Flyby Anomaly Test Integrating Multiple Approaches

Is the Physics Within the Solar System Really Understood?

Claus Lämmerzahl[1], Oliver Preuss[2], and Hansjörg Dittus[1]

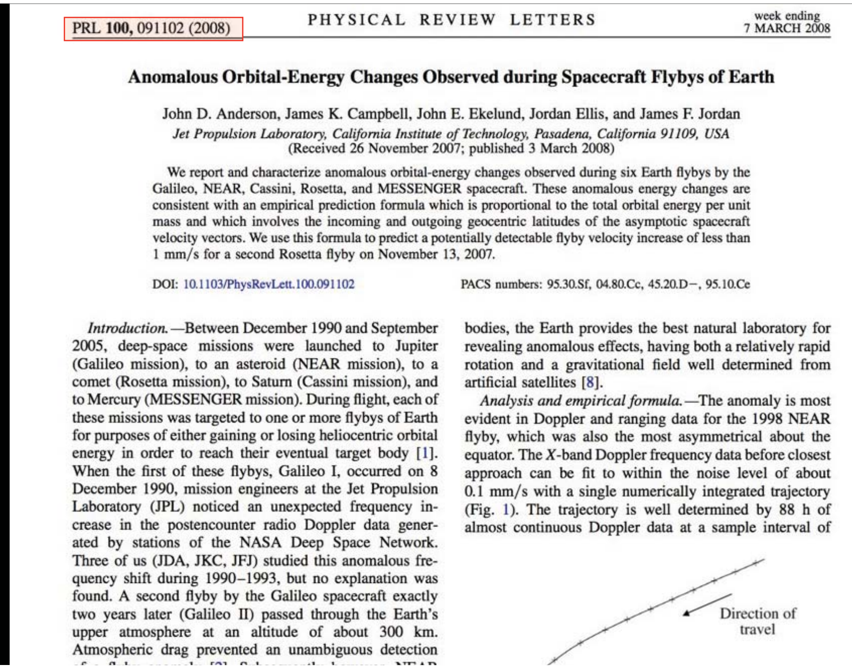
[1] ZARM, University of Bremen, Am Fallturm, 28359 Bremen, Germany
[2] Max-Planck-Institute for Solar System Research, Max-Planck-Str. 2, 37191 Katlenburg-Lindau, Germany

Summary. A collection is made of presently unexplained phenomena within our solar system and in the universe. These phenomena are (1) the Pioneer anomaly, (2) the flyby anomaly, (3) the increase of the astronomical unit, (4) the quadrupole and octupole anomaly, (5) dark energy, and (6) dark matter. A new data analysis of the complete set of Pioneer data is announced to search for systematic effects or to confirm the unexplained acceleration. We also review the mysterious flyby anomaly where the velocities of spacecraft after Earth swingbys are larger than expected. We emphasize the scientific aspects of this anomaly and propose systematic and continuous observations and studies at the occasion of future flybys. Further anomalies within the solar system are the increase of the astronomical unit and the quadrupole and octupole anomaly. We briefly mention dark matter and dark energy as in some cases a relation between them and the solar system anomalies have been speculated.

1 Introduction

Progress in physics has always been stimulated by observations which could not be explained within the presently standard physical theories. In the late

source: http://arxiv.org/pdf/gr-qc/0604052v1.pdf


PRL **100,** 091102 (2008) PHYSICAL REVIEW LETTERS week ending 7 MARCH 2008

Anomalous Orbital-Energy Changes Observed during Spacecraft Flybys of Earth

John D. Anderson, James K. Campbell, John E. Ekelund, Jordan Ellis, and James F. Jordan
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA
(Received 26 November 2007; published 3 March 2008)

We report and characterize anomalous orbital-energy changes observed during six Earth flybys by the Galileo, NEAR, Cassini, Rosetta, and MESSENGER spacecraft. These anomalous energy changes are consistent with an empirical prediction formula which is proportional to the total orbital energy per unit mass and which involves the incoming and outgoing geocentric latitudes of the asymptotic spacecraft velocity vectors. We use this formula to predict a potentially detectable flyby velocity increase of less than 1 mm/s for a second Rosetta flyby on November 13, 2007.

