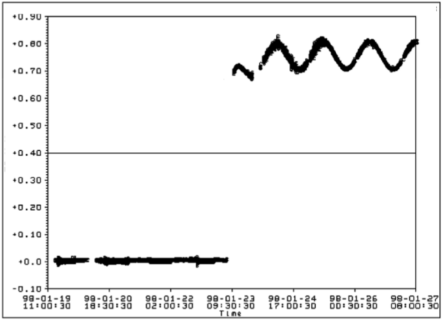
- The trajectory of bodies near the Earth is largely determined by Earth's gravity.
- Specific mechanical energy: $\epsilon = \frac{v^2}{2} - \frac{\mu}{r}$ is conserved throughout trajectory. Here $\mu = Gm_e$.
- Trajectory is a conic section: $r = \frac{h^2}{\mu}\frac{1}{1+e\cos\theta}$
- Hyperbolic orbits are referred to as fly-bys.
- Probes use fly-bys to boost their velocity with respect to the Sun. The maneuver is called *gravity assist*.

The NEAR Flyby



The Flyby Anomaly

Jet Propulsion Laboratory navigation group led by Anderson, et al, (2008) documents anomalous changes in ϵ during flybys. Other groups at the DLR (Germany's NASA) and the UT Austin Center for Space Reseach confirmed the anomalies.



Here the NEAR mission shows an unexpective shift in velocity that causes the Doppler signal to shift over 0.8 Hertz.

The Flyby Anomaly, by the Numbers

Mission	Year	ΔV (mm/s)	$\Delta E/E$
Galileo I	1990	3.92	8.76×10^{-7}
Galileo II	1992	-4.60	1.03×10^{-6}
NEAR	1998	13.5	3.93×10^{-6}
Cassini	1999	-20.0	-2.50×10^{-7}
Rosetta	2005	18.0	9.32×10^{-7}
MESSENGER	2005	.02	9.86×10^{-9}

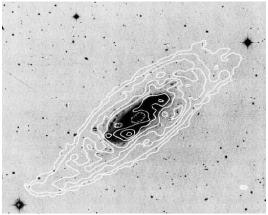
In October 2013 the JUNO mission performed a flyby but at this time JPL has not released the observations. JUNO is spin stabilized which biases Doppler measurements.

Flyby Hypotheses

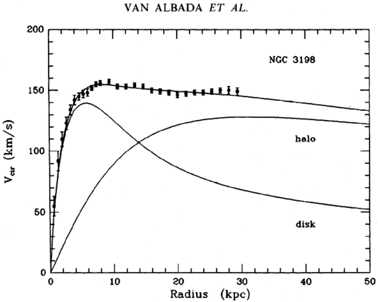
- Anderson, et al (2008): $\frac{\Delta E}{E} = K(\cos\delta_i - \cos\delta_o)$, where δ is the declination of the inbound i or outbound o asymptote. Consant $K = \frac{2\omega_E R_E}{c} = 3.99 \cdot 10^{-6}$
- Lämmerzahl, et all (2008): Dark matter.
- Adler (2009): Dark matter halo. Suggests looking at orbits higher than LEO for anomalies.
- Mbelek (2009): $\frac{\Delta V_\infty}{V_\infty} = K\frac{\cos\phi_S}{\cos\alpha}(\cos\delta_i - \cos\delta_o)$, where ϕ_S is the latitude of the reference station and α is the "angle made by the direction from the s/c to a DSN station with the difference vector $\Delta\vec{V}_\infty = \vec{V}_{\infty,o} - \vec{V}_{\infty,i}$".
- Hasse, et al (2009): dependent on velocity not position iff perturbation $f_{pert} \propto \frac{1}{r^2}$.
- Atchison and Peck (2010): not Lorentz force.
- Busack (2013): $\vec{g}(\vec{r}) = -\frac{G \cdot M \cdot \vec{r}}{r^3}\left[1 - A \cdot \exp\left(-\frac{r-R}{B-C\frac{\vec{r}\cdot\vec{v}}{r\cdot v_{Sun}}}\right)\right]$, where A, B and C are arbitrary constants.

The Galactic Velocity Anomaly

The stars orbit too quickly about their galactic centers.

