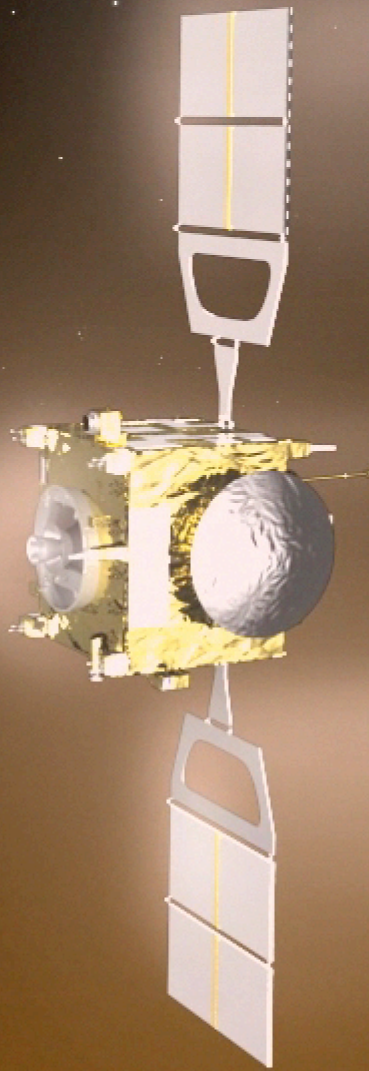


Venus Express Aerobraking Results

Håkan Svedhem
ESA/ESTEC

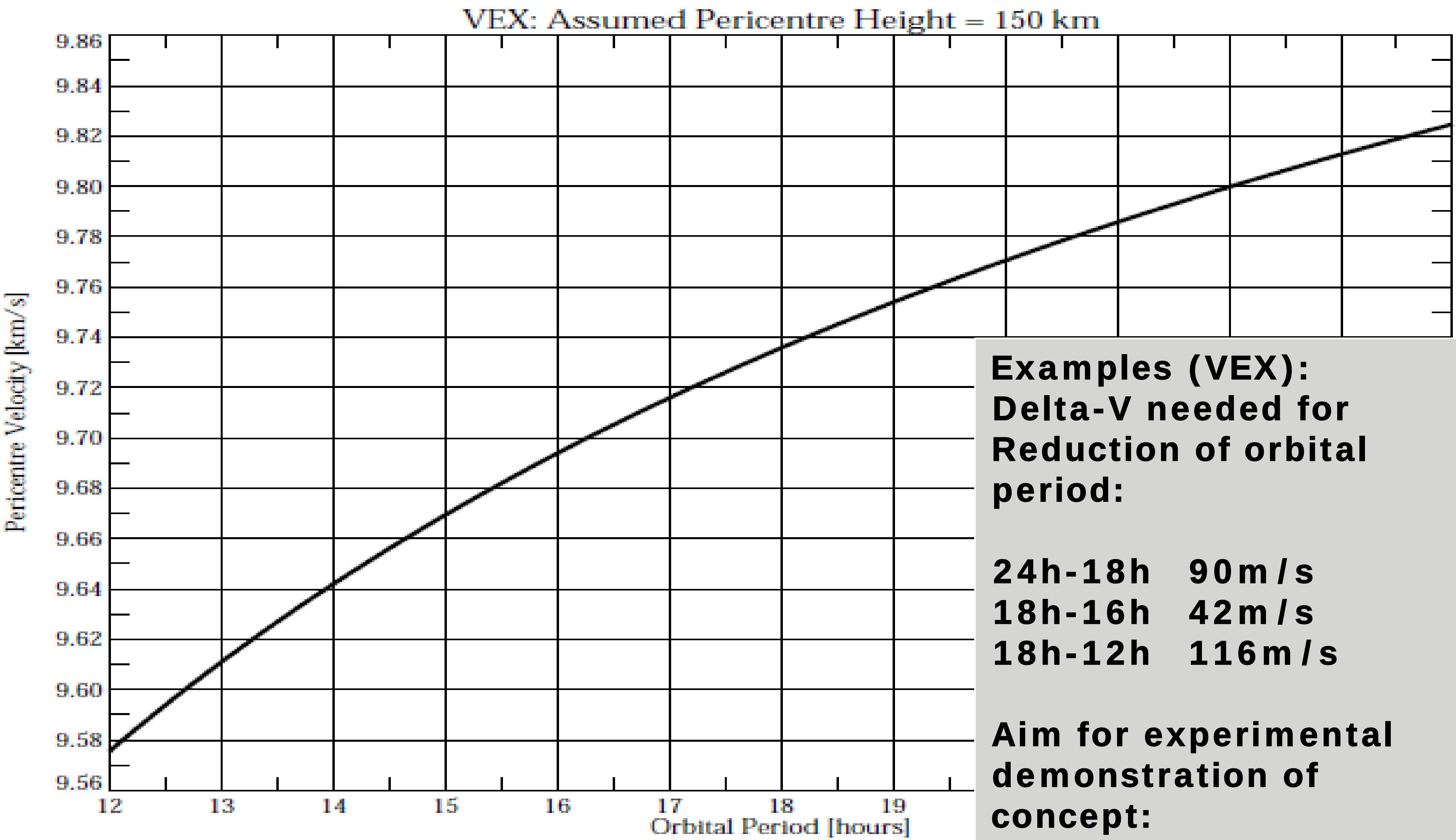
What is aerobraking?

