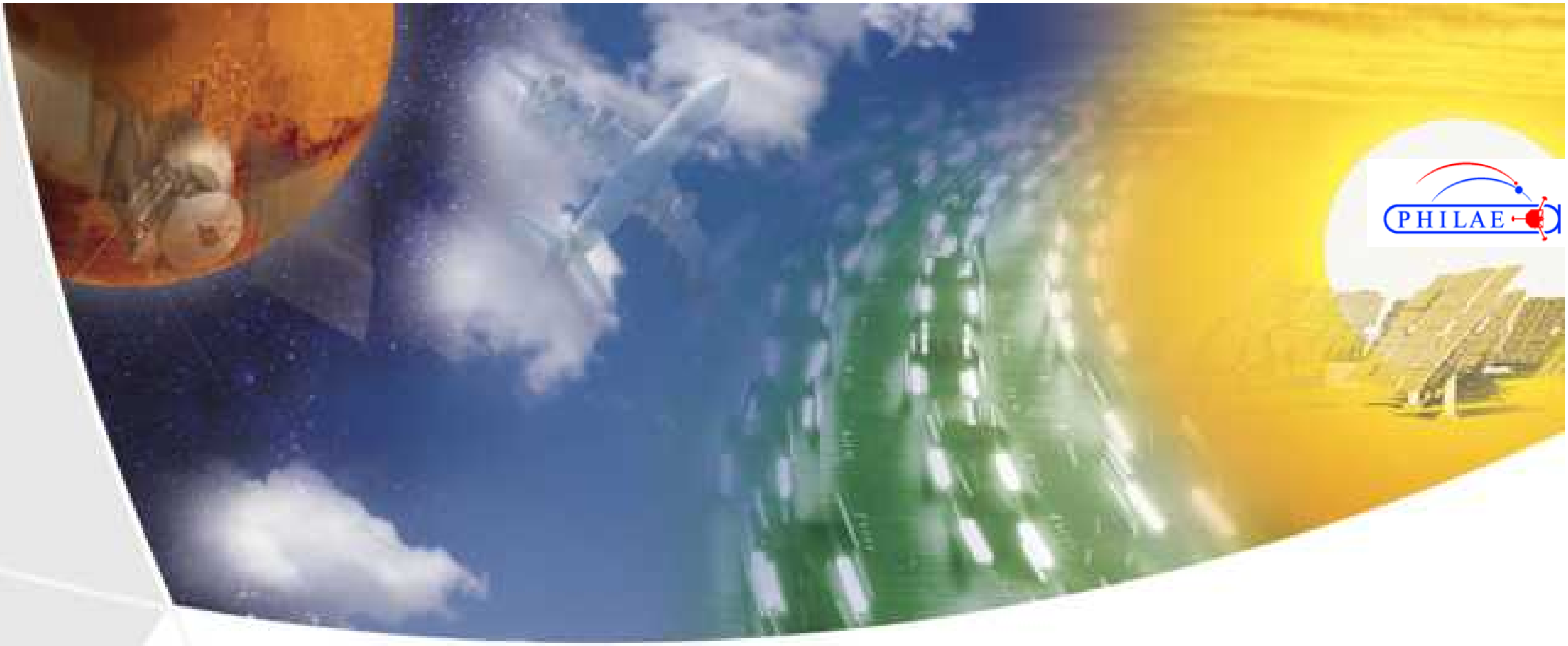


Navigation of the interplanetary Rosetta and Philae spacecraft and the determination of the gravitational field of comets and asteroids

J. Biele
(DLR) @ TU München, 2012

Abstract

The first ever dedicated comet Lander is Philae, an element of ESA´s Rosetta mission to comet 67/P Churyumov-Gerasimenko. Rosetta was launched in 2004. After about 7 years of interplanetary cruise (including three Earth and one Mars swing-by as well as two asteroid flybys) the spacecraft went into a deep space hibernation in June 2011. When approaching the target comet in early 2014, Rosetta is re-activated. The cometary nucleus will be characterized remotely to prepare Lander delivery, currently foreseen for November 2014. Comet escort by the spacecraft will continue until end 2015.

In contrast to small body flyby missions (e.g., ESA's Giotto mission to Halley's comet in 1986), Rosetta will actually orbit or "quasi-orbit" the comet nucleus, being inside it's Hill sphere. Strong perturbations by the comet's irregular shape and drag by the outgassing (coma) are expected and will limit the accuracy to which the gravitational field can be retrieved - depending on activity (only second harmonics may be retrievable). Since comets are believed to be rather homogeneous in density, an accurate semi-empirical gravity field (down to the surface) will be computed, using the optical shape model, constant density and considering a few mascons if necessary.

RF communications with ground stations on Earth is in X and S band; together with an ultra-stable oscillator on board the spacecraft, accurate tracking (range, range-rate) is possible. Navigation will further be aided by DDOR. Of course, no GPS-like navigation system exists hitherto for interplanetary spaceflight, and active laser ranging is in its infancy.

The talk will conclude with a discussion of the so-called Rosetta fly-by anomaly, a deviation of the measured trajectory from the calculated one during Rosetta's Earth flybys and sometimes compared with the Pioneer anomaly.

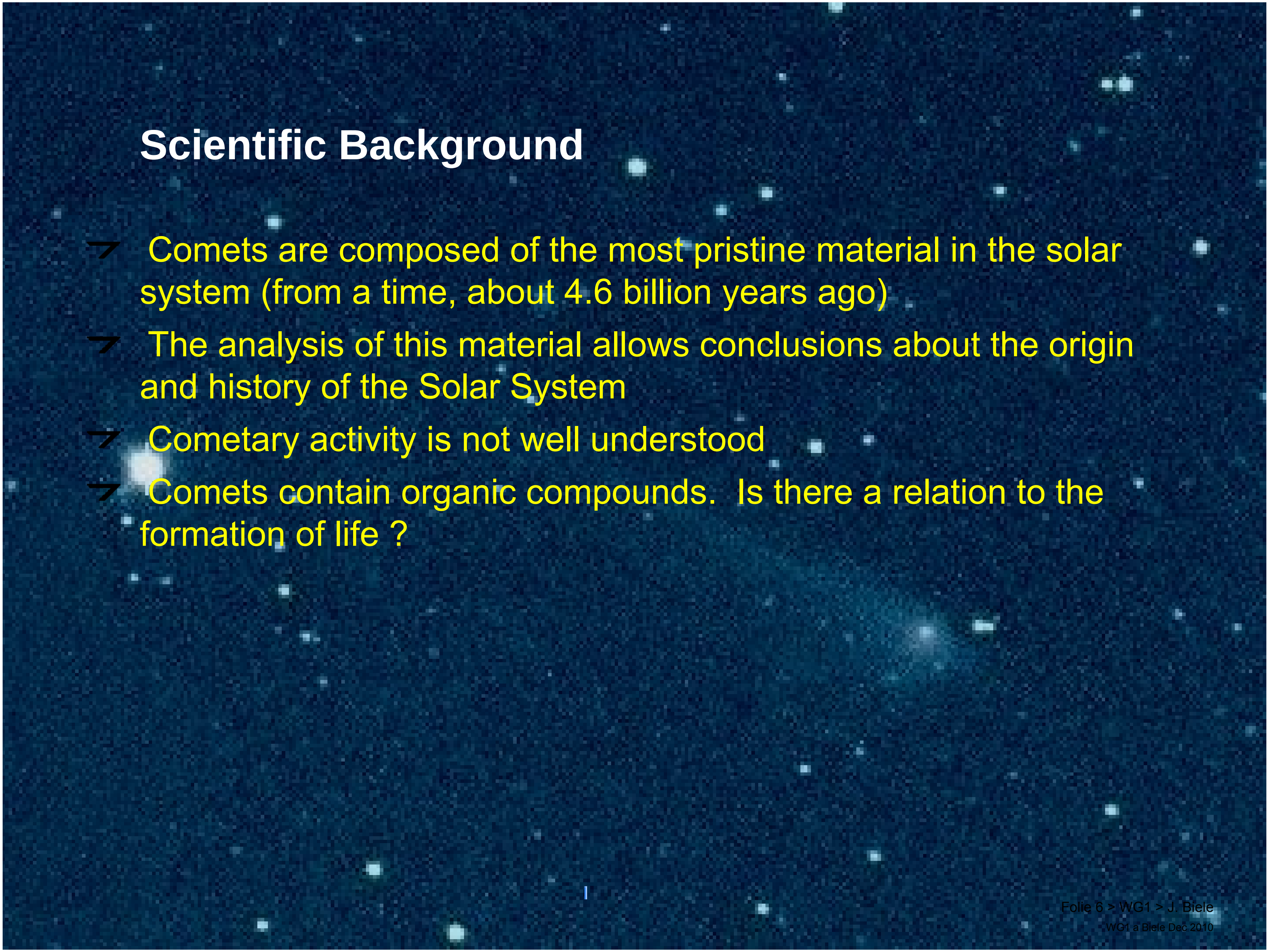
Rosetta - Philae

- The Rosetta Stone was discovered during Napoleon's Egyptian expedition in 1799 near Rashid (Rosetta). It shows a text from the time of Ptolemy V Epiphanes (205-180 B.C) written in Hieroglyphic, Demotic und Greek.
- An Obelisk from Philae showed the same royal cartuches (Ptolemy and Cleopatra)
- Using this text, Jean-Francois Champollion (1790-1832) was able to decipher the Egyptian Hieroglyphs (the final work was published in 1822).
- The Rosetta Stone is now in the British Museum; the Obelisk in Cornwall

Philae

- Rosetta is an ESA cornerstone Mission to Comet 67P/Churyumov Gerasimenko
- 11 Orbiter Instruments plus the Lander
- Launch: March, 2004
- Arrival: May 2014,

Lander separation: Nov.2014

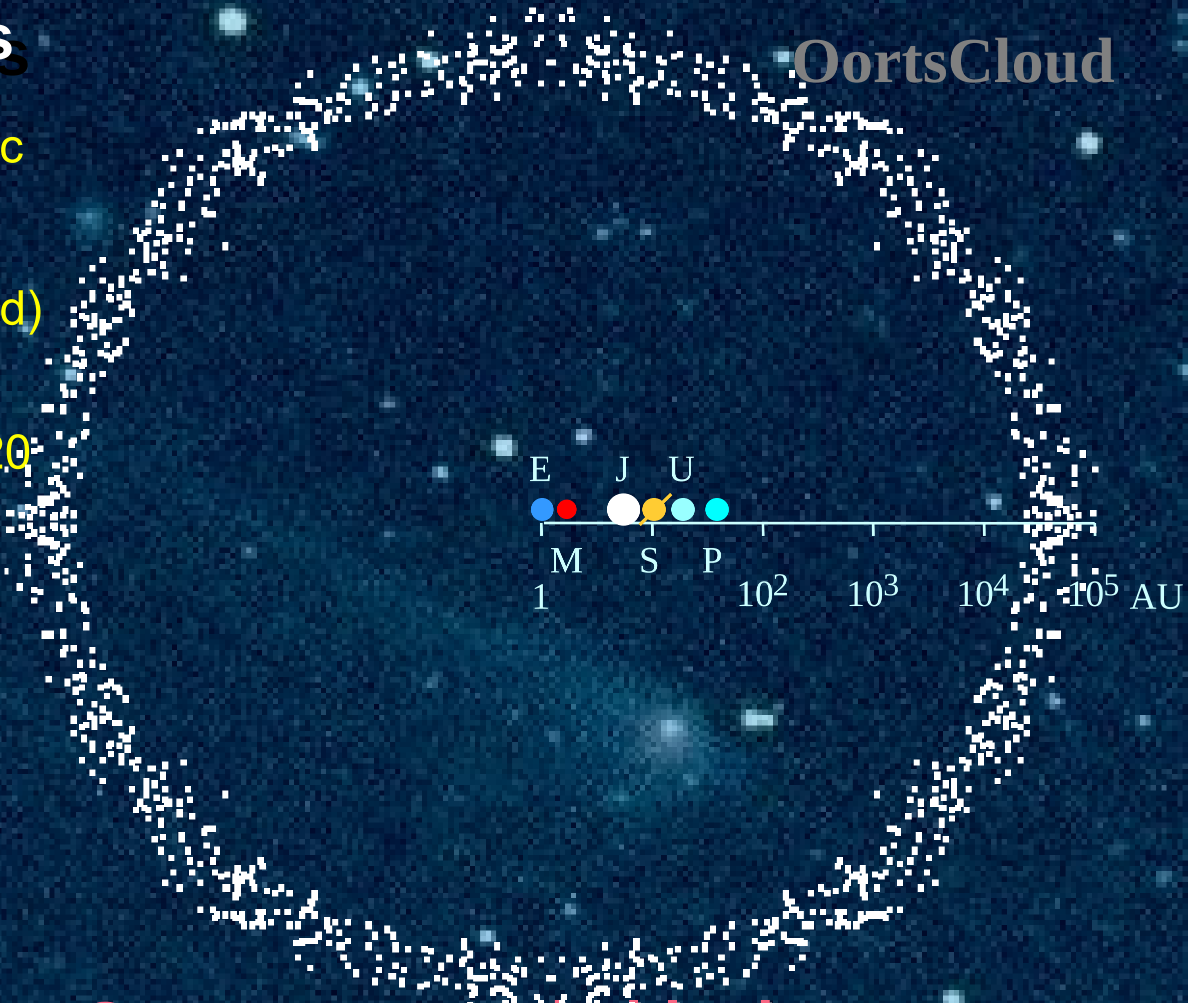


Scientific Background

- Comets are composed of the most pristine material in the solar system (from a time, about 4.6 billion years ago)
- The analysis of this material allows conclusions about the origin and history of the Solar System
- Cometary activity is not well understood
- Comets contain organic compounds. Is there a relation to the formation of life ?

Origin of Comets

- Relicts of pre-planetary disc
- Distances 10^2- 10^5 AU (Kuiper-Belt und Oort-Cloud)
- Partially aggregated
- Almost unchanged at 5 - 20 K
- Reach orbits close to sun due to gravi-tational disturbances



Comets are probably the most pristine Objects in the Solar System

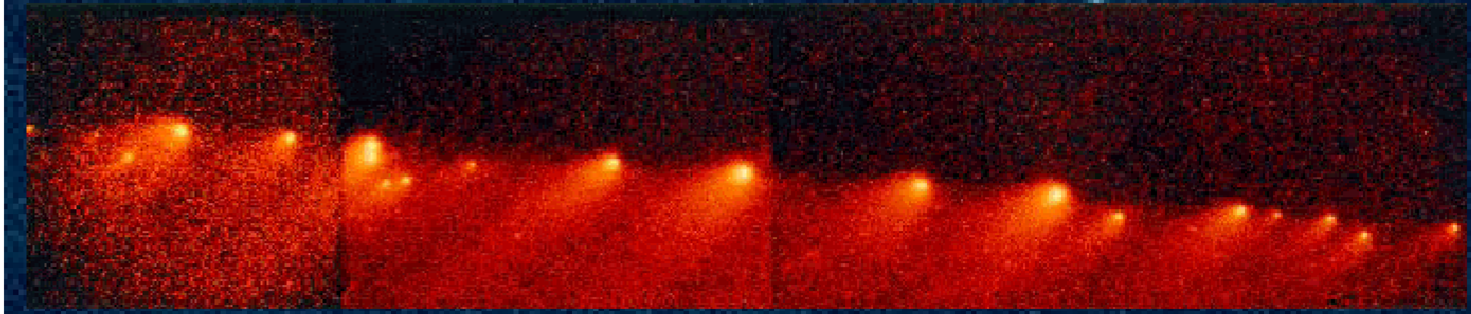
Hale Bopp

Knowledge since Giotto

- ESA-Giotto-Mission 1986 to Comet Halley
- Results:
  - Comets do have a nucleus
  - they have a very low albedo (a=0.03)
  - only about 20% of the surface is active (jets)
  - they are composed of ice and dust
  - there are organic components
  - comets are very porous
  - the nucleus is a few km in size, the coma 10^6 -10^8 km