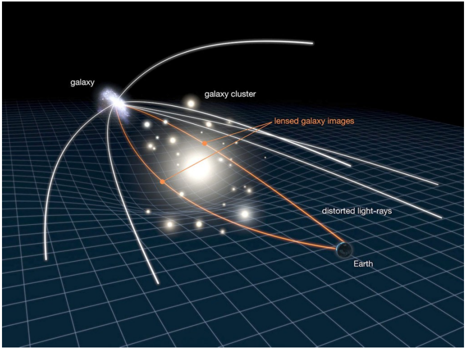


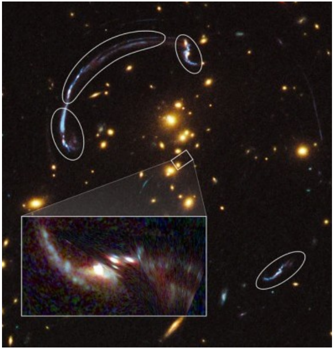
Recall from the two body problem the circular orbit solution $V = \sqrt{\frac{Gm_g}{r}}$



Gravitational Lensing as the Smoking Gun

Dark matter also helps explain cases of gravitational lensing. Researchers at the University of Chicago captured lensing that could not be possible based on the known amount of matter in the cluster RCS2 032727-132623.

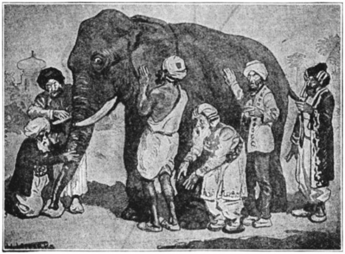


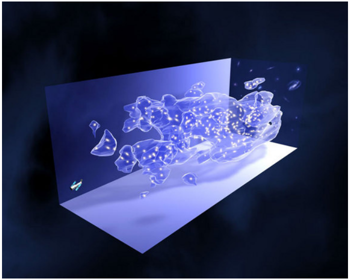


Getting a Grip on Dark Matter

Elephant to Blind Men

- Spear
- Column
- Fan
- Snake
- Rope





Dark Matter to Humans

- Anomaly: Speed, Optics
- Particle
- Topology / Hierarchy
- New Physics
- The new Aether

Challenges to Developing the DM Hypothesis for Flybys

- Paucity of flybys and their measurements.
  - Only 7 flybys since 1990.
  - Doppler observations are not available, due to lack of archive requirements for each mission.

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- Depends on spatial distribution, a.k.a. topology, heirarchy.
  - Dark matter is thought to cluster heirarchically (Fukushige and Makino, 2003; Schneider, et al, 2010).
  - Sun is thought to capture DM (Peter, 2009; Lages and Shellyansky, 2012; Xu and Siegel, 2013).
  - Earth capture is possible (Lundberg and Edsjö, 2004).
  - Secular increases in μ have been observed (Raicu, 2001).

A DM Hypothesis for GNSS Orbit and Clock Anomalies

- Recall Adler's suggestion to use satellites higher then LEO.
  - Implies a change of observable from Doppler to ....?
  - Which satellites would be the most likely yield DM structure?
    - Highly eccentric satellites, such as Sirius.
    - GPS and similar satellites.

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- Dynamics are the *raison d'être* for GPS
  - Positions known to 10^{-2} m, clocks to 10^{-12} s.
  - Orbit processes account for anomalies using process noise and empirical forces to fit observation to a table called a precise ephemeris.
  - Precise ephemerides available from the 1990s to today.
  - ... but GPS orbits have little variety.

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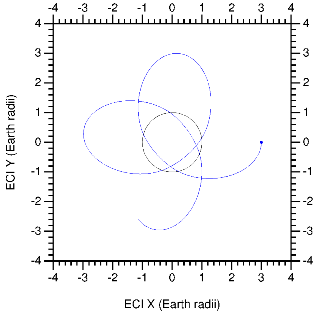
  - Precise ephemerides available from the 1990s to today.
  - ... but GPS orbits have little variety.
- Other global navigation satellite systems (GNSSs) operate!
  - Russia's Cold War era system, GLONASS.
  - European Union's Galileo.
  - Japan's Quazi-Zenith Satellite System, QZSS.