DOI: 10.1103/PhysRevLett.100.091102 PACS numbers: 95.30.Sf, 04.80.Cc, 45.20.D−, 95.10.Ce

Introduction.—Between December 1990 and September 2005, deep-space missions were launched to Jupiter (Galileo mission), to an asteroid (NEAR mission), to a comet (Rosetta mission), to Saturn (Cassini mission), and to Mercury (MESSENGER mission). During flight, each of these missions was targeted to one or more flybys of Earth for purposes of either gaining or losing heliocentric orbital energy in order to reach their eventual target body [1]. When the first of these flybys, Galileo I, occurred on 8 December 1990, mission engineers at the Jet Propulsion Laboratory (JPL) noticed an unexpected frequency increase in the postencounter radio Doppler data generated by stations of the NASA Deep Space Network. Three of us (JDA, JKC, JFJ) studied this anomalous frequency shift during 1990–1993, but no explanation was found. A second flyby by the Galileo spacecraft exactly two years later (Galileo II) passed through the Earth's upper atmosphere at an altitude of about 300 km. Atmospheric drag prevented an unambiguous detection

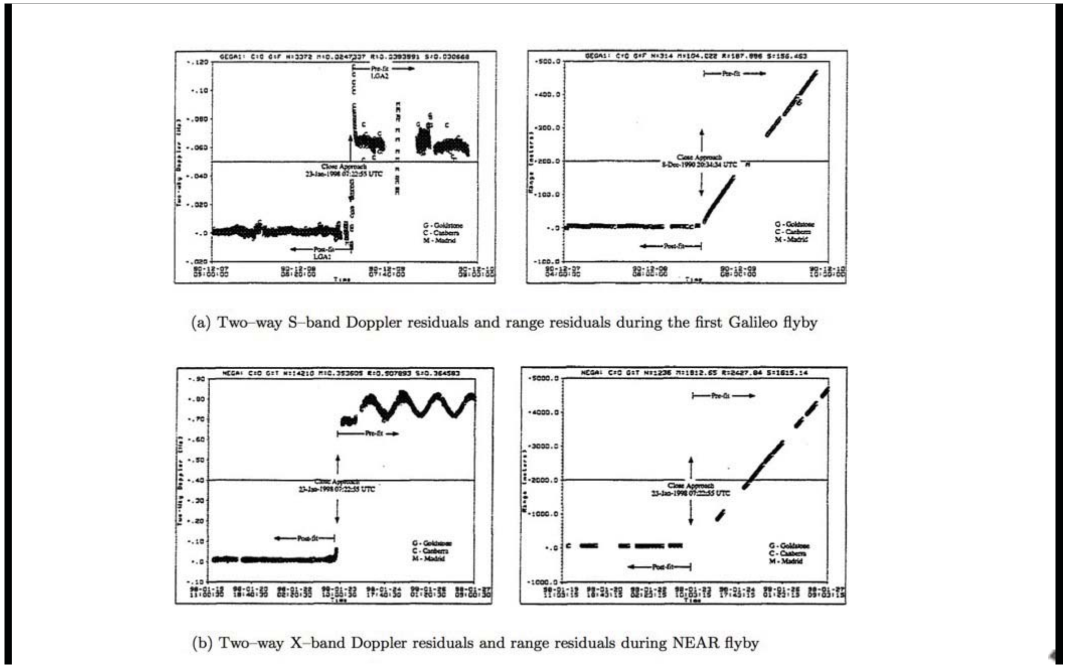
bodies, the Earth provides the best natural laboratory for revealing anomalous effects, having both a relatively rapid rotation and a gravitational field well determined from artificial satellites [8].