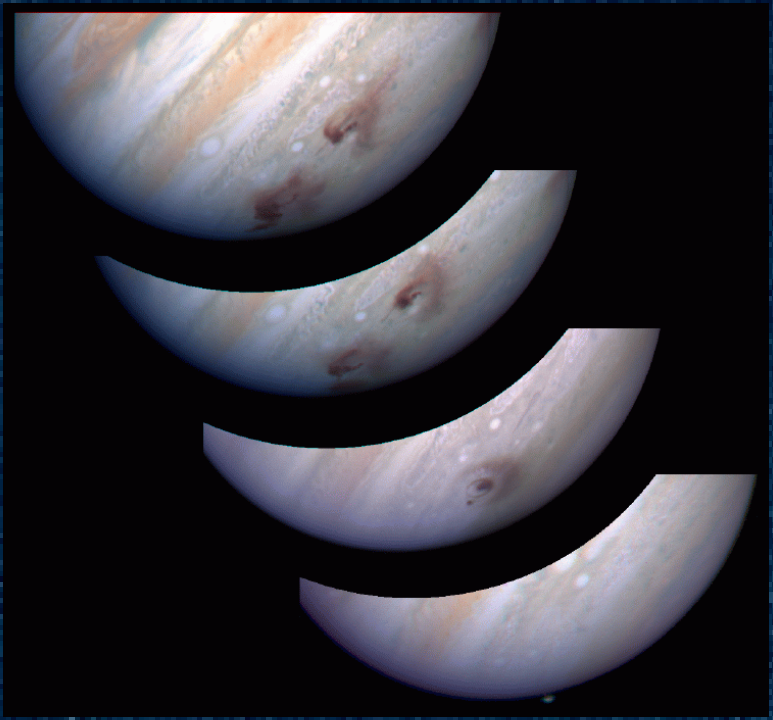
Image: MPS

Shoemaker Levy 9

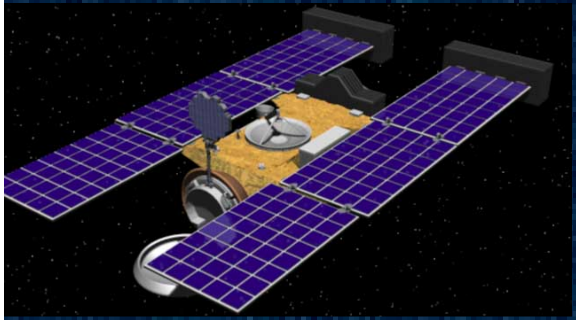


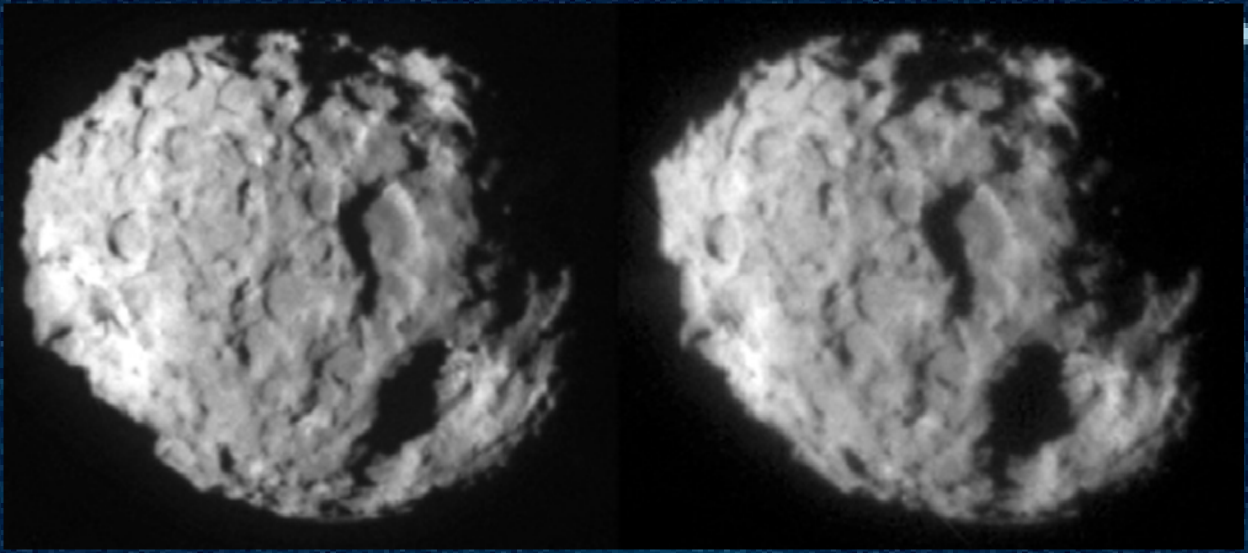
In July 1994
comet
Shoemaker Levy 9
impacted at
Jupiter

Over 20 fragments
were observed



Comet Wild 2 (Stardust Mission)

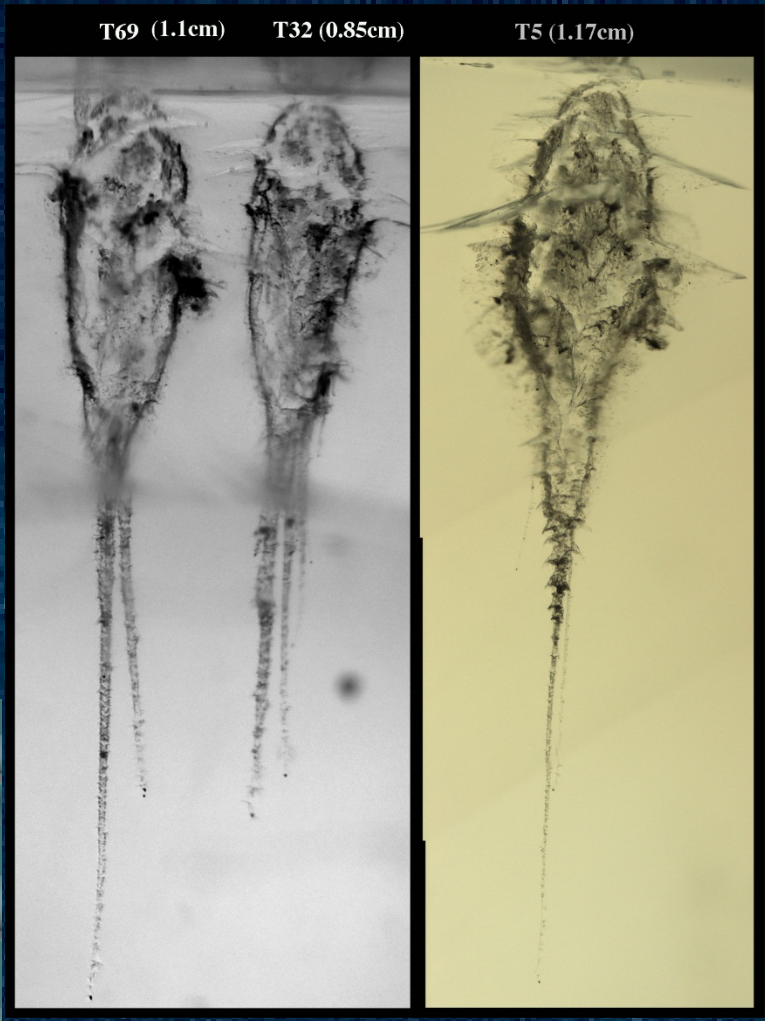




Stardust flew-by comet Wild 2 in Jan. 2004 and returned dust samples from the coma, back to Earth in Jan. 2006

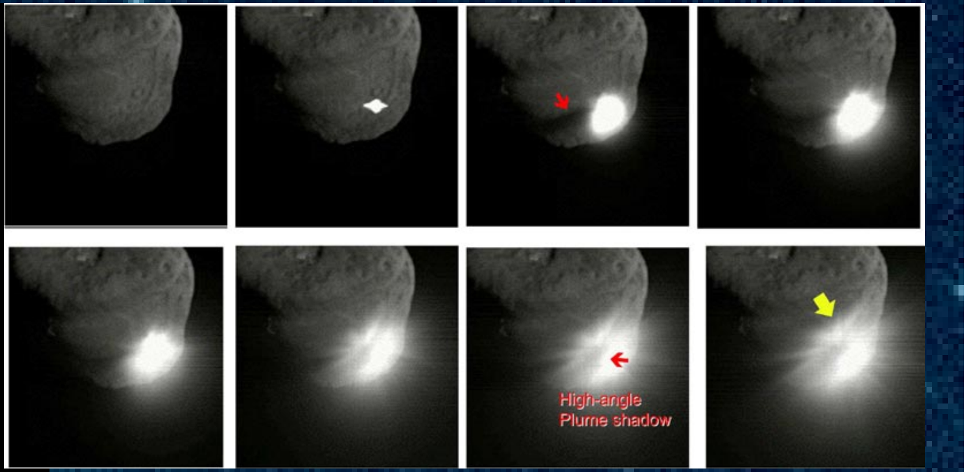
Images: NASA/JPL

Stardust Samples

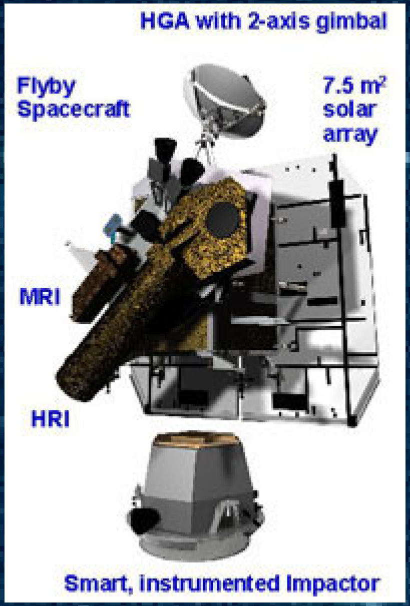


Images: NASA/JPL

Comet Tempel 1 (Deep Impact)



Impact;
4. Juli 2005



Rosetta Target: Comet 67P/Churyumov-Gerasimenko

Discovered by Klim Churyumov in photographs of 32P/Comas Solá taken by Svetlana Gerasimenko on 9/11, 1969.

- Characteristica:

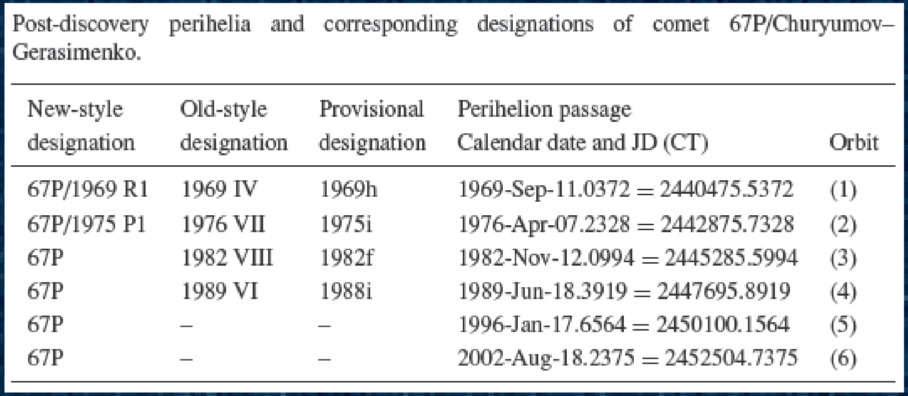
Diameter	~4000 m
Density	0.2-1.5 gcm^{-3}
Aphel	5,75 AU
Perihel	1,29 AU
Orb.period	6,57 years
Albedo	ca. 0,04 ??
Rotation	12,6 h

- Perihelion: August 18 2002

Discovered 1969

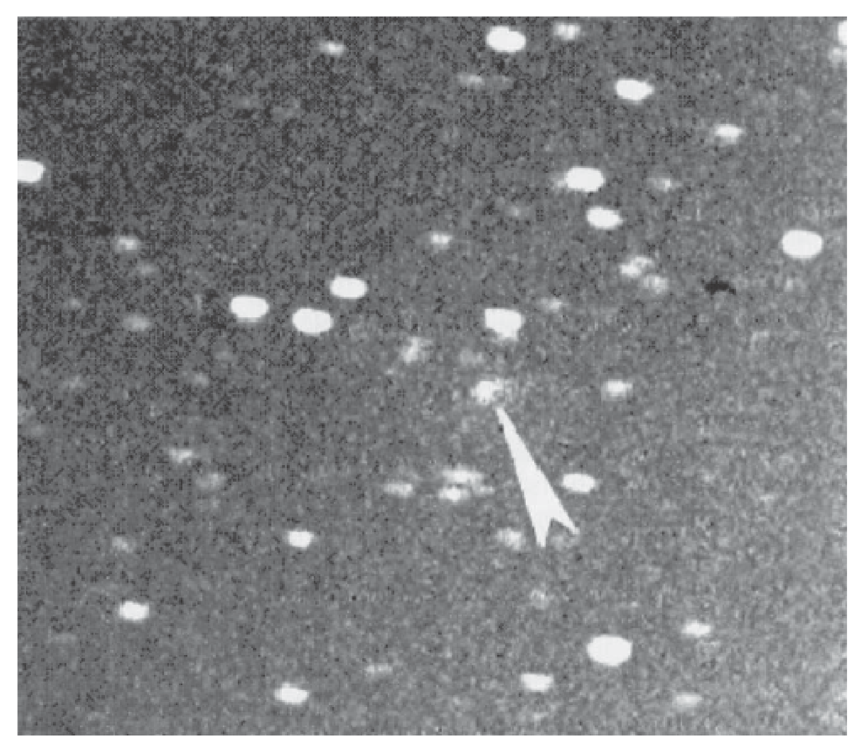
Discovery of 67P

- The Comet was discovered 1969 by K. Churyumov and S. Gerasimenko
- Close (0.05 AU) encounter at Jupiter February 1959 [perihel dropped from 2.7 to 1,3 AU]



Post-discovery perihelia and corresponding designations of comet 67P/Churyumov–Gerasimenko.

New-style designation	Old-style designation	Provisional designation	Perihelion passage Calendar date and JD (CT)	Orbit
67P/1969 R1	1969 IV	1969h	1969-Sep-11.0372 = 2440475.5372	(1)
67P/1975 P1	1976 VII	1975i	1976-Apr-07.2328 = 2442875.7328	(2)
67P	1982 VIII	1982f	1982-Nov-12.0994 = 2445285.5994	(3)
67P	1989 VI	1988i	1989-Jun-18.3919 = 2447695.8919	(4)
67P	–	–	1996-Jan-17.6564 = 2450100.1564	(5)
67P	–	–	2002-Aug-18.2375 = 2452504.7375	(6)



Discovery Image of 67P Churyumov-Gerasimenko, from 1969

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67P/Cl
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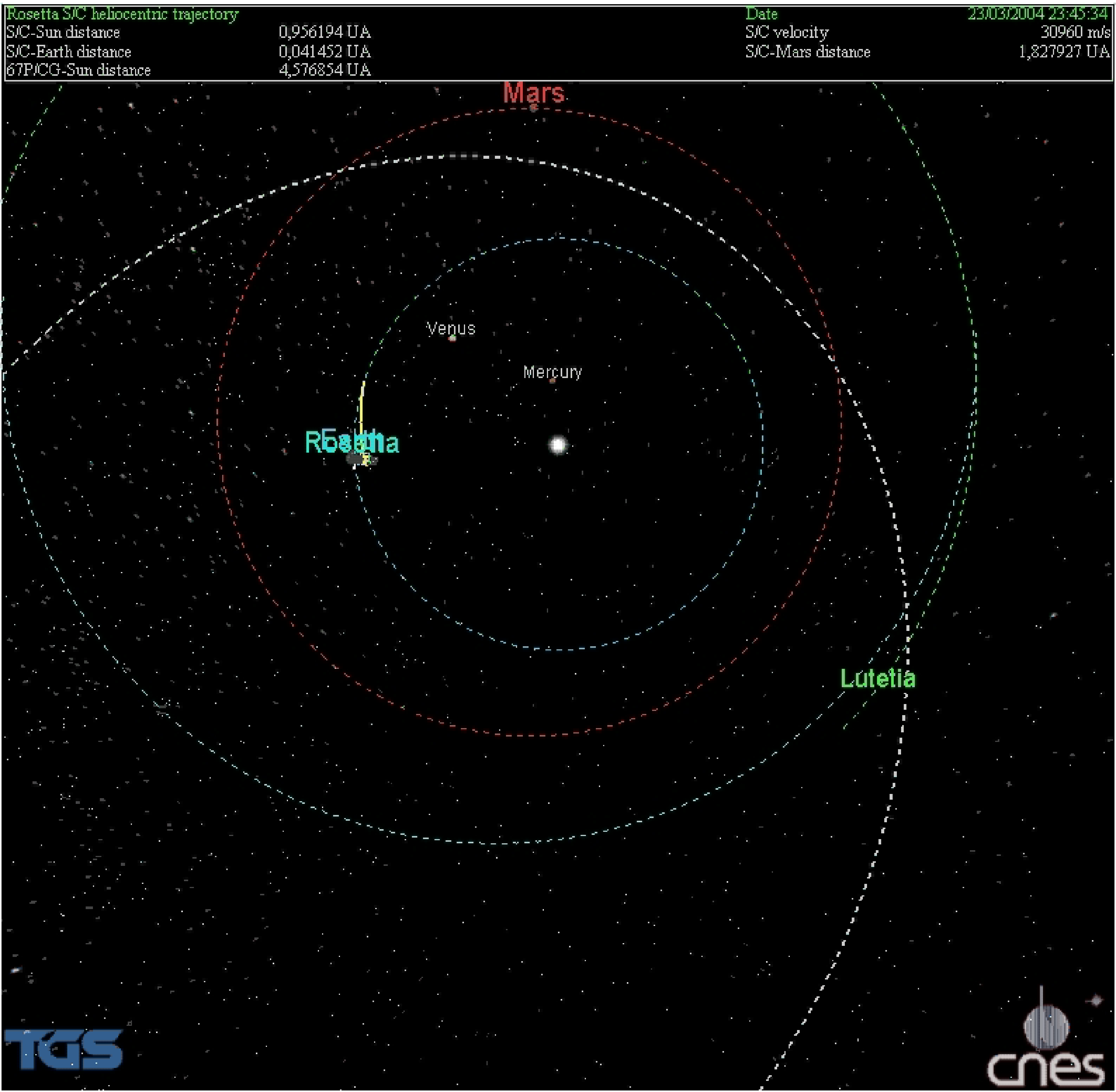


```
Rosetta S/C heliocentric trajectory                          Date                 23/03/2004 23:45:34
S/C-Sun distance          0,956194 UA                        S/C velocity                  30960 m/s
S/C-Earth distance        0,041452 UA                        S/C-Mars distance           1,827927 UA
67P/CG-Sun distance       4,576854 UA
```