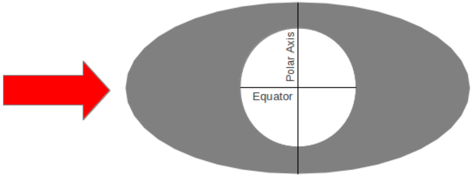
Do We Have a Different Part of the Elephant?

Framing the Investigation

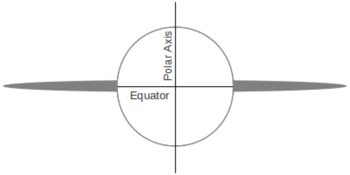
- Goal: map the anomalies from GNSS to flyby.
- Obstacles:
  - Configuration of dark matter near Earth.
  - Observable to support mapping dark matter.

Dynamics for Earth-bound Dark Matter



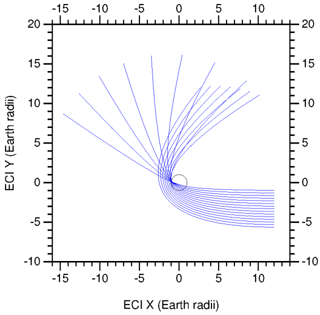


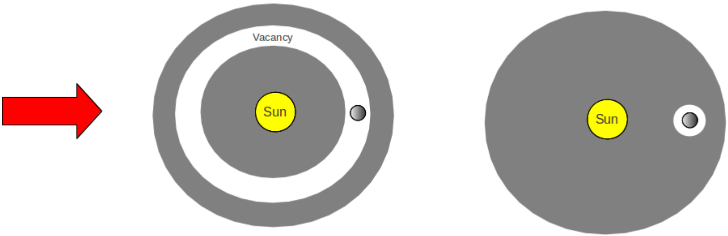
Dark matter is distributed as an oblate spheroid.



Dark matter is distributed as a ring.

Dynamics of Sun-bound Dark Matter



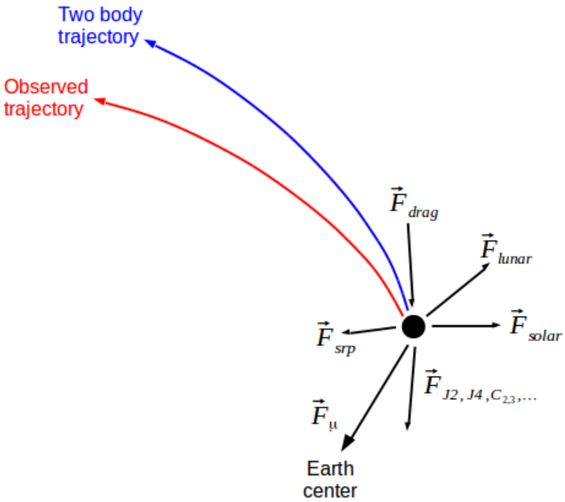


Force as the Observable

- Observables must be *sensitive*, *independent* and *mappable*.
- Sensitivy based on flyby: 10 mm/s over 24 hours requires 10^{-8} m/s^2.
- GPS signal is spread spectrum, thus insensitive to Doppler.
- Existing ephemeris production technology
  - Position solution every 5 to 15 minutes. At most 100 per orbit.
  - Lagrange interpolation involve over 20 sequential solutions to estimate position.
  - More required for force!
  - GPS based gravimetry known to be limited to 10^{-6} m/s^2.
  - Given access we could "overdrive" an existing ephemeris process.
  - Ephemeris processes better used for long term evaluation.

Force Observable Coupling

To use force as the observable, we must decouple it from a number of other environmental forces.



Period as the Observable

God does not care about our mathematical difficulties. He integrates empirically. –Einstein

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Given the relationship between period T, μ and a as

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

The mean semi-major axis $\bar{a}$ can be derived from the distance r using

$$\bar{a} = \frac{\bar{r}}{1 + \frac{e^2}{2}}$$

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

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

Period and Energy

For elliptic orbits

$$\epsilon = -\frac{\mu}{2a}$$

allowing us to relate period and unit energy

$$T^2 = \frac{4\pi^2 a^3}{\mu} = -\frac{32\pi^2 \epsilon^3}{\mu^4}$$

If we add energy, we add period.