Analysis and empirical formula.—The anomaly is most evident in Doppler and ranging data for the 1998 NEAR flyby, which was also the most asymmetrical about the equator. The X-band Doppler frequency data before closest approach can be fit to within the noise level of about 0.1 mm/s with a single numerically integrated trajectory (Fig. 1). The trajectory is well determined by 88 h of almost continuous Doppler data at a sample interval of

Direction of travel

“We report here on results from a recent study involving the data analysis and interpretation of radio Doppler data from all six flybys. We find that there is indeed an anomalous energy change during Earth flybys on the order of 10-6, although we have been unable to find a physical cause or systematic error source for the anomaly”....

source http://prl.aps.org/abstract/PRL/v100/i9/e091102



(a) Two–way S–band Doppler residuals and range residuals during the first Galileo flyby

(b) Two–way X–band Doppler residuals and range residuals during NEAR flyby

“This inconsistency is not limited to the Doppler data. When the ranging data is differenced and compared to the Doppler data, exactly the same inconsistency is observed”

source http://prl.aps.org/abstract/PRL/v100/i9/e091102

The main problem is not just the limited number of flybys for which sufficiently precise data are publicly available so that the anomaly can be seen at all. Even these available data suffer from low cadence (the anomaly often appears between two data points) and so far only allow an anomaly in the speed, but not in the direction of motion etc. to be identified. Precise data at a much higher cadence of all the motion parameters of the spacecraft prior to, during and after the flyby would allow a qualitatively improved analysis.

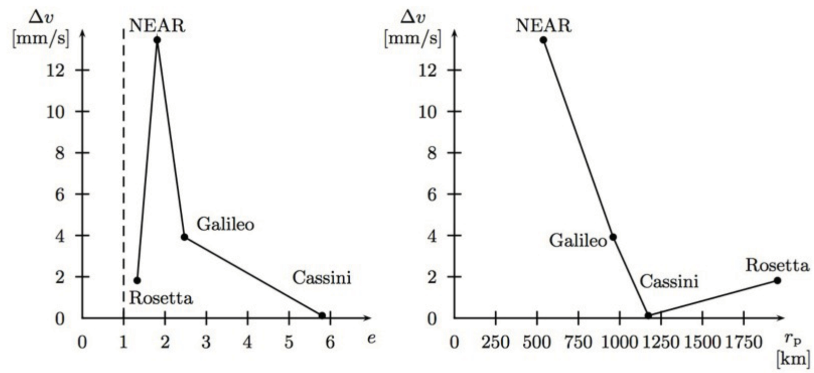


Figure 2: The velocity increase Δv as function of the eccentricity and of the perigee.

source http://prl.aps.org/abstract/PRL/v100/i9/e091102

PRL **100**, 091102 (2008) PHYSICAL REVIEW LETTERS week ending 7 MARCH 2008

TABLE I. Earth flyby parameters at closest approach for Galileo, NEAR, Cassini, Rosetta, and MESSENGER (M'GER) spacecraft. The altitude H is referenced to an Earth geoid, the geocentric latitude ϕ and longitude λ are listed for the closest approach location, V_f is the inertial spacecraft velocity at closest approach, V_∞ is the osculating hyperbolic excess velocity, the deflection angle (DA) is the angle between the incoming and outgoing asymptotic velocity vectors, the angle I is the inclination of the orbital plane on the Earth's equator, the next four rows represent the right ascension α and declination δ of the incoming (i) and outgoing (o) osculating asymptotic velocity vectors, and M_{SC} is a best estimate of the total mass of the spacecraft during the encounter. The last three rows of the table give the measured change in V_∞, the estimated realistic error in ΔV_∞, and the prediction of ΔV_∞ by Eq. (1). The measured ΔV_∞ for GLL-II is actually—8 mm/s, but it is reduced in magnitude after subtracting out an estimated atmospheric drag of -3.4 mm/s.

Parameter	GLL-I	GLL-II	NEAR	Cassini	Rosetta	M'GER
Date	12/8/90	12/8/92	1/23/98	8/18/99	3/4/05	8/2/05
H (km)	960	303	539	1175	1956	2347
ϕ (deg)	25.2	−33.8	33.0	−23.5	20.20	46.95
λ (deg)	296.5	354.4	47.2	231.4	246.8	107.5
V_f (km/s)	13.740	14.080	12.739	19.026	10.517	10.389
V_∞ (km/s)	8.949	8.877	6.851	16.010	3.863	4.056
DA (deg)	47.7	51.1	66.9	19.7	99.3	94.7
I (deg)	142.9	138.7	108.0	25.4	144.9	133.1
α_i (deg)	266.76	219.35	261.17	334.31	346.12	292.61
δ_i (deg)	−12.52	−34.26	−20.76	−12.92	−2.81	31.44
α_o (deg)	219.97	174.35	183.49	352.54	246.51	227.17
δ_o (deg)	−34.15	−4.87	−71.96	−4.99	−34.29	−31.92
M_{SC} (kg)	2497	2497	730	4612	2895	1086
ΔV_∞ (mm/s)	3.92	−4.6	13.46	−2	1.80	0.02
σ_{V_∞} (mm/s)	0.3	1.0	0.01	1	0.03	0.01
Equation (1) (mm/s)	4.12	−4.67	13.28	−1.07	2.07	0.06