Graph by ESA/E

d 2004

arch 2005

b. 2007

ov. 2007

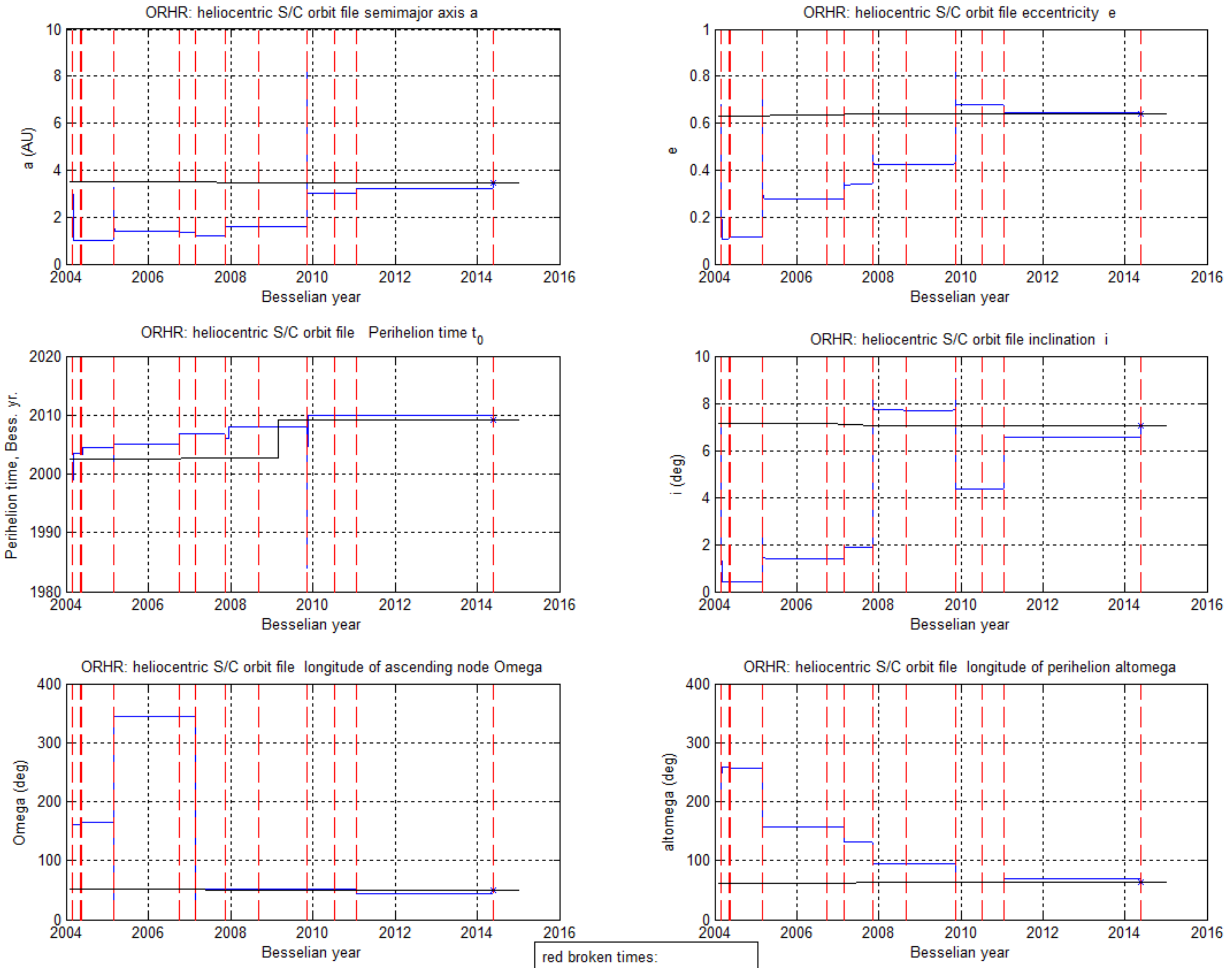
. 2008

ov. 2009

2010

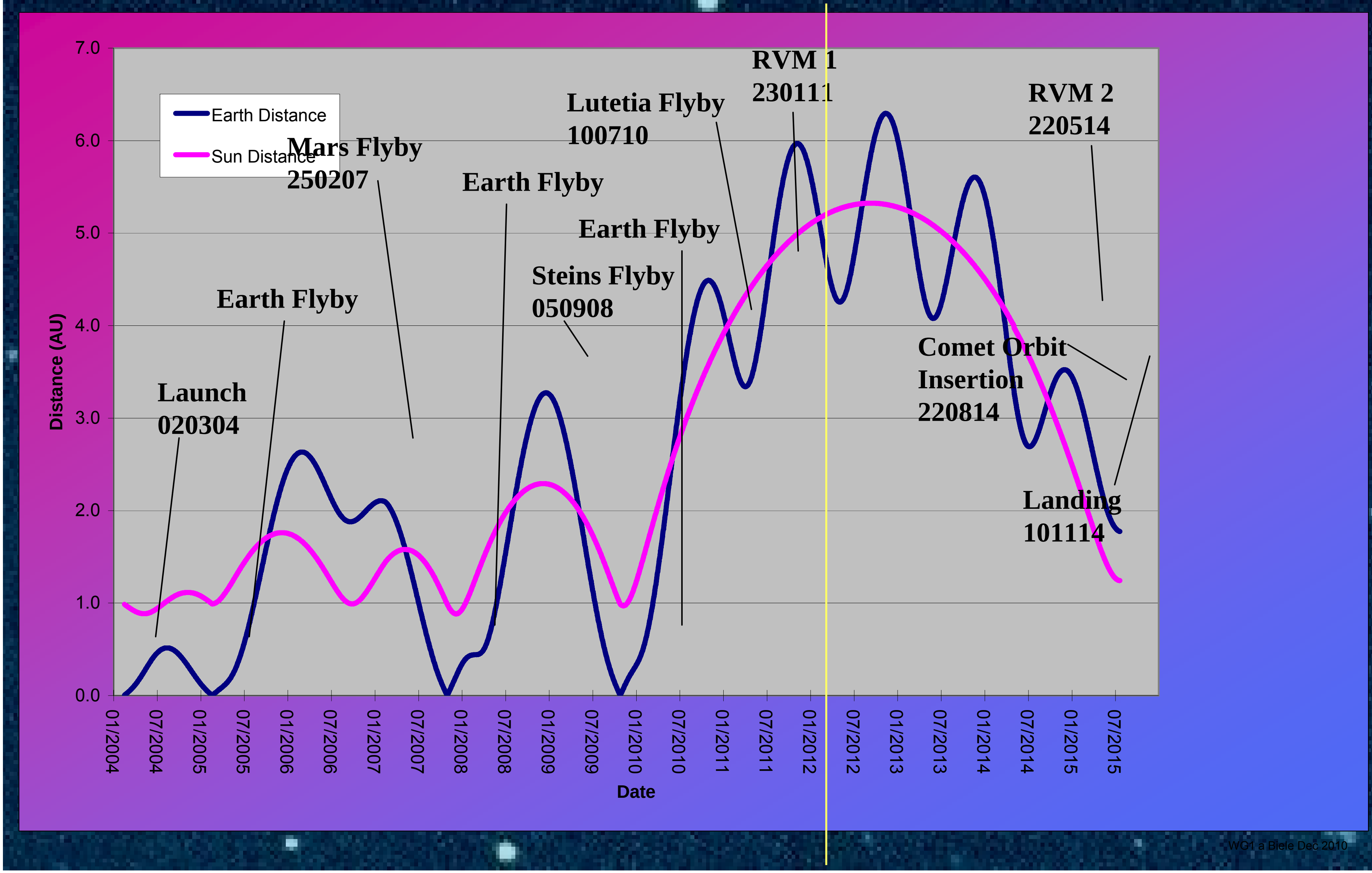
ay 2014

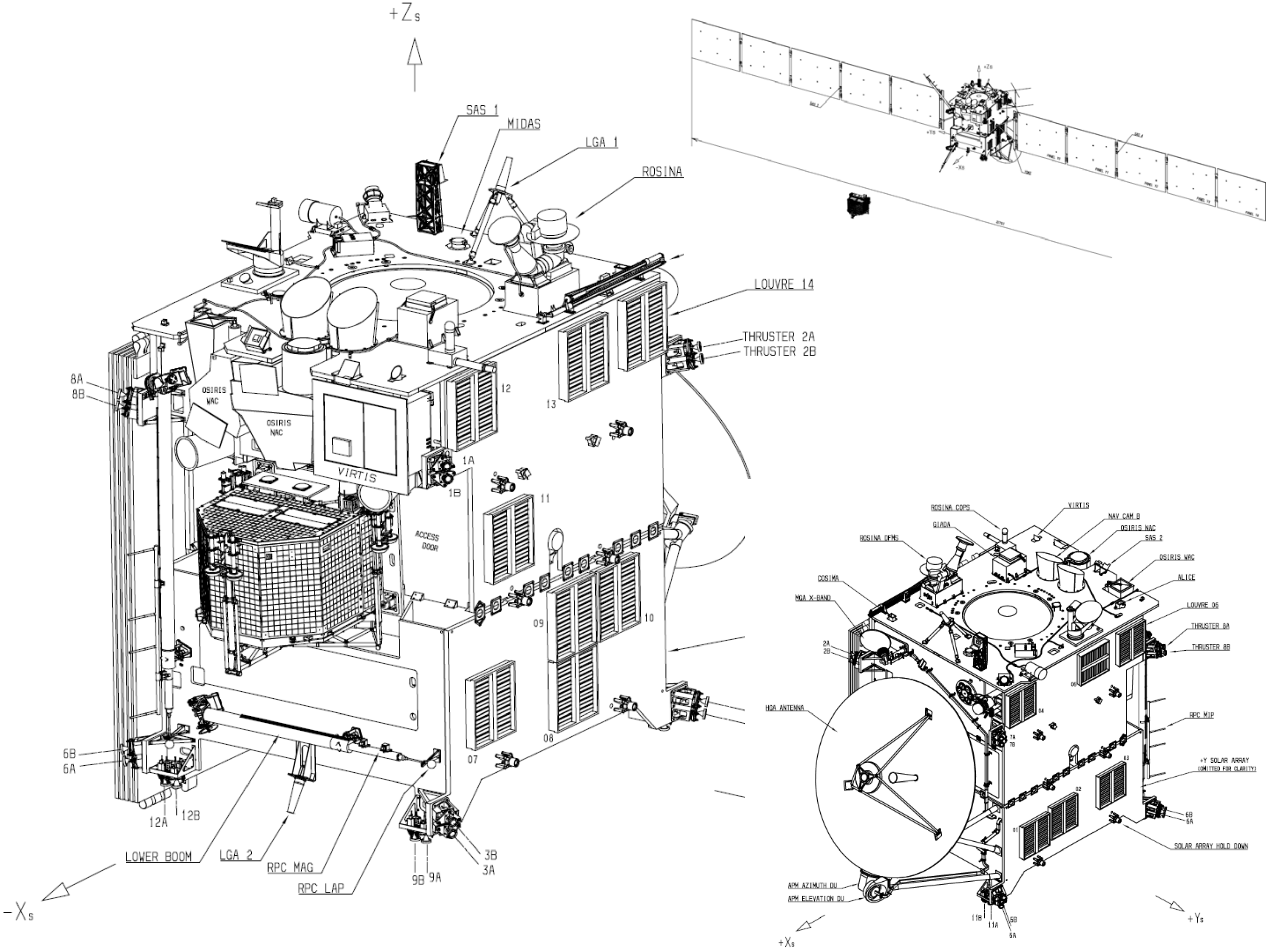
Patched conics



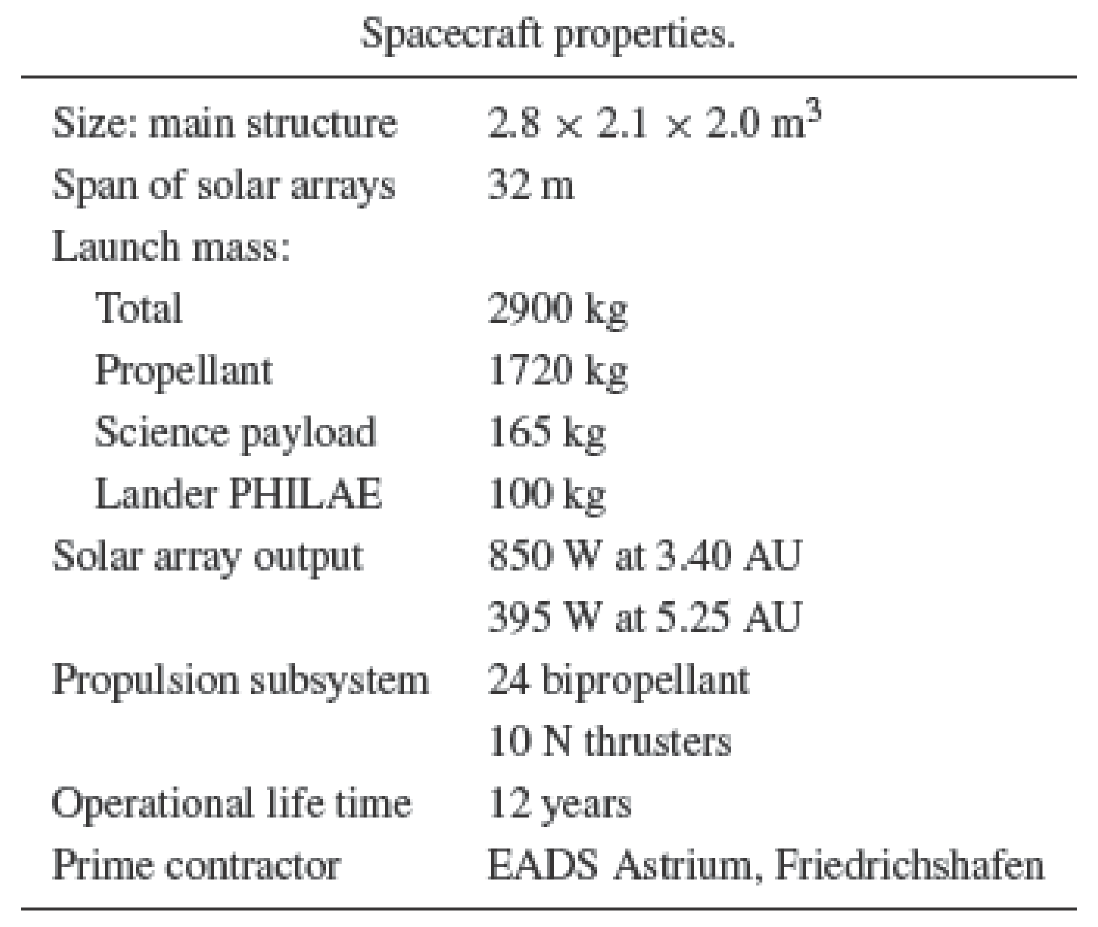
red broken times:
maneuvres
and swingbys
black lines:
comet 67P

Overview of trajectory vs. time




+Zs
SAS 1
MIDAS
LGA 1
ROSINA
LOUVRE 14
THRUSTER 2A
THRUSTER 2B
8A
8B
OSIRIS WAC
OSIRIS NAC
VIRTIS
12
13
1A
1B
11
ACCESS DOOR
09
10
08
07
6B
6A
12A
12B
3B
3A
9B
9A
LOWER BOOM
LGA 2
RPC MAG
RPC LAP
-Xs
+Zs
+Ys
-Xs
ROSINA COPS
VIRTIS
GIADA
NAV CAM B
OSIRIS NAC
ROSINA DFMS
SAS 2
OSIRIS WAC
COSIMA
ALICE
MGA X-BAND
LOUVRE 06
THRUSTER 8A
THRUSTER 8B
2A
2B
05
HGA ANTENNA
04
RPC MIP
7A
7B
03
+Y SOLAR ARRAY (OMITTED FOR CLARITY)
02
01
6B
6A
SOLAR ARRAY HOLD DOWN
APM AZIMUTH DU
APM ELEVATION DU
11B
11A
5B
5A
+Xs
+Ys

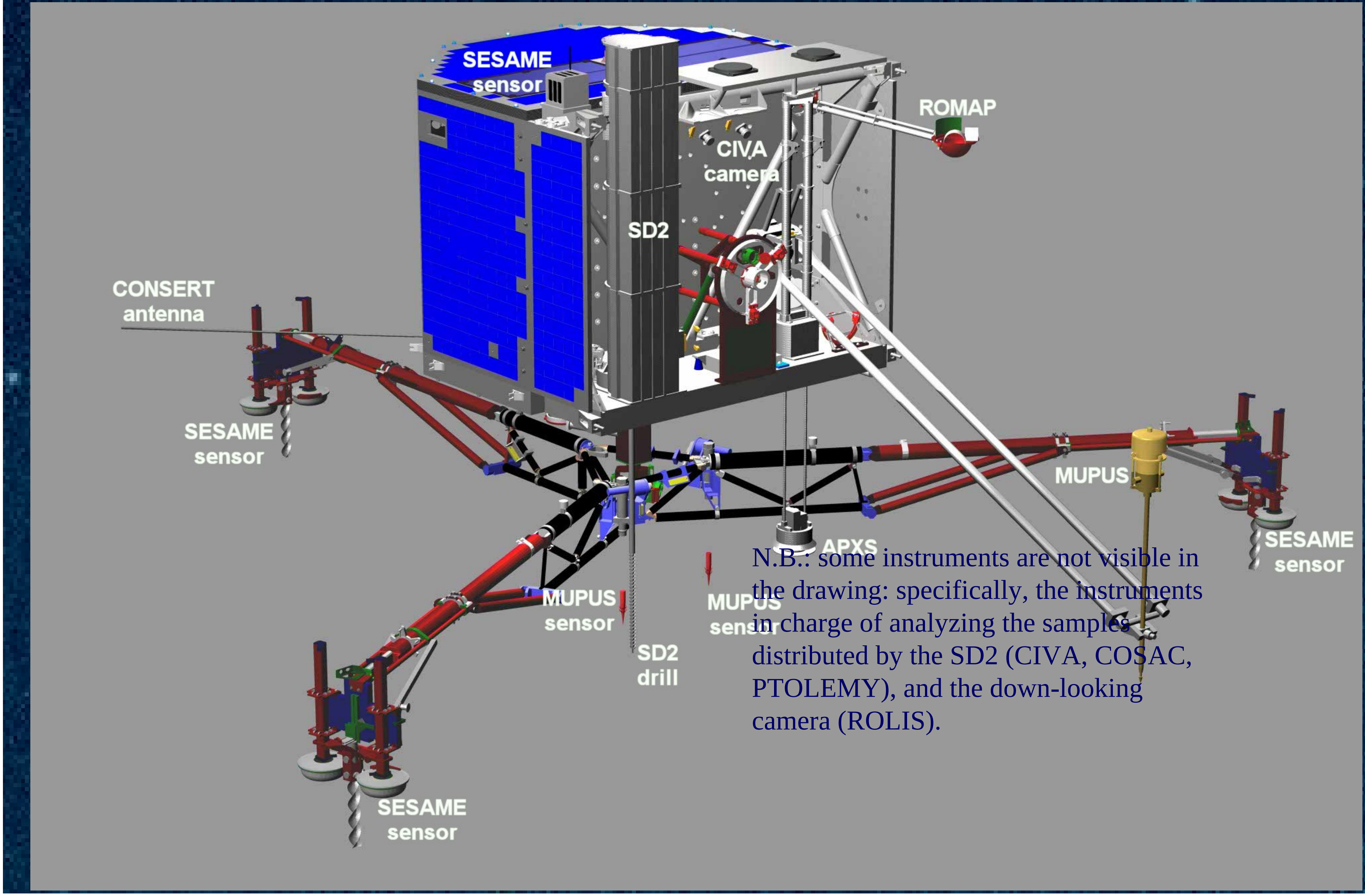
Rosetta – Exploded View



Spacecraft properties.