- Constant component of external forces do not add to T.
- Periodic component of external force *may* add to T iff they add energy.
- Path dependent forces and accelerations modify period.
- Higher order gravity (J2, etc) add as they have noncentral components.

Precision of Observable T

Variational analysis of the Kepler relation shows the best we can predict Earth mass is dependent on the pecision of a and T.

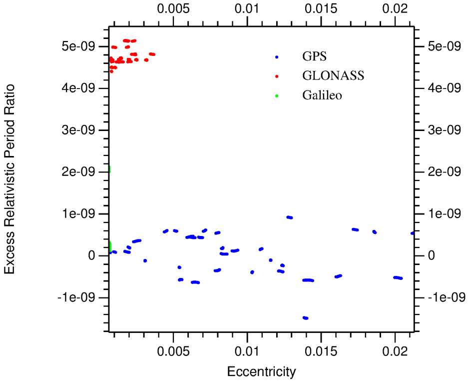
$$\frac{\delta m_e}{m_e} = \frac{12\pi^2}{Gm_e}\frac{a^2}{T^2}\delta a + \frac{\delta T}{T}$$

If we can refine T and a to the purely two body components, we can measure μ *accurately*.

- At each epoch, ephemeris processes can observe r to the cm level. Recall $\bar{a} = \frac{\bar{r}}{1+\frac{e^2}{2}}$.
- We can analyze ephemerides to observed T with accuracy of 10^{-8} s or better.
- General and special relativity contribute (next slide).
- If we remove all non-central force contributions, and relativistic effects, to T, a: $\frac{\delta m_e}{m_e} \approx 10^{-12}$.

Relativistic Bounds on T Accuracy

While the GPS and Galileo clocks are tuned to balance the contributions to GR and SR, eccentricity in the orbit causes variation in clock. GLONASS is not balanced. This is $\delta T/T$ caused by relativity for select orbits of GPS, GLONASS and Galileo for thirteen weeks of observation.

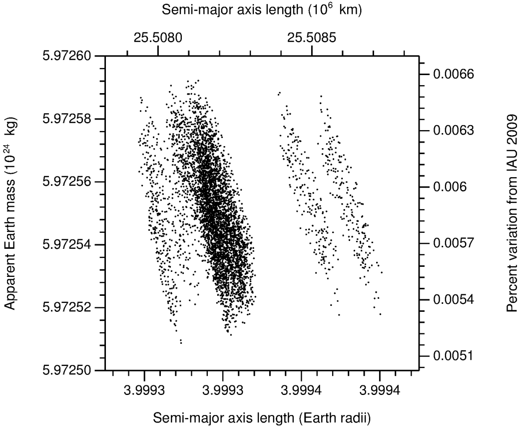


Known Perturbations to Period

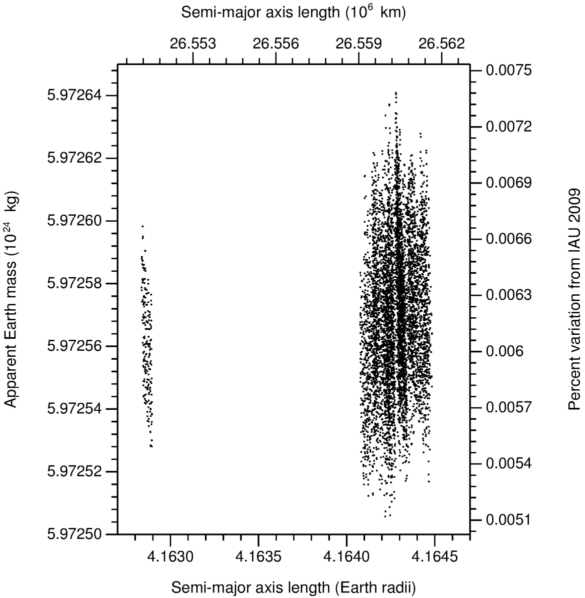
The Earth's oblateness perturbs the orbit rate as well. This correction is provided by Kaula (1966).