source http://prl.aps.org/abstract/PRL/v100/i9/e091102

Atmosphere If a spacecraft of mass m_s and effective area A_s moves with velocity v_s through a medium of density ρ, then it experiences a drag acceleration again given by (6). For a mass of 1 t, an area of 2 m^2, a velocity of 30 km/s and an atmospheric density at 1000 km height of approx $\rho \approx 10^{-14}$ kg/m^3 we get an acceleration of $a_{drag} \approx 4 \cdot 10^{-8}$ m/s^2 what is far too small to be of any relevance for our problem. Furthermore, this acceleration due to drag has the wrong sign.

Ocean tides The ocean tides will lead to a change of the Earth's surface of the order of $\delta r \pm 10$ m. This means that the corresponding quadrupole part of the Earth's gravitational potential is of the order $\epsilon = 2\delta r / R_\oplus$ smaller than the monopole part of the Earth, where $R_\oplus$ is the radius of the Earth. Since $\epsilon \approx 10^{-6}$, the corresponding additional acceleration also is factor 10^{-6} smaller than the ordinary acceleration from the monopole part of the Earth's gravitational field. The latter being less than 10 m/s^2, the acceleration due to tides is at most 10^{-5} m/s^2 and, thus, cannot be responsible for the flyby anomaly.

Solid Earth tides Since Earth solid tides are much smaller than ocean tides, the analysis above shows that this cannot cause the effect.

Charging of the spacecraft In a recent study of charging of the LISA test masses [35] the charging has been estimated by 10^{-10} C. So, for the whole satellite it might be a conservative assumption that the charge is less than $Q \leq 10^{-7}$ C. A satellite of 1 t carrying a charge Q and moving with $v = 30$ km/s in the magnetic field of the Earth which is of the order 0.2 G will experience an acceleration 10^{-8} m/s^2 far below the observed effect.

Magnetic moment The force on such a body carrying a magnetic moment $\boldsymbol{m}$ moving in a magnetic field $\boldsymbol{B}$ is $\boldsymbol{F} = \boldsymbol{\nabla}(\boldsymbol{m} \cdot \boldsymbol{B})$. Since the magnetic moment of a spacecraft is not more than 2 A m^2 and the steepness of the magnetic field can be estimated by $|\Delta B / \Delta x| \leq 2 \cdot 10^{-7}$ G/m, see Fig.3, the maximum force of a spacecraft is $F \leq 4 \cdot 10^{-11}$ N implying typically a maximum acceleration of $4 \cdot 10^{-15}$ m/s^2 which safely can be neglected.

Earth albedo The Earth albedo causes a pressure on the spacecraft of approx 1 μN/m^2 which leads, for an effective area of 2 m^2 to a force of 2.4 μN. For a mass of the spacecraft of 1 t this will give an acceleration of $a_{albedo} \approx 2.4 \cdot 10^{-9}$ m/s^2 what can be neglected compared to the searched for effect of 10^{-4} m/s^2.

Solar wind The solar wind exerts on spacecraft a pressure of approx 4 μN/m^2 which gives an acceleration of max $a_{solar\ wind} \approx 2.4 \cdot 10^{-9}$ m/s^2 which again can be safely neglected.

Spin–rotation coupling A coupling of the helicity of the radio waves with the rotation of the spacecraft and the rotation of the Earth also leads to an effect which simulates a changing velocity [22]. This, however, applies to the two–way Doppler data only. Since simultaneously also ranging, what is independent of the helicity–rotation coupling, indicated an increase of the velocity, spin–rotation cannot be responsible for this observation.