Size: main structure	$2.8 \times 2.1 \times 2.0\ m^3$
Span of solar arrays	32 m
Launch mass:	
Total	2900 kg
Propellant	1720 kg
Science payload	165 kg
Lander PHILAE	100 kg
Solar array output	850 W at 3.40 AU 395 W at 5.25 AU
Propulsion subsystem	24 bipropellant 10 N thrusters
Operational life time	12 years
Prime contractor	EADS Astrium, Friedrichshafen

Schematic view of the Philae lander



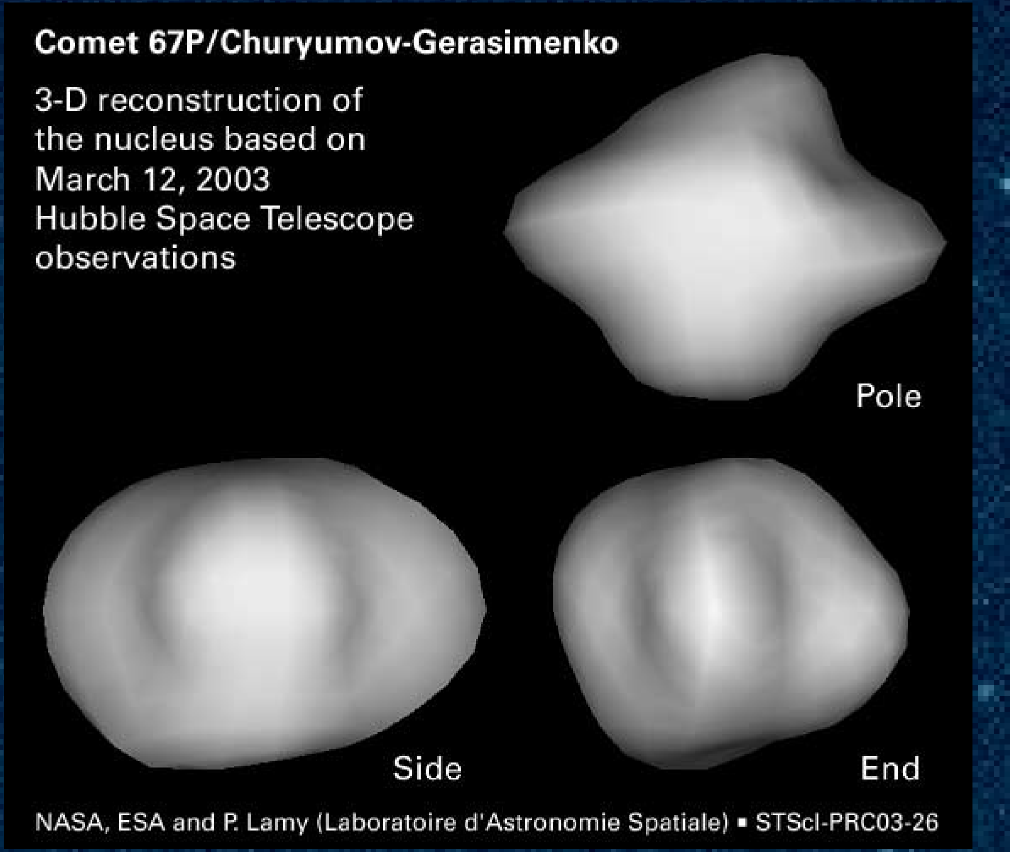
N.B.: some instruments are not visible in the drawing: specifically, the instruments in charge of analyzing the samples distributed by the SD2 (CIVA, COSAC, PTOLEMY), and the down-looking camera (ROLIS).

Technical Challenge

- Soft Landing on a Comet -
  Nobody has tried this so far... How soft is the comet, anyway?
- Size, mass, day-night period, temperature and surface properties of the comet are only vaguely known
- Longterm Operations of a Lander in Deep Space without RTG´s
- 10 Science Instruments aboard a 100 kg Lander

Local Environment

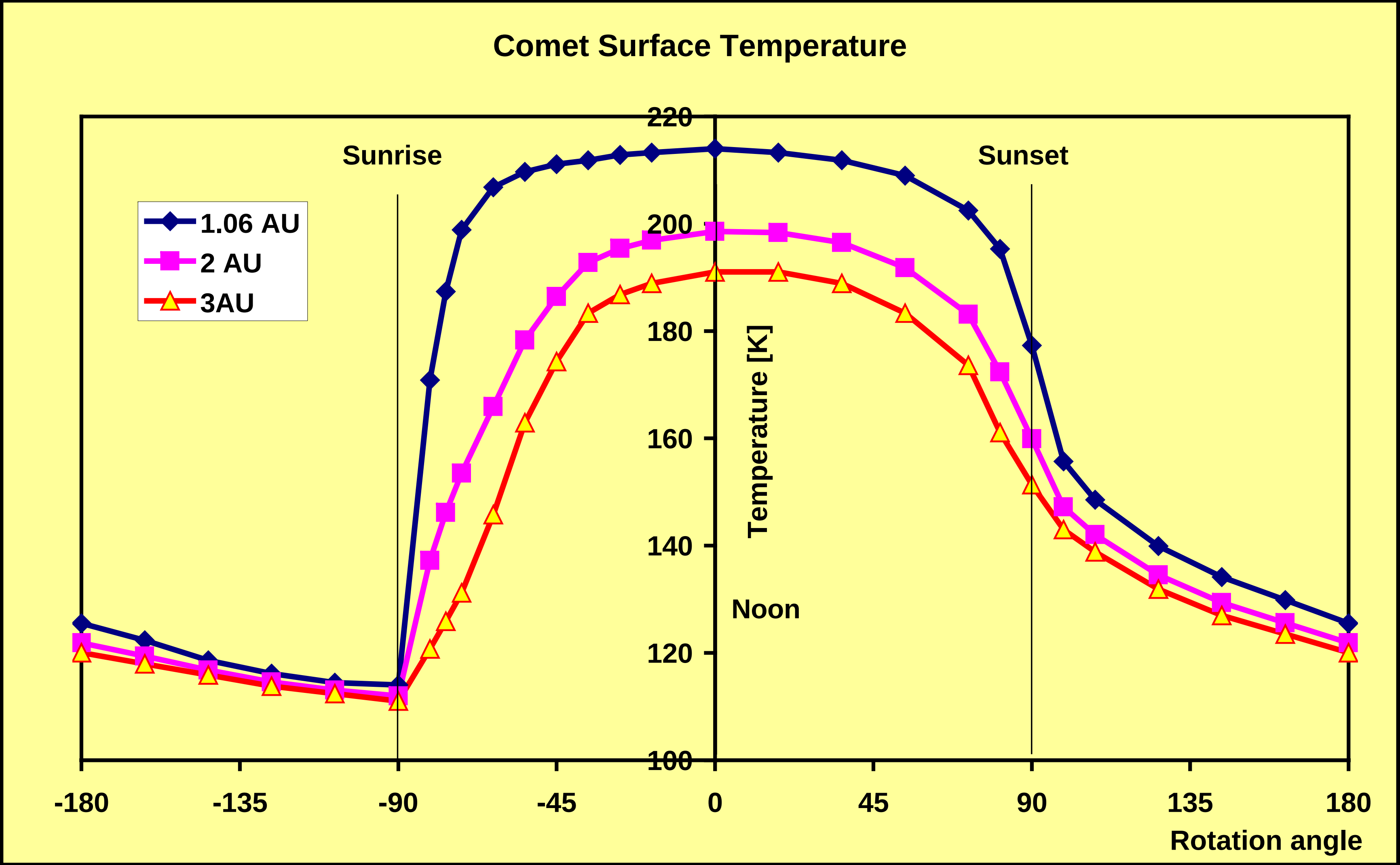
- Unknown topography and surface
- Shape [km] about 3×5
- Temperatures
  - Day ~ -80 to 200 °C
  - Night > -200 °C
- Rotation period 12.7 h
- Surface strength: 1 kPa to 2 Mpa
- Gravity ~10^{-4} g


Comet 67P/Churyumov-Gerasimenko

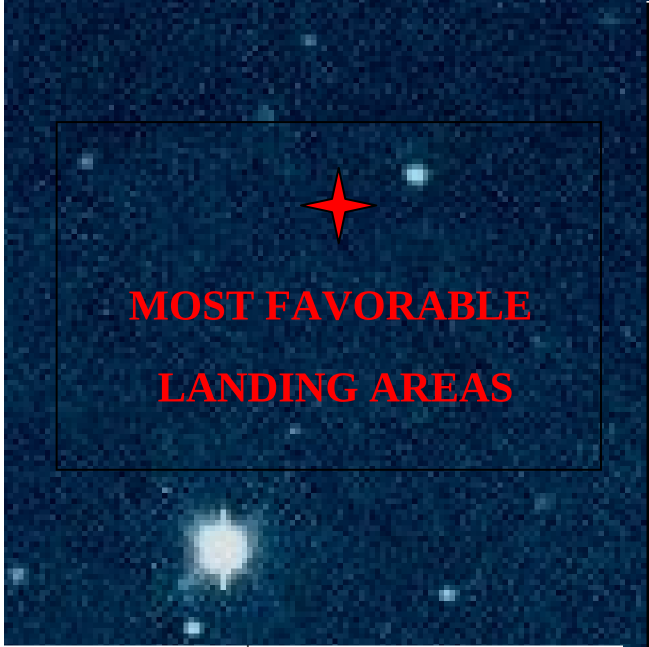
3-D reconstruction of
the nucleus based on
March 12, 2003
Hubble Space Telescope
observations