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

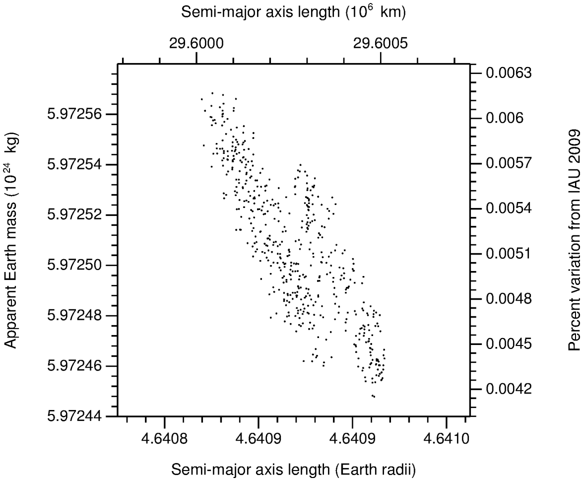
Observations of μ Using GLONASS



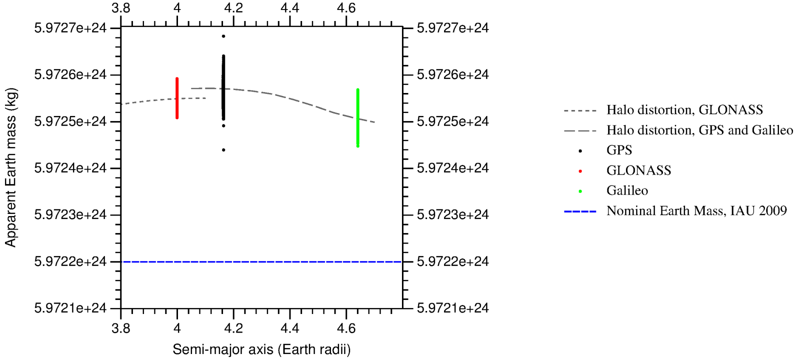
Observations of μ Using GPS



Observations of μ Using Galileo



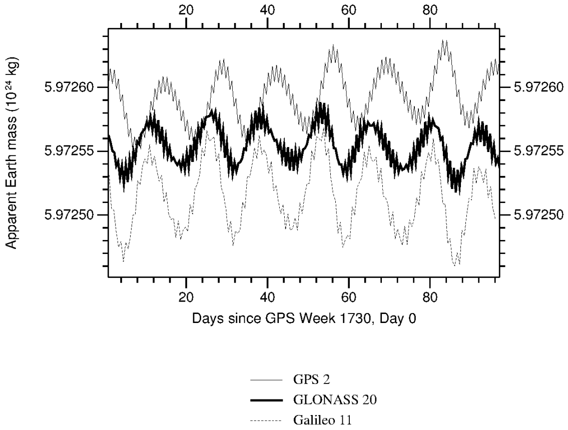
Systematic Variation in μ



The grey line shows the observations a halo would induce according to a gravity model for an oblate spheroid provided by Hvoždara and Kohút (2011). $\mu_{dm} = .0027\% \ \mu_e$, $a_{dm} = 4.5a_e$, $b_{dm} = .003a_e$.

Temporal Variation in μ

The Sun and Moon clearly influence T



To what extent does the Moon add energy (net torque) to each orbit? the Sun?

Force Contribution from DM Disk

Gravity force	Magnitude
Lunar, variable	9.1×10^{-9}
Disk, minimum	9.8×10^{-9}
Disk, maximum	2.8×10^{-8}
Lunar, constant	3.8×10^{-8}

Disk force is sandwiched between variable and constant part of lunar gravity. Recall T is invariant to constant force terms.

Next Steps

- Remove T contributions from Moon, Sun, relativity. Can we achieve 10^{-12}? What will we see?
- Jet Propulsion Laboratory is granting a free license to GYPSY, their ephemeris production software. We can see if a dark matter model improves precise ephemeris process.
- University of Reno group predicts possible spatial variation in GNSS clocks. Do we see waves DM causing GR induced fluctuation at galactic speeds?