Also estimates of the influence of the Moon including Moon oblateness, the Sun, other planets, relativistic effects, and indirect oblateness of the Earth have been shown to be order of magnitude smaller than the observed effect [33].

None of these disturbing effects could explain the flyby–anomaly.

source: http://arxiv.org/pdf/gr-qc/0604052v1.pdf

Mission Requirements

Multiple Earth flybys

Minimal delta-v after initial orbit insertion

Multiple independent methods for simultaneous high-precision position and velocity measurements

Low cost

FATIMA Trajectory Design

Cyrus Foster
9/12/2013

Problem statement:
It is of interest to launch a dedicated spacecraft to study the Flyby Anomaly. To recreate the conditions of historical observations (Galileo, NEAR, Cassini, Rosetta, etc), it is of interest to flyby the Earth on hyperbolic trajectories at low altitudes and with large differences in the declination of incoming and outgoing asymptotes. Frequent flyby opportunities are desired to study the anomaly.

Proposed solution:
It is proposed to launch into a heliocentric orbit similar to Earth's but inclined to allow for a flyby 0.5 years later on the descending node. Unfortunately one cannot target an outgoing asymptote on this flyby to reenter an inclined circular heliocentric orbit as before, but one can instead enter an eccentric orbit with equal period to the Earth's, allowing for a flyby 1.0 years later. On this second flyby, the spacecraft can now retarget an inclined circular heliocentric orbit allowing for a third flyby 0.5 years later, and repeat this cycle ad infinitum.

Solution Characteristics:
-Can launch anytime (no launch window constraints), since Earth is the only body to target
-Will perform an Earth flyby every 0.75 years on average
-Can vary launch C3 (drives subsequent flyby speeds), flyby altitude and asymptote declinations on each flyby if certain relational constraints are met.
-Can achieve large differences in declination of incoming and outgoing asymptotes.

Mission duration	# of flybys
0.5 years	*1*
1.5 years	*2*
2.0 years	*3*
3.0 years	*4*
3.5 years	*5*
4.5 years	*6*
5.0 years	*7*
etc	*etc*

Design allows for flyby every 0.75 years on average

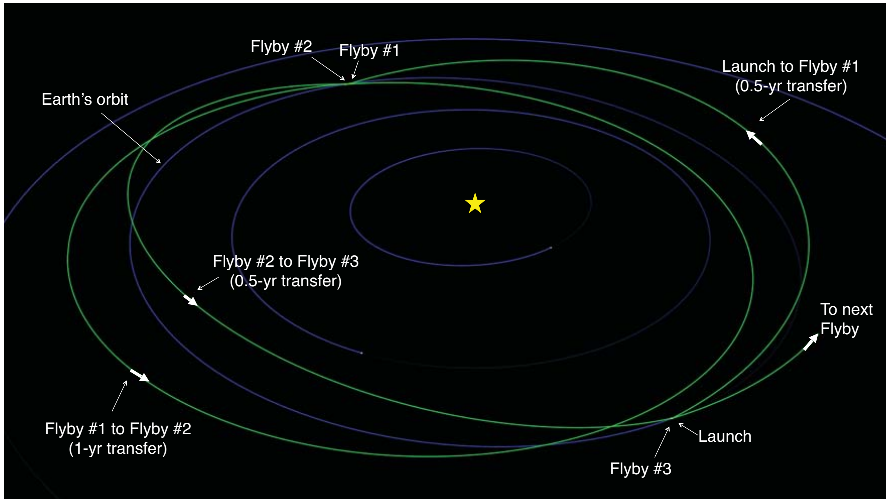
Notional 2-yr trajectory with 3 flybys

(High-fidelity numerical propagator solution)