NASA, ESA and P. Lamy (Laboratoire d'Astronomie Spatiale) ▪ STScI-PRC03-26

Local Environment

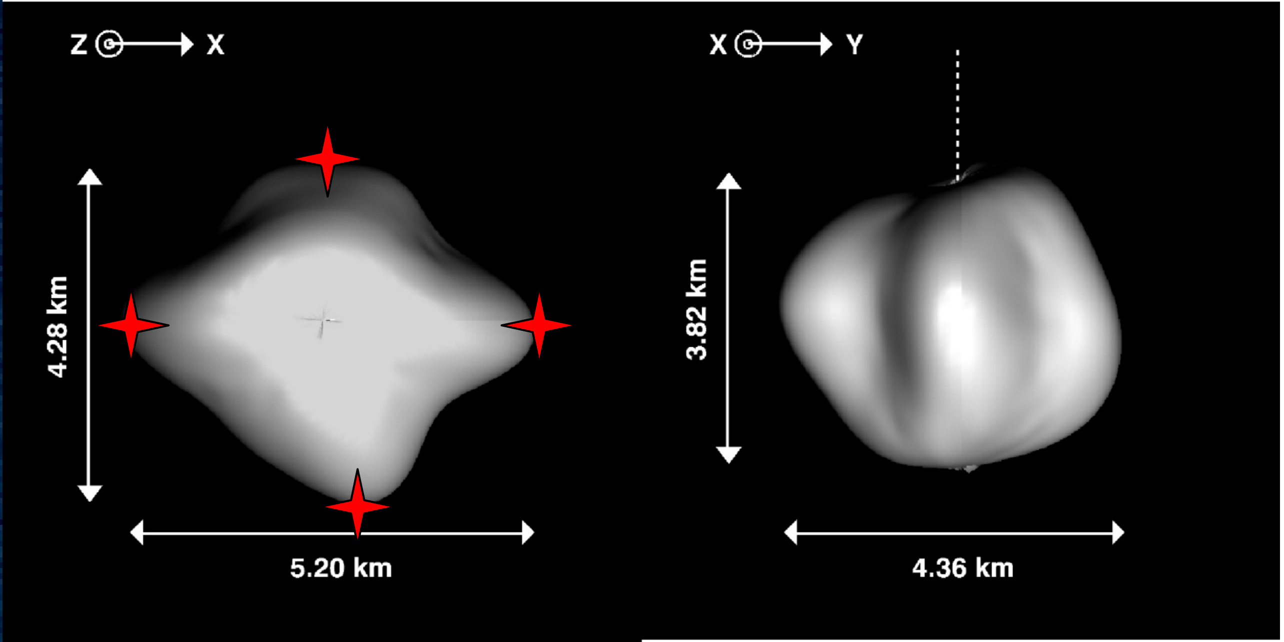


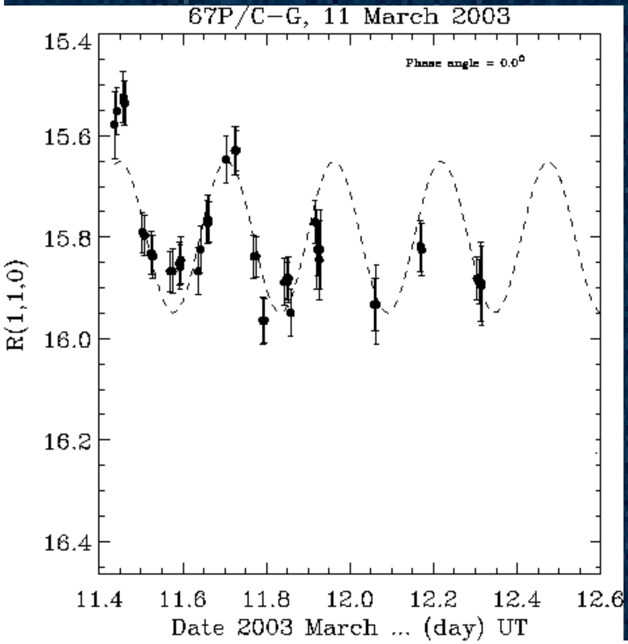
Shape, Landing areas

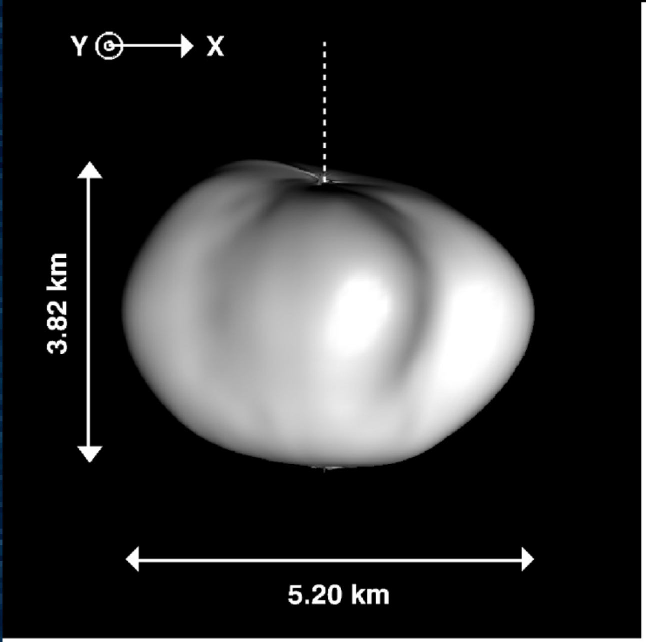


MOST FAVORABLE

LANDING AREAS







FROM THIS LIGHT CURVE DERIVED

FROM HST OBSERVATIONS

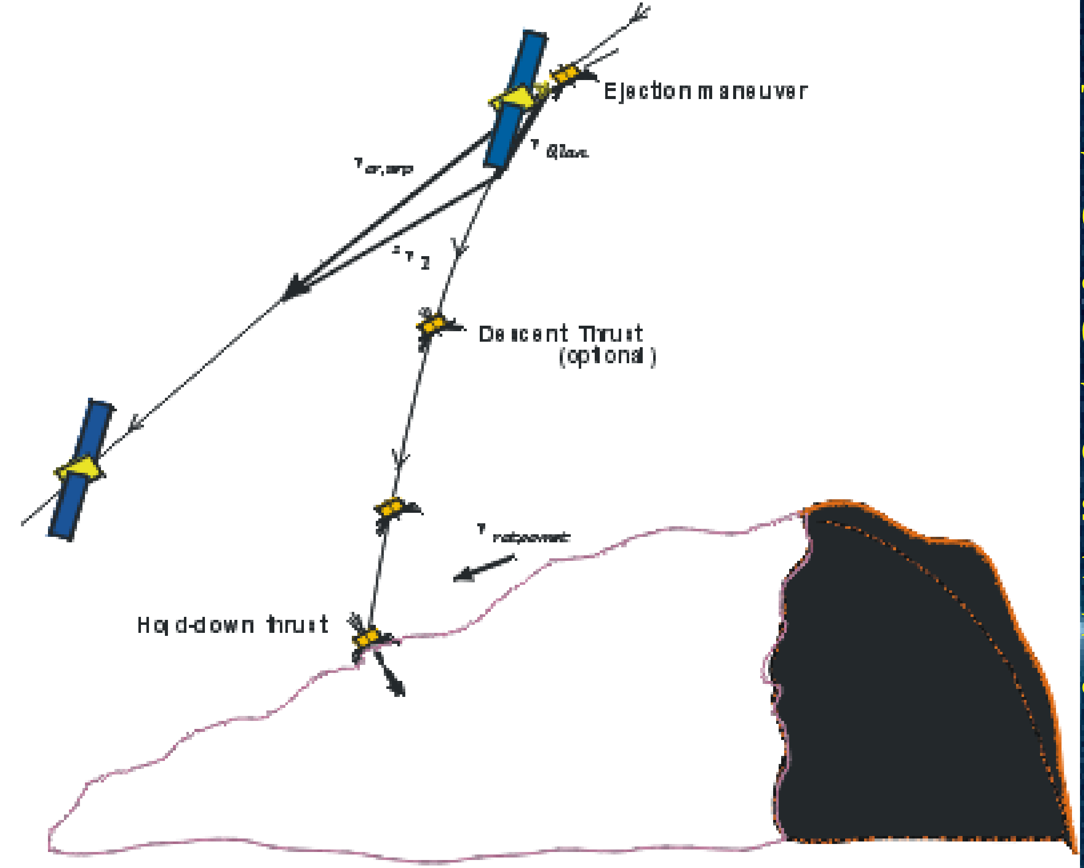
ON MARCH 2003 ,

THE P.LAMY TEAM MODELLED

A POSSIBLE CG NUCLEUS SHAPE

(DPS 2003 presentation – CNES/NASA grant)

Eject and landing



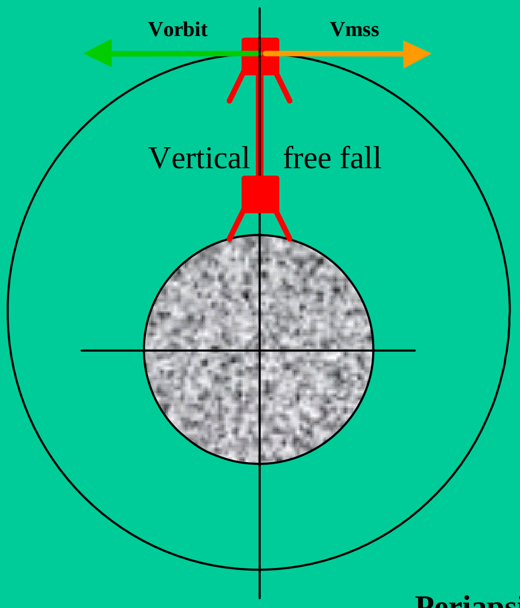
The Rosetta Lander will separate from the Orbiter with an adjustable velocity of 0,05 to 0,52 m/s and will descend to the comet´s surface stabilised by an internal flywheel and (if required) supported by a cold gas system

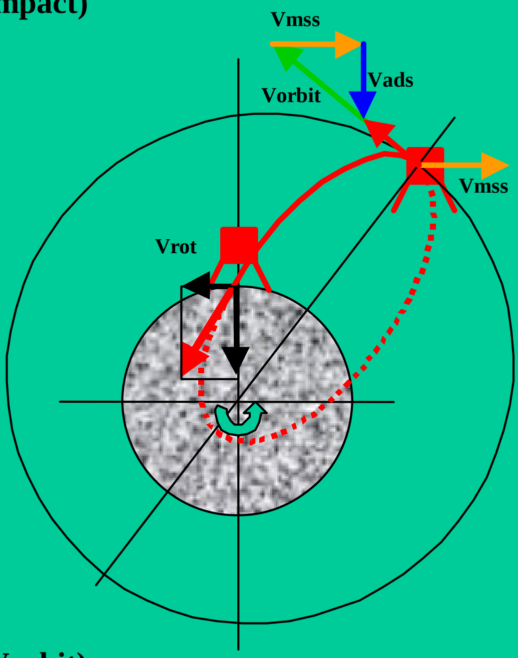
Delivery Strategy

A : WITHOUT ROTATION OR POLAR LANDING

B : WITH ROTATION AND EQUATORIAL LANDING

Delivery at apoapsis (minimises Vimpact)





Periapsis 1 mean radius (minimises Vorbit)

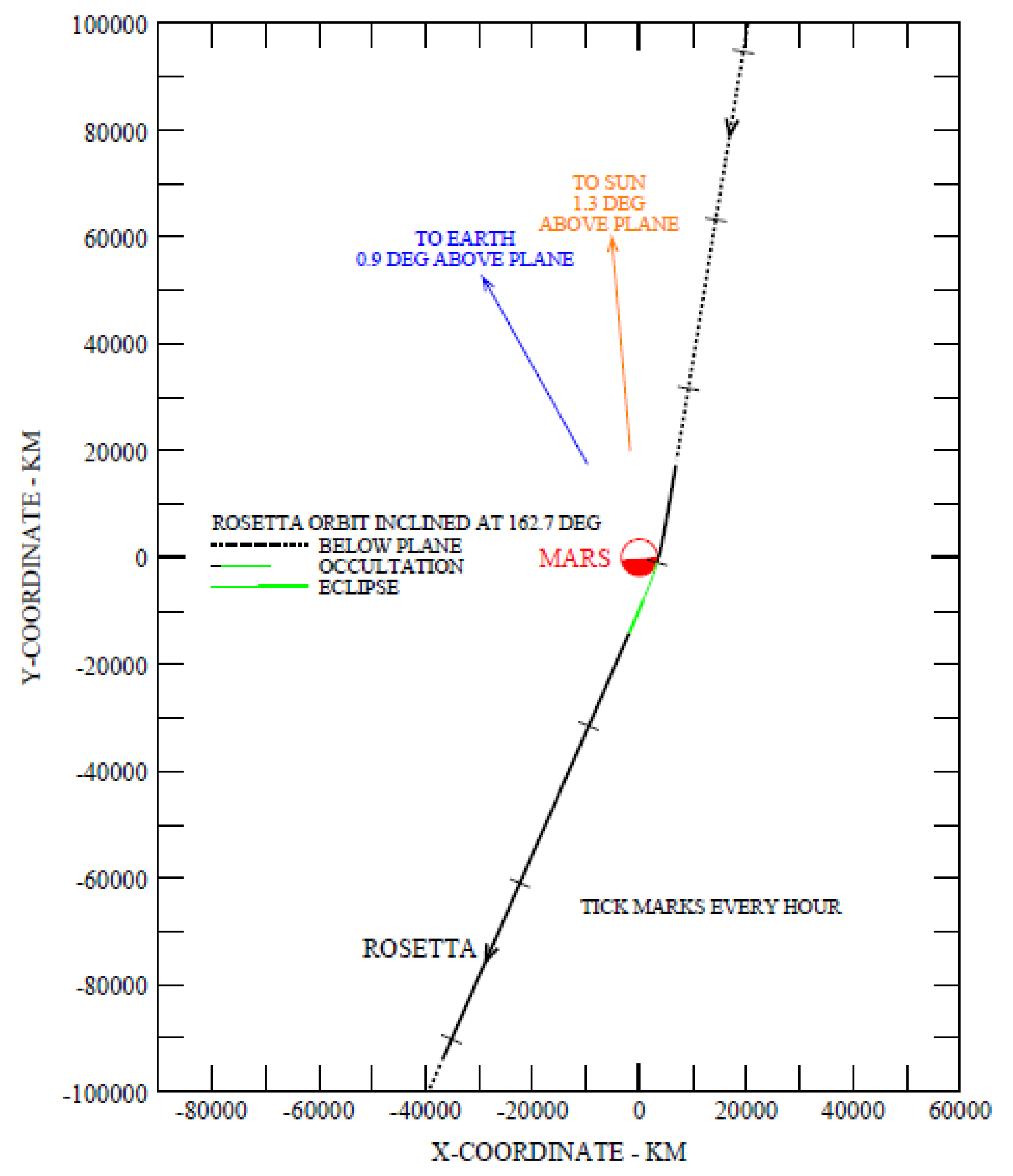
Landing strategy

- delivery foreseen in November 2014 at a distance of about 3 Astronomical Units (AU) to the Sun
- change of the target comet has a major impact on the Philae landing safety, since the expected touchdown velocity is much higher than in the case of P/Wirtanen (the original target of the Rosetta mission), due to the much larger size of P/Churyumov-Gerasimenko. Some hardware changes have been implemented, to increase robustness at touch-down. However, the safe landing remains highly sensitive to actual nucleus properties, largely unknown at this time.
- Consequently, a dedicated mapping phase will take place several months prior to separation, acquiring data from Orbiter instruments to update environmental and surface cometary models, towards an optimized selection of the landing site and of the release strategy.
- Following touch-down, Philae will have mission priority over Orbiter investigations for one week
- After this phase, Philae will share resources with the Orbiter investigations.

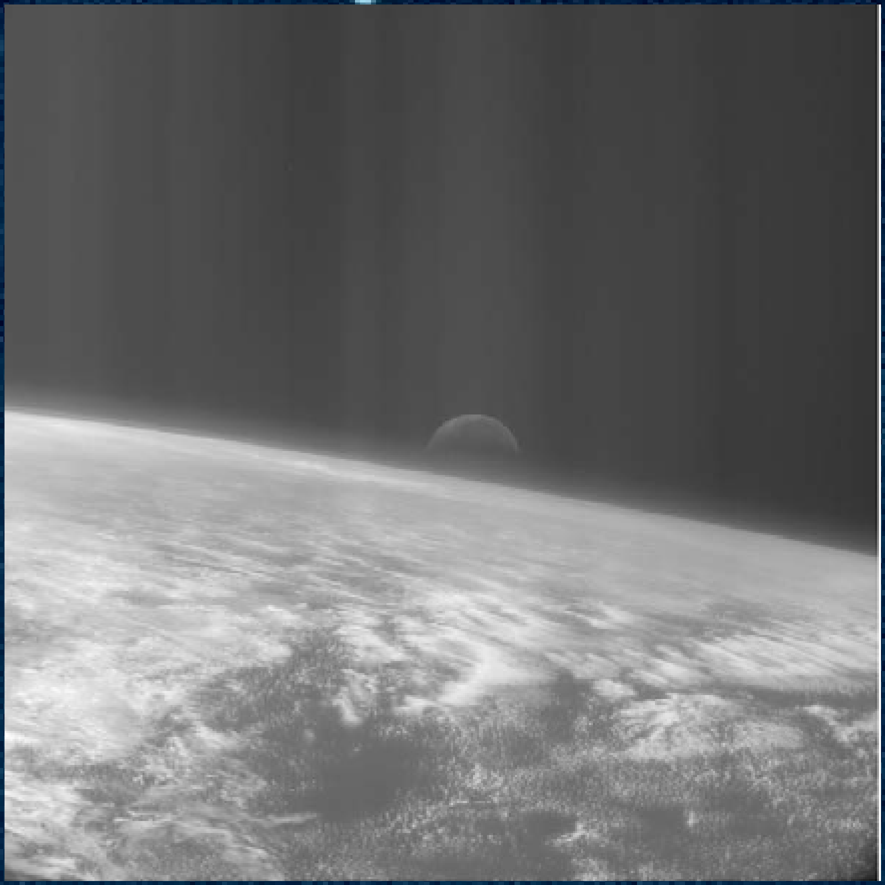
Mars swingby

Feb 25, 2007

Pericentre at 25 February 2007	01:59:04.46 TDB
Pericentre Radius	3648.084 km
Pericentre Velocity	10.053 km/s
Semi-major Axis	-551.986 km
Eccentricity	7.609013
Inclination	156.827º
R.A. of Ascending Node	135.369º
Argument or Pericentre	154.902º
Asymptotic Velocity	8.808 km/s
Semi-deflection Angle	7.552º
Heliocentric: Velocity Vector Change	2.315 km/s
Velocity Magnitude Change	-2.193 km/s
Velocity Direction Change	1.856º



Earth, Mars, asteroid flybys

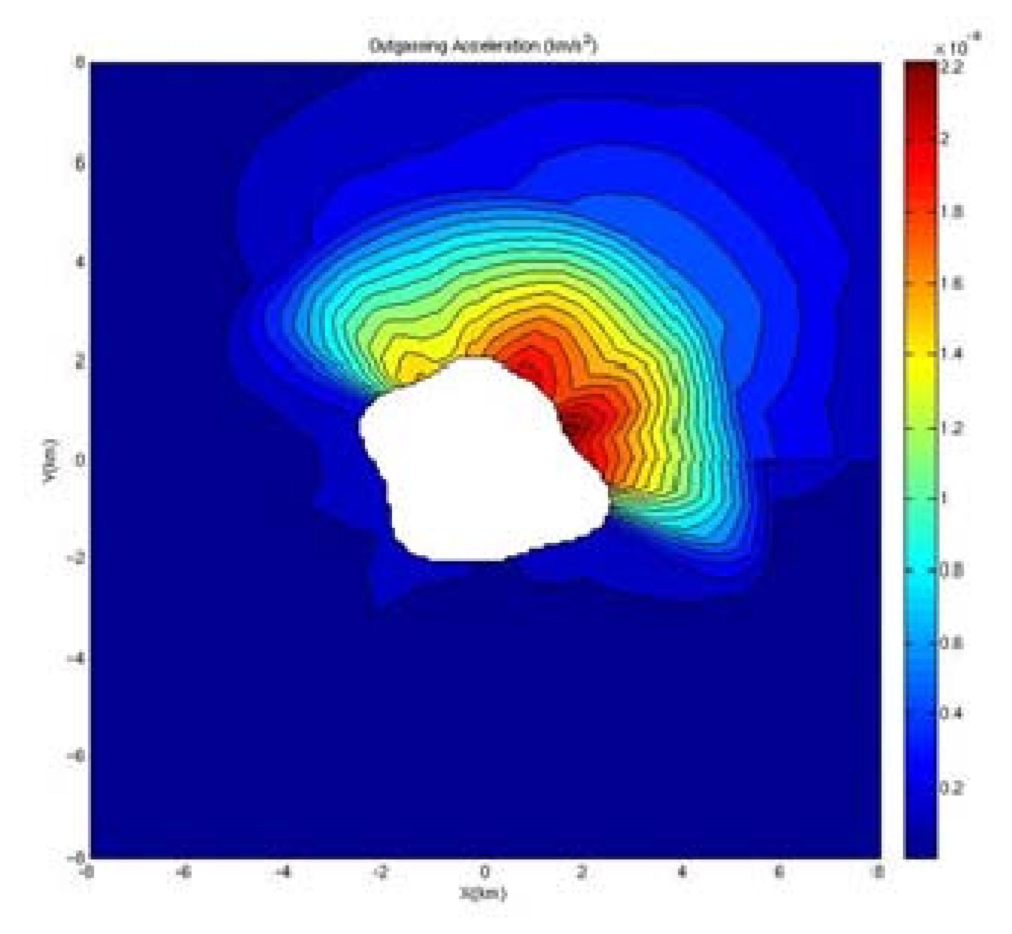


Earth swingby 1: Moonrise

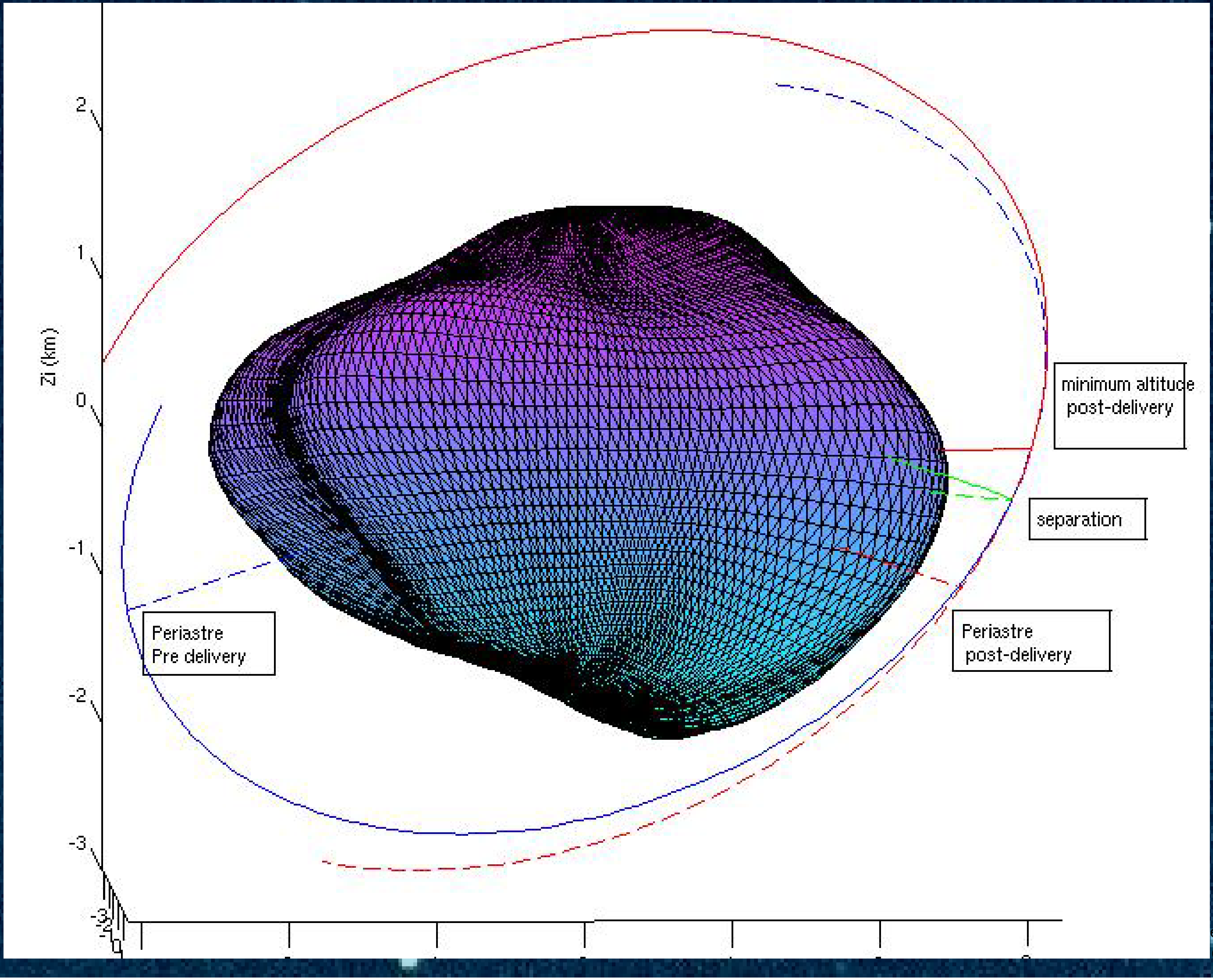
Mars by the Osiris camera

Quasi-orbiting a comet

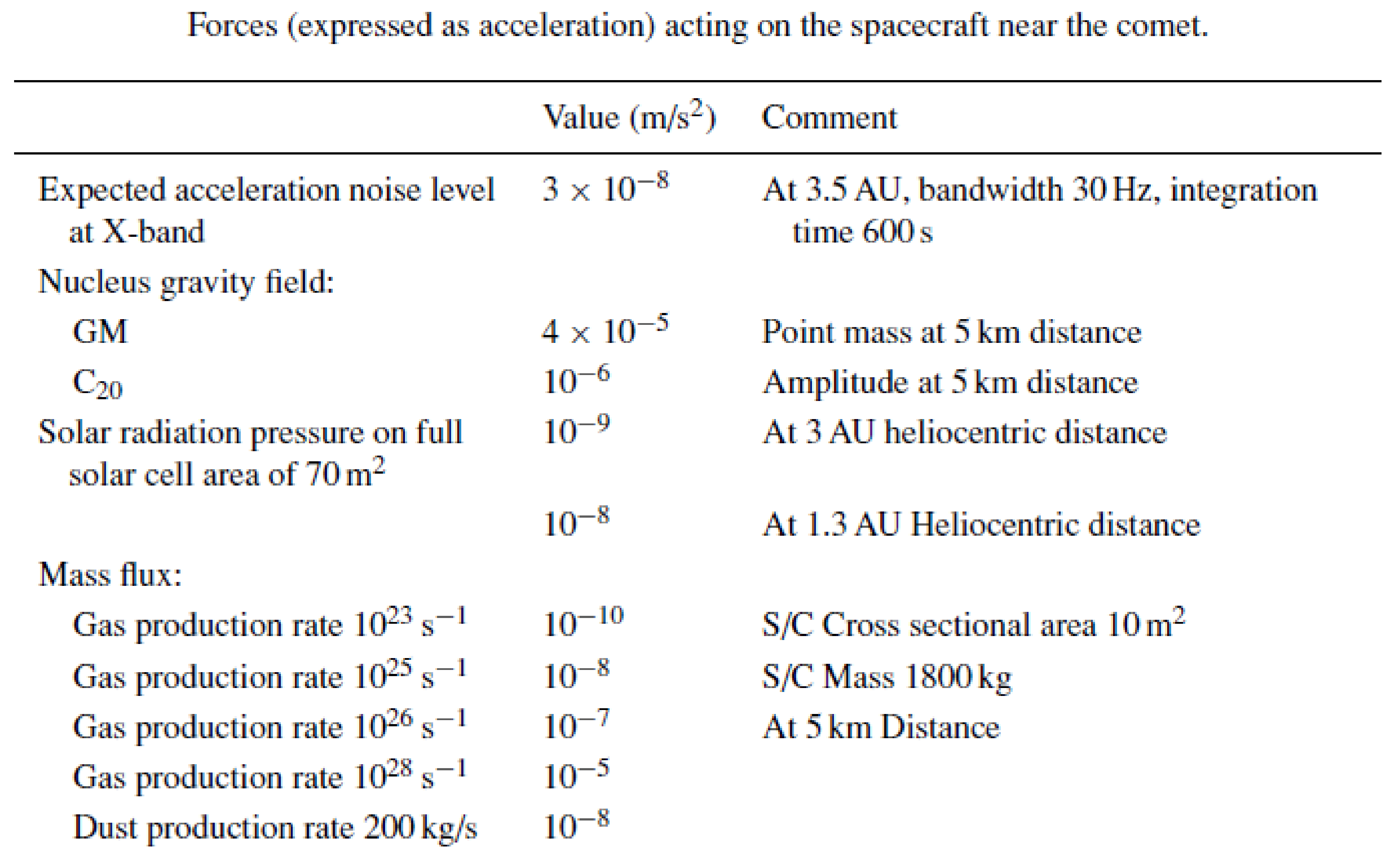
- In contrast to small body flyby missions (e.g., ESA's Giotto miss actually orbit or "qua Hill sphere (hun
- Orb
- Stro and by irregular shap



$$R\left(\frac{1}{3}\frac{M}{M_{Sun}}\right)^{1/3}$$


Zi (km)
2
1
0
-1
-2
-3
minimum altitude post-delivery
separation
Periastre Pre delivery
Periastre post-delivery

Force comparison

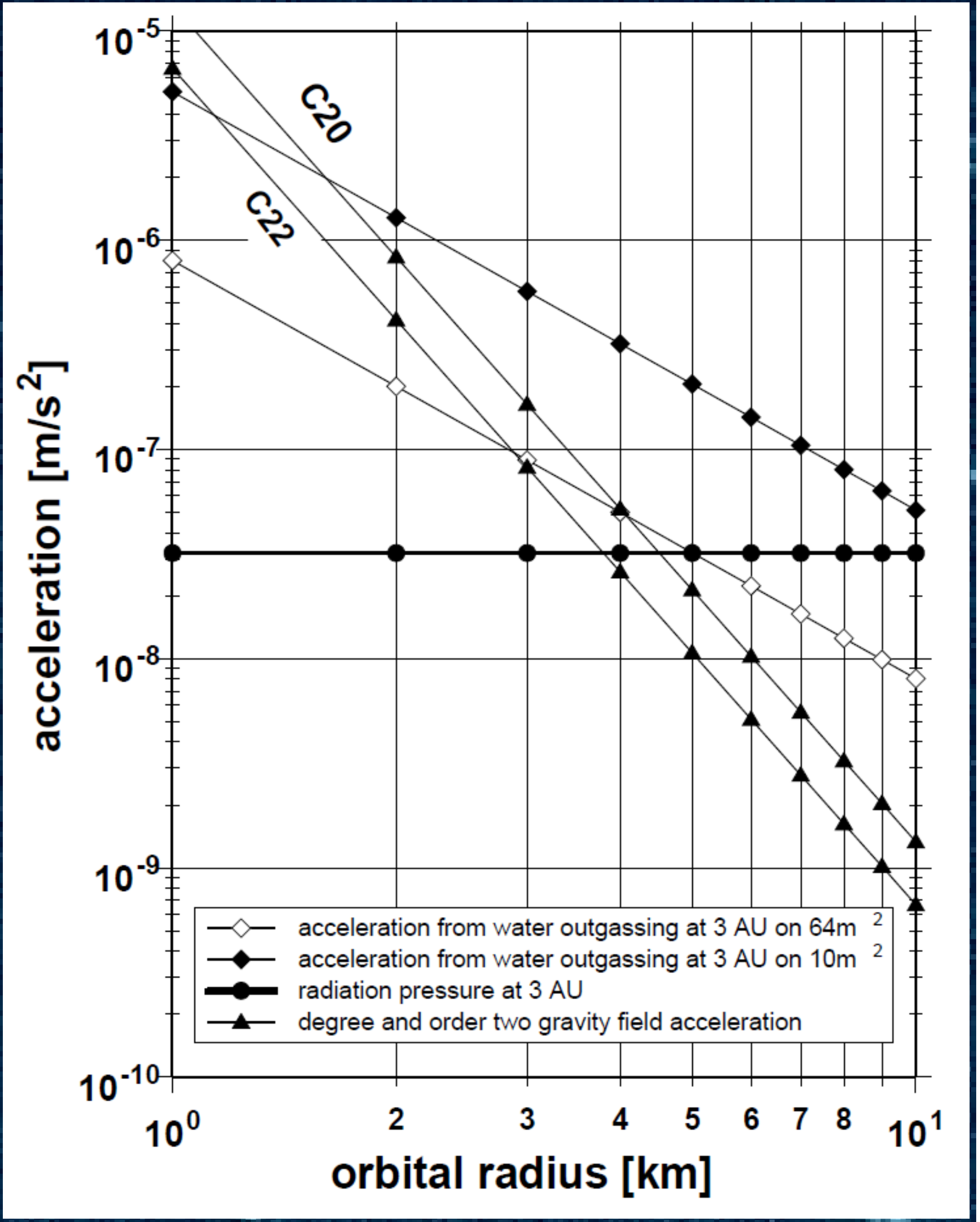


Forces (expressed as acceleration) acting on the spacecraft near the comet.

	Value (m/s^2)	Comment
Expected acceleration noise level at X-band	3×10^{-8}	At 3.5 AU, bandwidth 30 Hz, integration time 600 s
Nucleus gravity field:		
GM	4×10^{-5}	Point mass at 5 km distance
C_{20}	10^{-6}	Amplitude at 5 km distance
Solar radiation pressure on full solar cell area of 70 m^2	10^{-9}	At 3 AU heliocentric distance
	10^{-8}	At 1.3 AU Heliocentric distance
Mass flux:		
Gas production rate 10^{23} s^{-1}	10^{-10}	S/C Cross sectional area 10 m^2
Gas production rate 10^{25} s^{-1}	10^{-8}	S/C Mass 1800 kg
Gas production rate 10^{26} s^{-1}	10^{-7}	At 5 km Distance
Gas production rate 10^{28} s^{-1}	10^{-5}	
Dust production rate 200 kg/s	10^{-8}	

Gravity field

- Strong perturbations by the comet's irregular shape and drag by the outgassing (coma) are expected and will limit the accuracy to which the gravitational field can be retrieved - depending on activity (only second harmonics C20, C22 may be retrievable).
- Since comets are believed to be rather homogeneous in density, an accurate semi-empirical gravity field (down to the surface) will be computed, using the optical shape model, constant density and considering a few mascons if necessary.



Mass estimate of 2867 Steins and 21 Lutetia using flybys

Steins (800 km): no detection (no surprise, only 5 km body)

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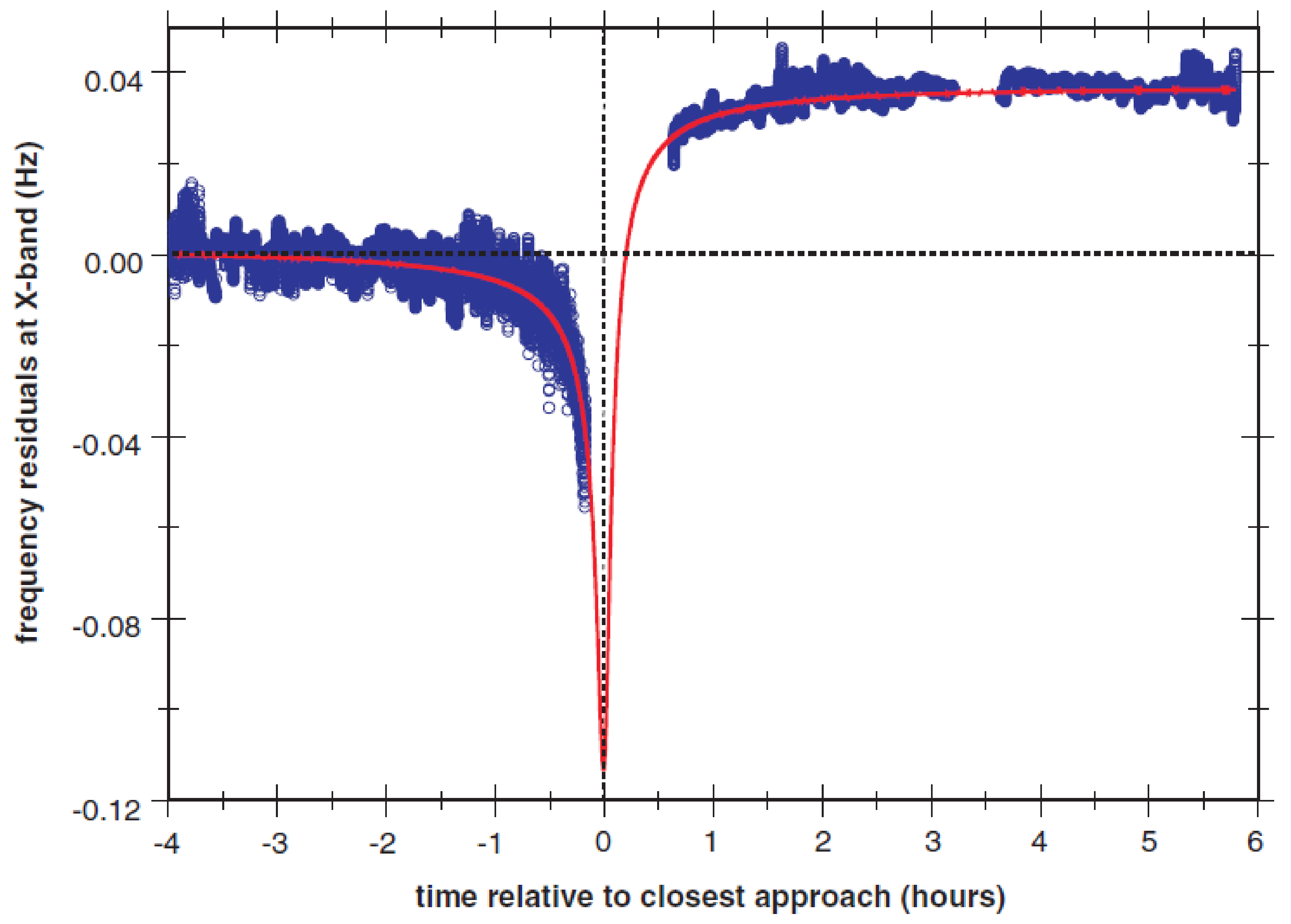


Filtered and adjusted frequency residuals at X-band frequency from 4 hours before closest
approach to 6 hours after closest approach. The red solid line is a least-squares fit to the data from which GM is determined.