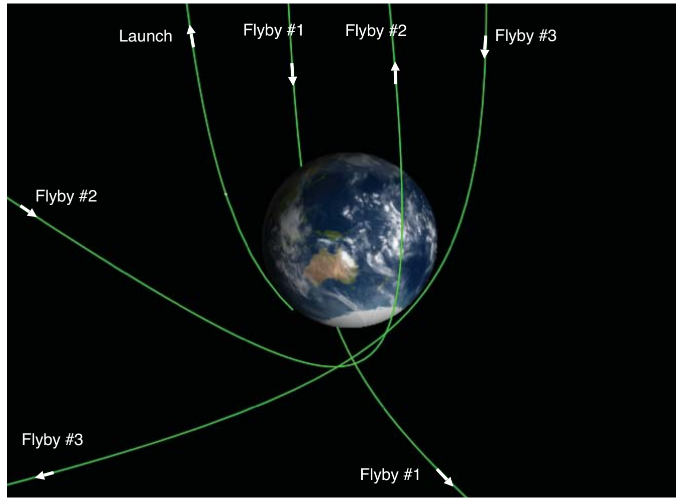
<table>
<tr><th>Event</th><th>Date</th><th>Flyby altitude</th><th>V flyby</th><th>Dec Incoming Asymptote</th><th>Dec Outgoing Asymptote</th></tr>
<tr><td>Launch</td><td>2017-01-01</td><td>N/A</td><td>C3 = 25 km²/s²</td><td>N/A</td><td>67°</td></tr>
<tr><td colspan="6">0.5-yr transfer</td></tr>
<tr><td>Flyby #1</td><td>2017-07-01</td><td>786 km</td><td>11.57 km/s</td><td>-67°</td><td>-23°</td></tr>
<tr><td colspan="6">1-yr transfer
with deep space maneuver (DSM) ΔV = 73 m/s</td></tr>
<tr><td>Flyby #2</td><td>2018-07-03</td><td>1045 km</td><td>11.41 km/s</td><td>-23°</td><td>65°</td></tr>
<tr><td colspan="6">0.5-yr transfer</td></tr>
<tr><td>Flyby #3</td><td>2019-01-01</td><td>500 km</td><td>11.66 km/s</td><td>-65°</td><td>free parameter</td></tr>
<tr><td colspan="6">… can easily be extended with subsequent flybys at alternating 0.5-yr and 1-yr intervals</td></tr>
</table>

Total required spacecraft ΔV for 2-yr mission: 73 m/s (+navigation corrections)

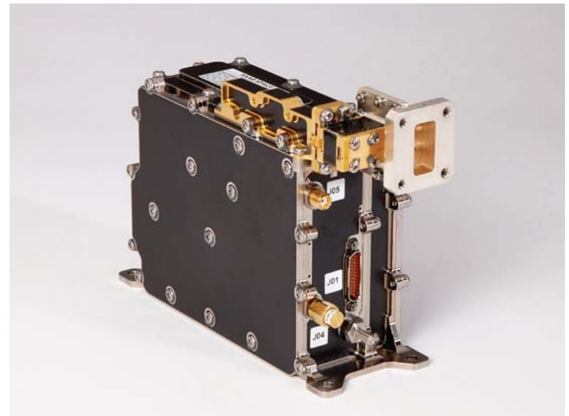
Heliocentric view of notional 2-yr trajectory



Geocentric view of notional 2-yr trajectory



Instruments



First method of precision orbit determination:
S-band / Ka-band Radios, suitable for high-precision one-way and two-way doppler
on left: for cubesats. on right: not for cubesats, includes high power LNA

http://www.stt-systemtechnik.de/index.php?id=80&L=1
http://innoflight.com/s-band_cubesat_radio/
http://www.ruag.com/space/Products/Satellite_Communication_Equipment/Receivers_Converters

Second independent method of precision orbit determination:
GNSS receiver: GPS + GLONASS + Galileo + COMPASS (BEIDU)

a multi-frequency GPS/GLONASS/Galileo/COMPASS receiver. AsteRx3 features proven simultaneous high-quality GPS, GLONASS and Galileo tracking, advanced multipath mitigation algorithm APME, LOCK+ tracking for exceptional tracking stability under high vibration conditions, RTK+ for extended RTK baselines and faster initialization, offering cm-level measurement quality even in challenging environments.

source: http://www.septentrio.com/products

Symmetricom SA.45s CSAC

With an extremely low power consumption of <120 mW and a volume of <16 cc, the Symmetricom® SA.45s Chip Scale Atomic Clock (CSAC) brings the accuracy and stability of an atomic clock to portable applications for the first time.