Radio communications and navigation

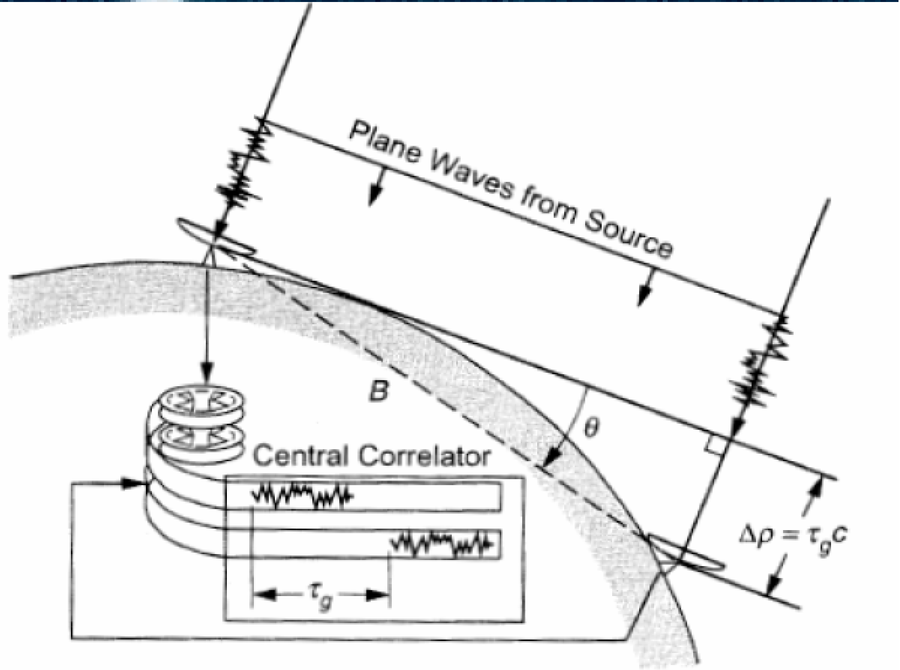
- RF communications with ground stations on Earth is in X and S band; together with an ultra-stable oscillator on board the spacecraft, accurate tracking (range, range-rate) is possible. Navigation will further be aided by DDOR. Of course, no GPS-like navigation system exists hitherto for interplanetary spaceflight, and active laser ranging is in its infancy.
- MEX doppler&ranging: rms 200 m (similar to orbit uncertainty)
- 2way ranging X-band to 1 m
- Doppler to 0.1 mm/s
- delta differential one-way ranging (delta-DOR) became mandatory for accurate orbit determination prior to critical maneuvers like planetary flybys or orbit insertions
- Delta-DOR is a deep-space navigation technique making use of at least two largely separated ground stations, receiving simultaneously in open-loop the signal transmitted from a deep-space probe and, for calibration purposes, from a radio source (e.g., a quasar)

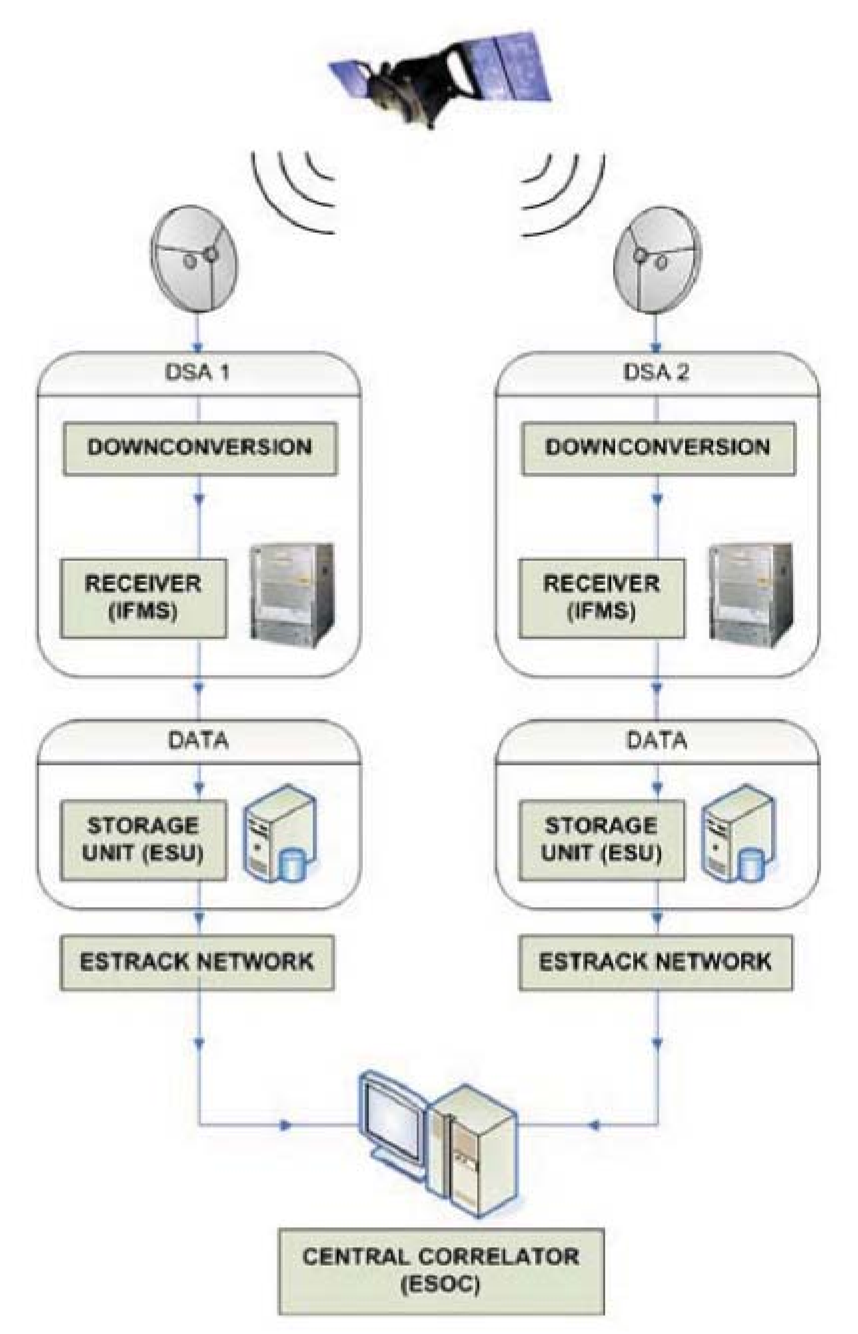
Radio science

- RSI using USO for one-way ranging and Doppler (M. Pätzold, RIU Köln)
- simultaneous and coherent dual-frequency downlinks via the High Gain Antenna (HGA) permit separation of contributions from the classical Doppler shift and the dispersive media effects
- scientific objectives of the gravity field investigations are the determination of the mass and bulk density of the nucleus, the low degree and order harmonic coefficients of the gravity field, the cometary moments of inertia, and the nongravitational forces acting on the nucleus

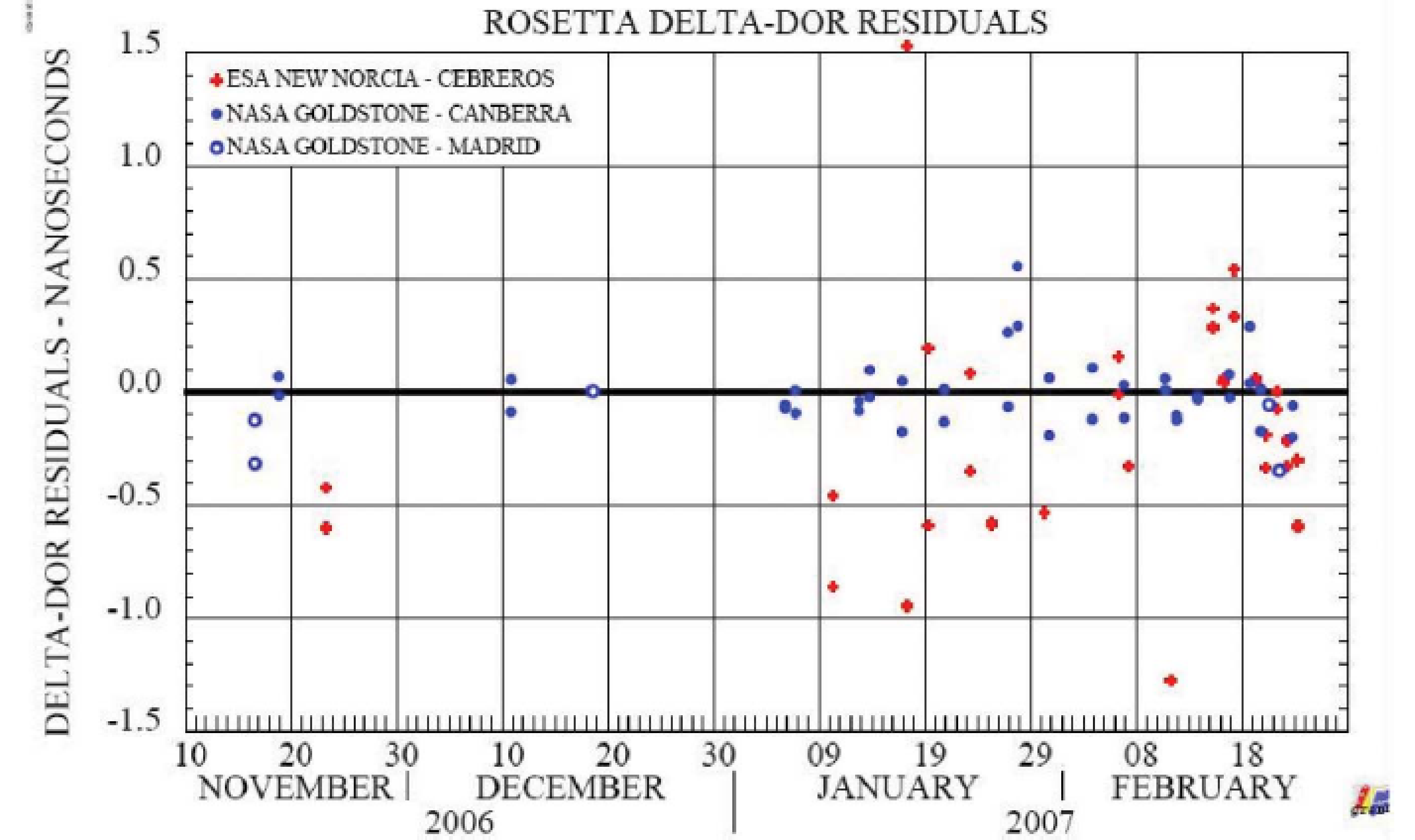
DDOR

It provides a direct measurement of one coordinate of Rosetta's position in the plane-of-sky which is a perfect complement to the line-of-sight Doppler and range measurements.





DDOR results for Rosetta 2006/2007

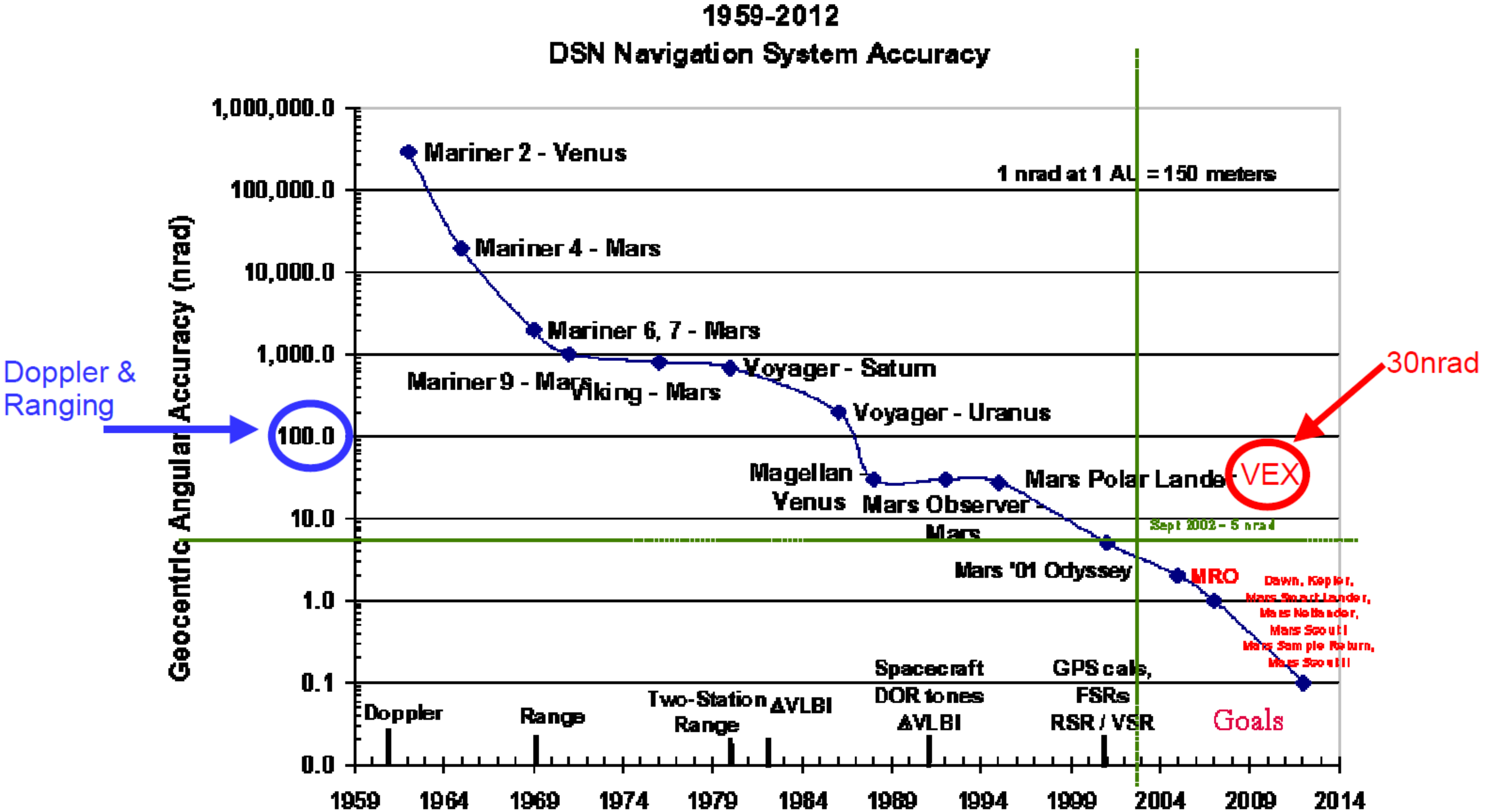


- DDOR results for Rosetta. RMS=0.53 ns /ESA, 0.16 ns /NASA, translates into ~10 nrad or a few km at SC.

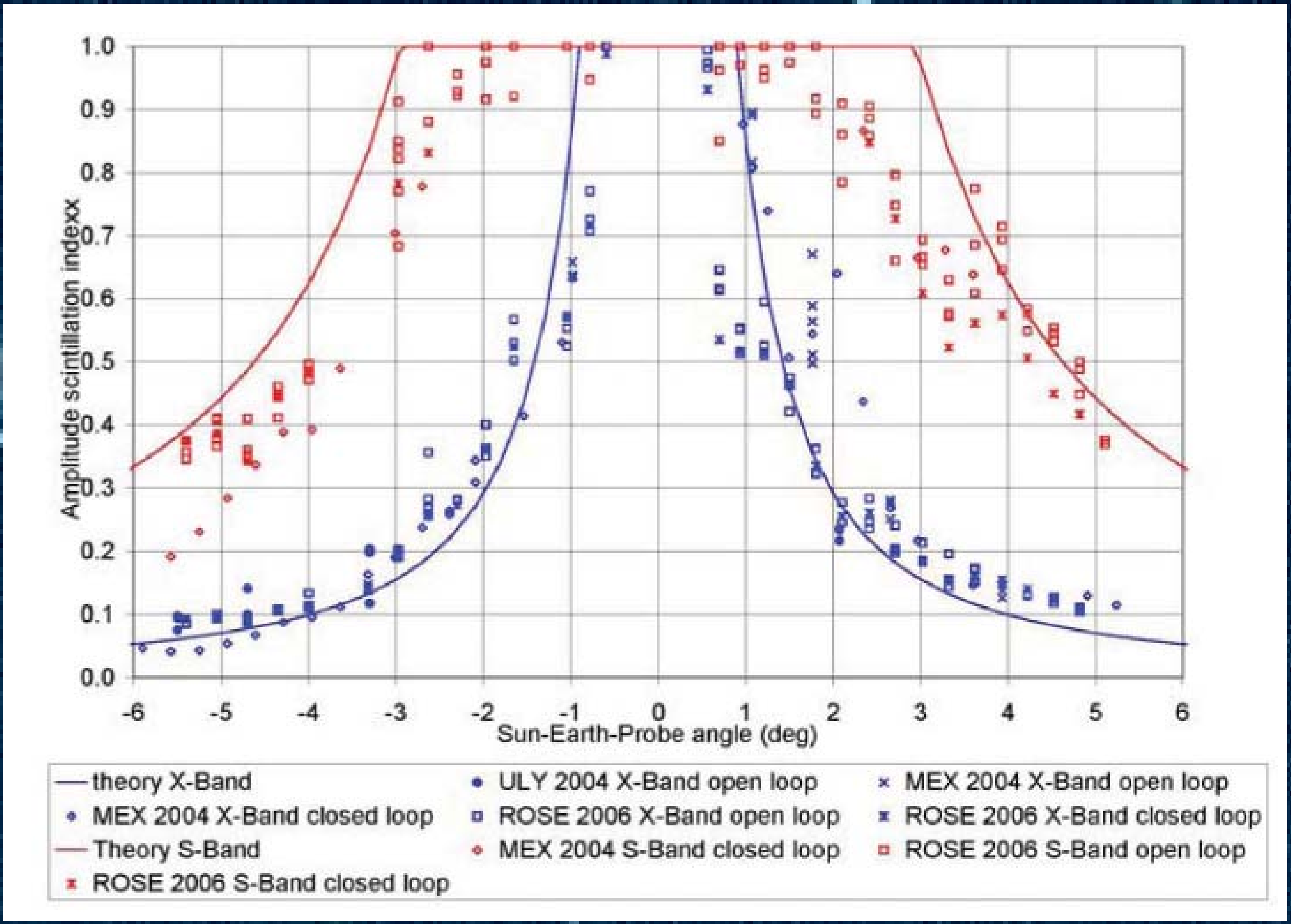
Plane-of sky coordinate improvement by DDOR