The SA.45s provides 10 MHz and 1 PPS outputs at standard CMOS levels, with short-term stability (Allan Deviation) of 1.5E-10 @ 1 sec, long-term aging of 3E-10/month, and frequency change over temperature of 5E-10 over an operating range of -10° C to +70° C. The unit can also be ordered with a wider temperature range (Option 002) of -40° C to +85° C, with slightly higher power consumption and a wider frequency change over temperature.

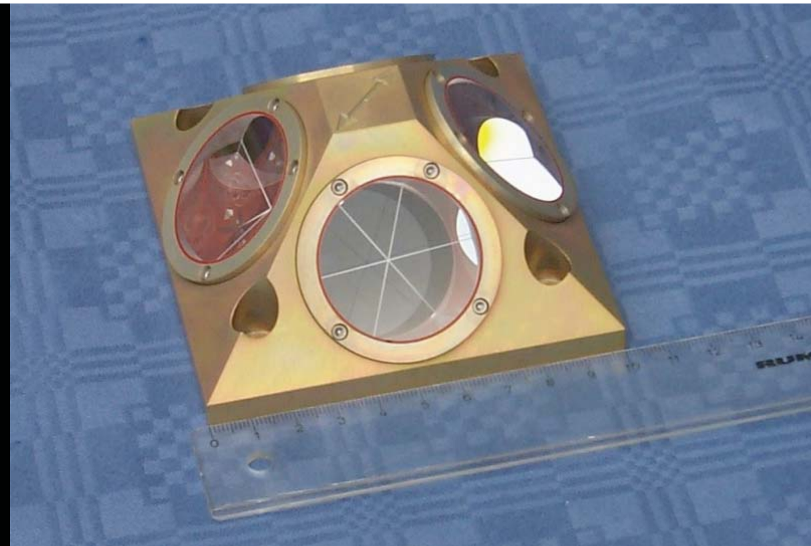
The SA.45s CSAC accepts a 1 PPS input that may be used to synchronize the unit's 1 PPS output to an external reference clock with ±100 ns accuracy. The CSAC can also use the 1 PPS input to discipline its phase and frequency to within 1 ns and 1.0E-12, respectively.

A standard CMOS-level RS-232 serial interface is built in to the SA.45s. This is used to control and calibrate the unit and also to provide a comprehensive set of status monitors. The interface is also used to set and read back the CSAC's internal time-of-day clock.

The SA.45s CSAC can also be programmed to operate in an ultra-low power mode. In this mode, the CSAC's physics package is turned off, and the unit operates as a free-running TCXO. The physics package is then periodically turned back on, and after warm-up (<130 sec), it re-disciplines the TCXO. This operating mode enables average power consumption levels of well below 50 mW.

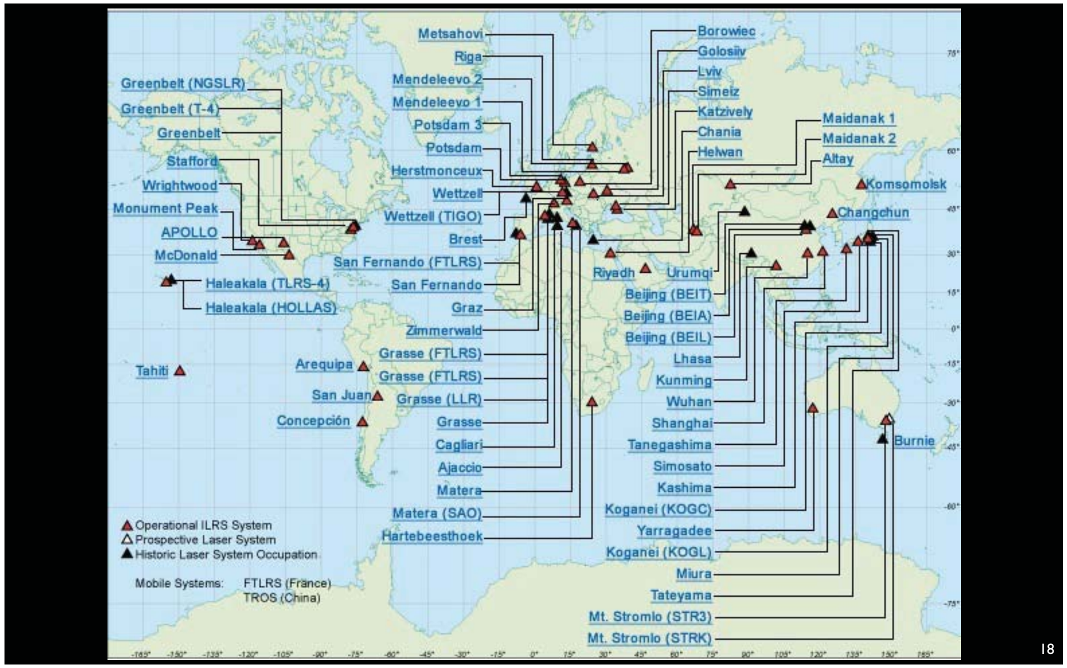
Third independent method of precision orbit determination: Chip-scale atomic clock

source: http://www.symmetricom.com/resources/download-library/documents/datasheets/quantum-sa45s-csac/



Fourth independent method of precision orbit determination:
laser retro-reflectors and International Laser Ranging System

carried on may satellites, this one was on the GRACE satellite.
source: http://op.gfz-potsdam.de/grace/payload/LRR.jpg



International Laser Ranging System
source: http://www.nasa.gov/centers/goddard/images/content/67443main_network_map.jpg

Instrument Summary

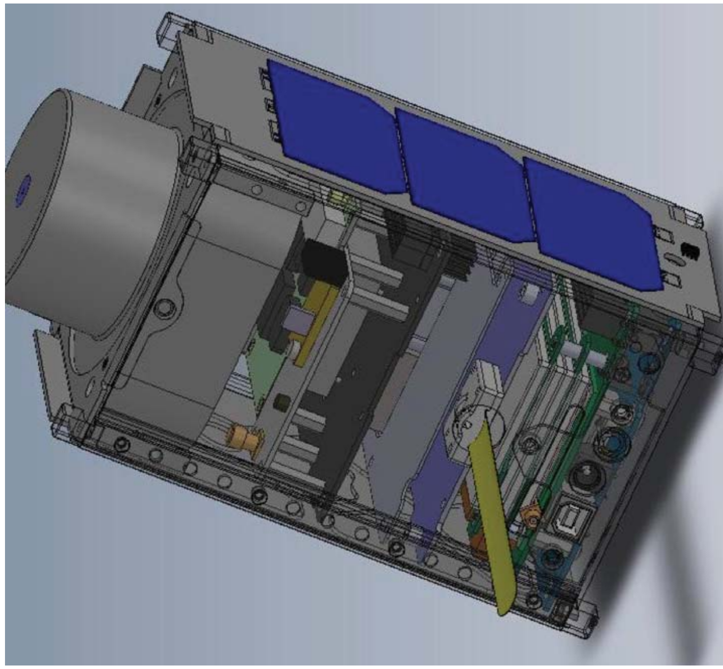
- one-way incoherent doppler
- two-way incoherent doppler
- laser ranging
- GNSS receiver
- onboard atomic clock
- coherent doppler?
- laser doppler ??

- All of these require very little downlink bandwidth

Spacecraft outline

- Instruments
- Radio(s)
- TCM propulsion
- Power
- Bus

also: antennas, solar arrays, propulsion
sources: see previous slides



Some Technical Questions

1. celestial mechanics / orbit / rideshare
2. mission design - spacecraft, instruments, **ground operations**
3. do we need DSN? Can we use ILRN/GNS at distance?
4. can we do other science? (heliophysics, lunar, basic physics..)

Mission Features Summary

- Allows big increase in number of earth flybys to date
- Anomaly measured with ≥3 independent instruments
- Low smallsat bus with low data rate instruments
- High TRL components
- No mechanisms, no micro-accelerometers
- No expensive (Cassini-class) radio & DSN?
- Vernier propulsion only (after orbit insertion)
- Low cost
- Fundamental science result with truly uncertain outcome
- People like this mission (acedemics, students, public)

Flyby

Anomaly

Test

Integrating

Multiple

Approaches