- If only conventional Doppler and range tracking data were available then no direct measure of the plane-of sky components would have been available.
- In this case the plane-of-sky information has to be deduced solely from the diurnal sinusoidal modulation of the Earth rotation on the range and Doppler data over a pass.
- Phase of the modulation is directly related to the spacecraft’s geocentric right ascension and the amplitude to the spacecraft’s geocentric declination.
- Typical accuracies 50 to 100 nrad only
- DDOR 5-10 nrad

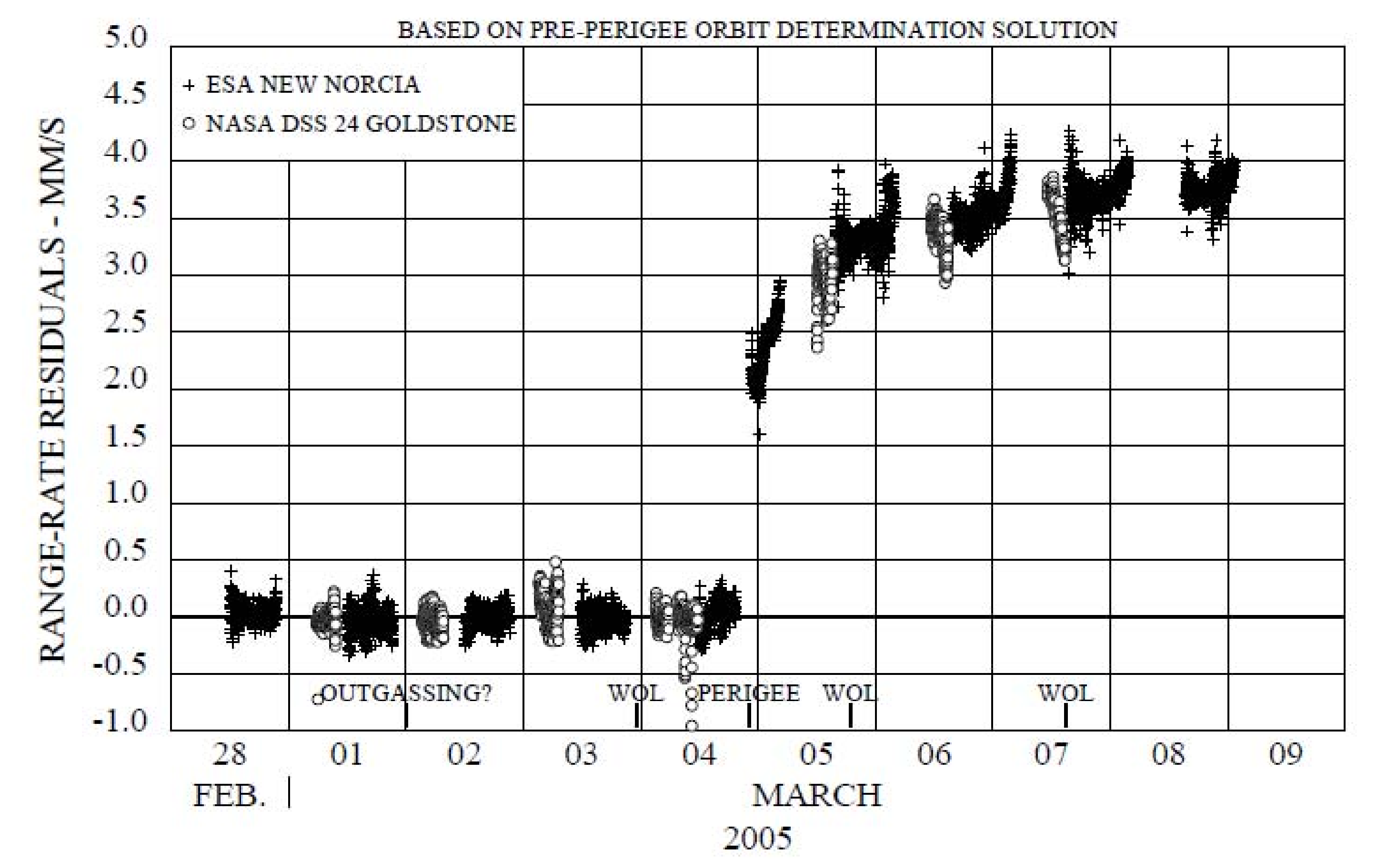
Interplanetary navigation accuracy from 1960 to 2011



Solar conjunctions



The flyby anomaly – new physics?



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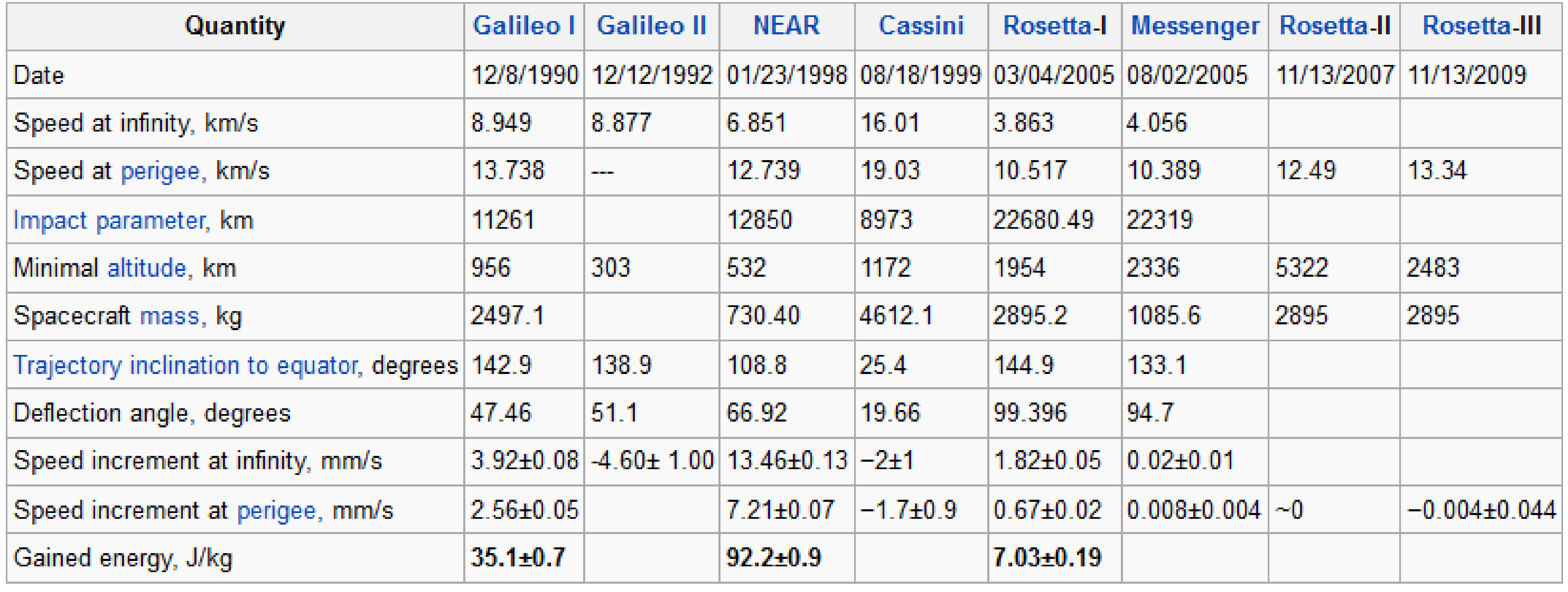
Post-fit 2-way S-Band range-rate residuals - with post-perigee data zero-weighted

Measurement overview flyby anomaly



Quantity	Galileo I	Galileo II	NEAR	Cassini	Rosetta-I	Messenger	Rosetta-II	Rosetta-III
Date	12/8/1990	12/12/1992	01/23/1998	08/18/1999	03/04/2005	08/02/2005	11/13/2007	11/13/2009
Speed at infinity, km/s	8.949	8.877	6.851	16.01	3.863	4.056		
Speed at perigee, km/s	13.738	---	12.739	19.03	10.517	10.389	12.49	13.34
Impact parameter, km	11261		12850	8973	22680.49	22319		
Minimal altitude, km	956	303	532	1172	1954	2336	5322	2483
Spacecraft mass, kg	2497.1		730.40	4612.1	2895.2	1085.6	2895	2895
Trajectory inclination to equator, degrees	142.9	138.9	108.8	25.4	144.9	133.1		
Deflection angle, degrees	47.46	51.1	66.92	19.66	99.396	94.7		
Speed increment at infinity, mm/s	3.92±0.08	-4.60± 1.00	13.46±0.13	−2±1	1.82±0.05	0.02±0.01		
Speed increment at perigee, mm/s	2.56±0.05		7.21±0.07	−1.7±0.9	0.67±0.02	0.008±0.004	~0	−0.004±0.044
Gained energy, J/kg	**35.1±0.7**		**92.2±0.9**		**7.03±0.19**			

Special relativiy effect? Software bug?

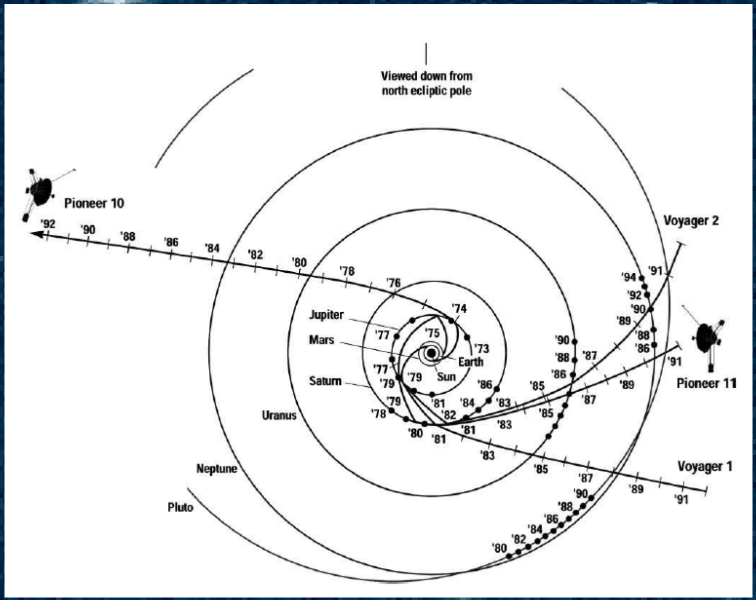
Flyby anomaly possible causes

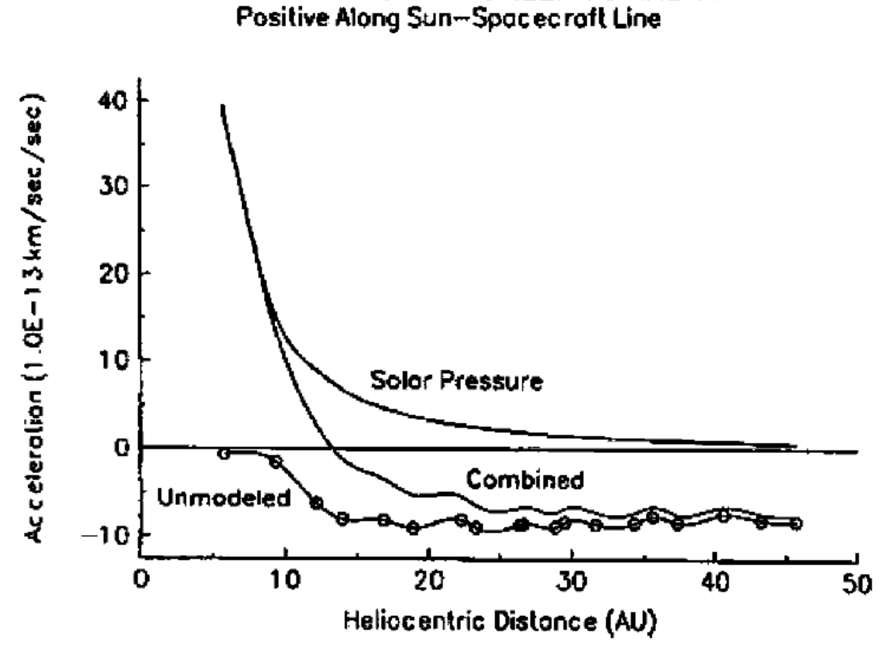
- The anomalous acceleration occurring in Earth flybys is of the order of 10^{-4}m/s^2 - much larger than the Pioneer anomaly.
- Acceleration phase seems to last only some few minutes.
- Standard error analysis (atmosphere / ocean tides / solid earth tides / charging of the spacecraft / magnetic moment / earth albedo / solar wind ...) gives no hint to the origin of the anomaly.
- No consistent explanations from ”new physics” (modifications of relativity etc) yet.
- Fitting formula (JPL) $\frac{\Delta V}{V} = \frac{2\omega_e R_e(\cos\varphi_i - \cos\varphi_o)}{c}$ does not explain

  Rosetta 2007 and 2009 flybys → dead

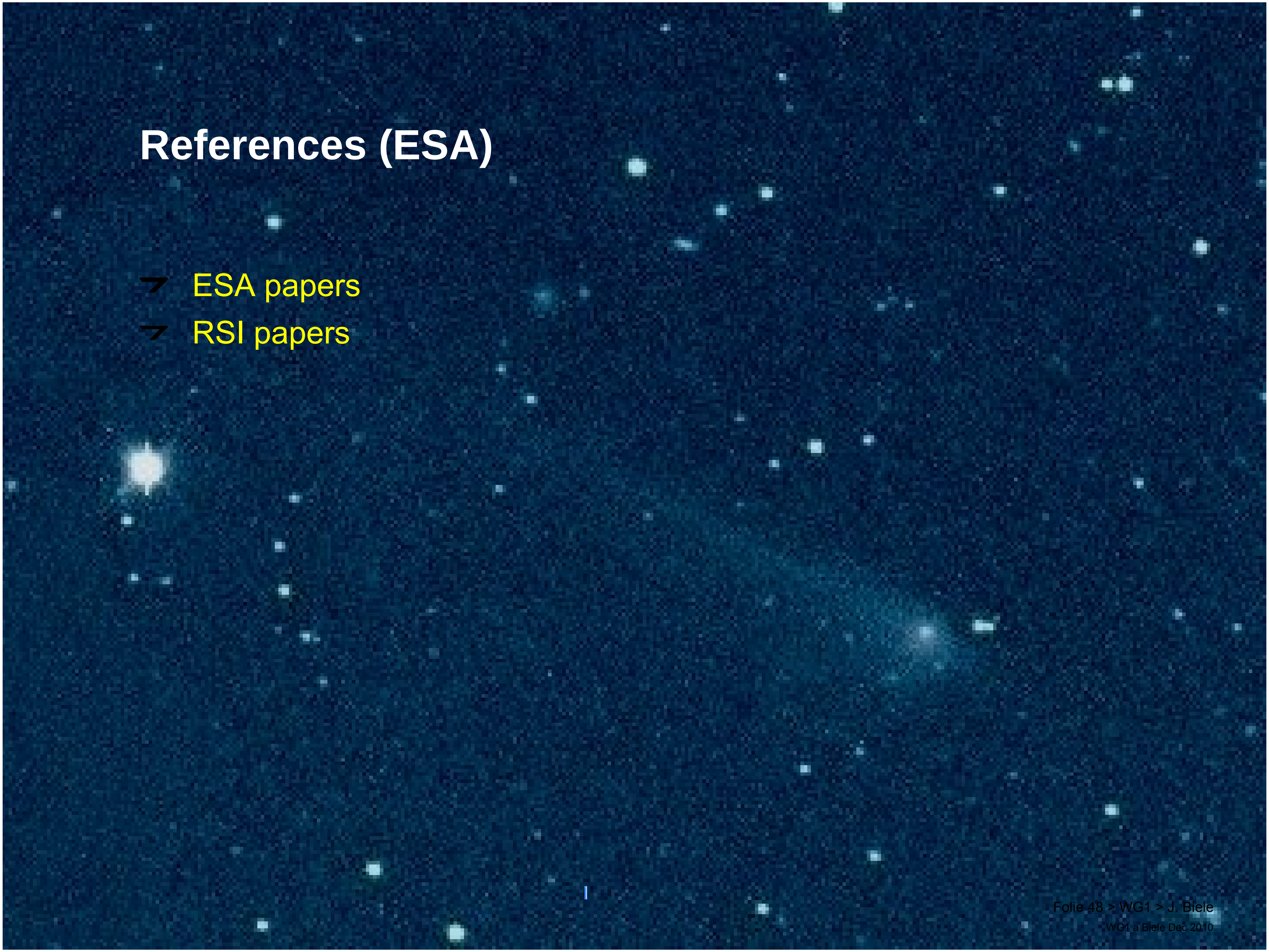
Pioneer anomaly

- sunward direction acceleration of 8.7E-10 m/s² observed with Pioneer 10,11 spacecraft (Anderson, 2002) - slowing SC down (400 km in 1 year)
- Observed only in outer solar system Probably not really new physics although a=H*c…
- Solved 2011: thermal pressure!





References (ESA)



- ESA papers
- RSI papers