1. Using the drag of atmosphere against the spacecraft body in order to reduce spacecraft speed. This will result in a lower apocenter altitude and a shorter orbital period. This will enable significant savings of fuel to reach an operational orbit and so enable new classes of missions.
2. The major limiting factors in aerobraking are the capability to maintain a stable attitude during the aerobraking, and the capability to withstand the dynamic loads and the aerothermal heat flux. All elements that related to the s/c design.
3. For the operations it is of great importance to ensure that the aerobraking is entered with the correct spacecraft attitude, therefore any safe modes should be avoided during this periods.

Specific points for Venus Express

1. Venus Express has a body/solar array layout that results in a dynamically stable attitude.
2. A software mode to operate the spacecraft is during aerobraking is a part of the on board software. Aerobraking was initially foreseen as a backup in case the Venus orbit insertion would fail, however it was never intended to be used as a part of the nominal mission. Only limited testing of this has been performed.
3. The most limiting factor on Venus Express is likely to be the aerothermal heat input on the Multi Layer Insulation on the –Z platform.
4. The uncertainty and variable character of the Atmosphere.

Pericentre velocity vs Orbital Period

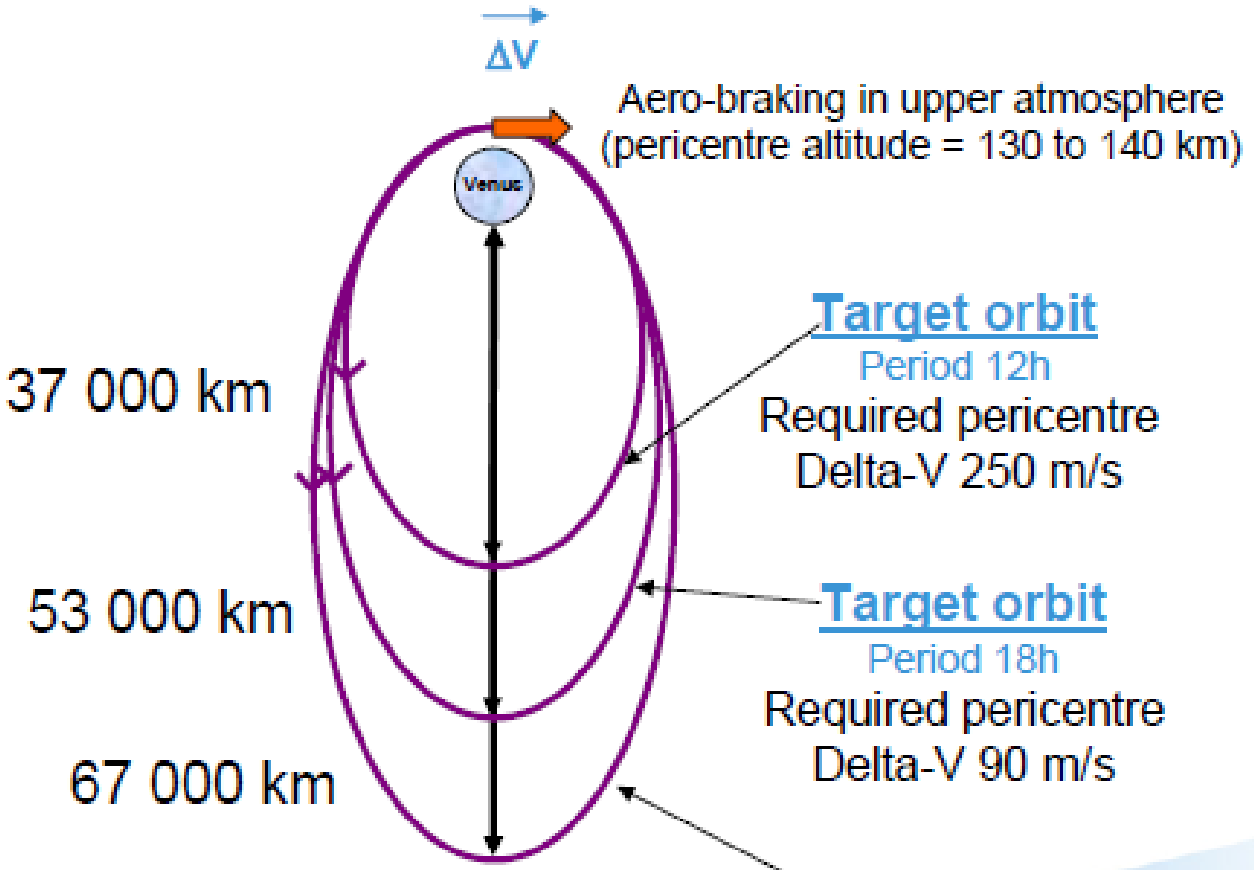


Examples (VEX):
Delta-V needed for Reduction of orbital period:

24h-18h 90m/s
18h-16h 42m/s
18h-12h 116m/s

Aim for experimental demonstration of concept:
24h-23h 12 m/s

Reducing Apocentre altitude



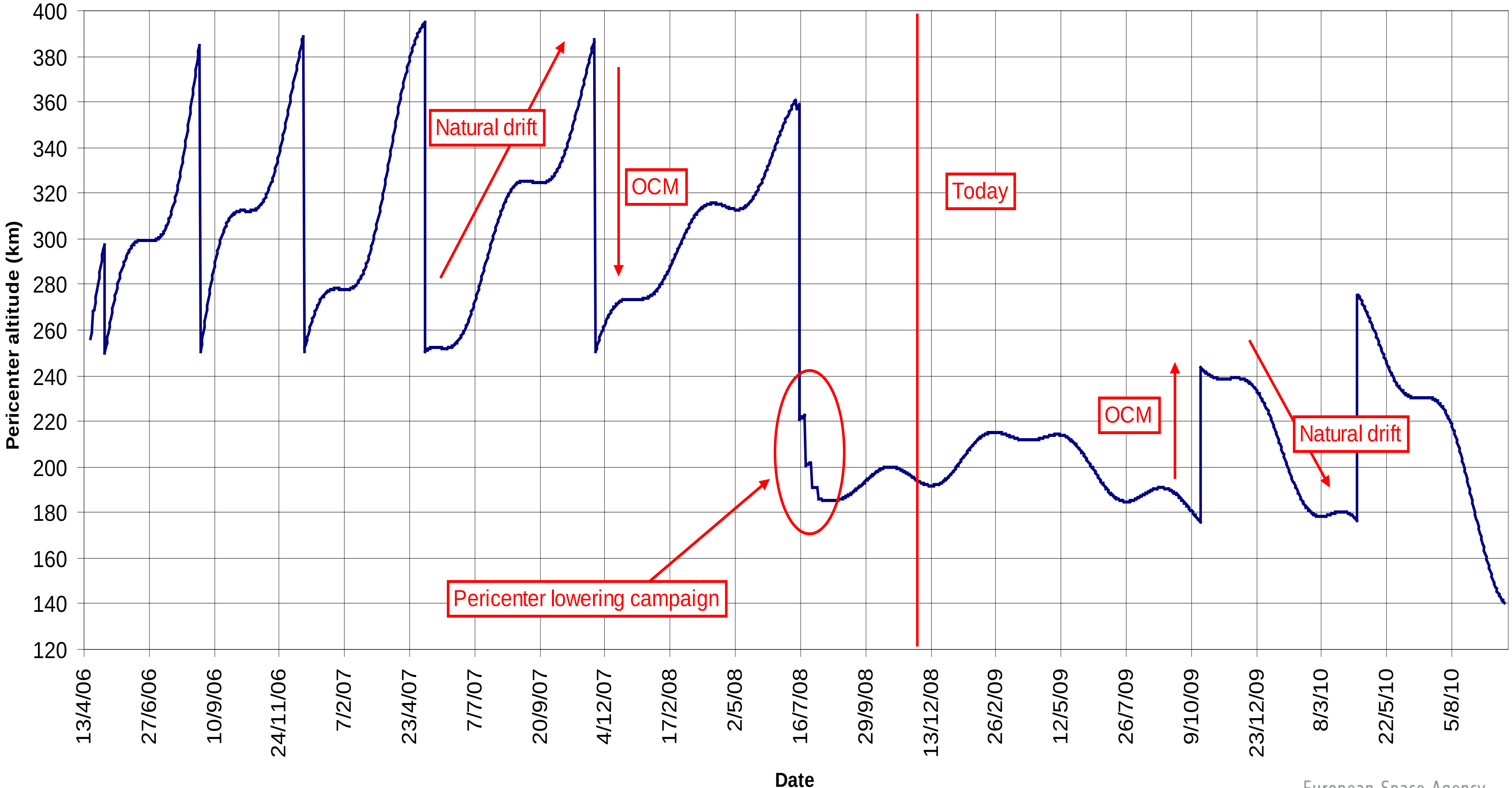
Venus Express Aerobraking

1. A reduction of the orbital period and apocentre altitude was discussed in 2010 in order to,
    a. Achieve new opportunities for science observations in new orbit, lower/shorter than the present 24 h orbit
    b. Reduce the pericentre downward drift and so save fuel and extend the operational life of the mission
2. At a review in 2011 it was considered that aerobraking would be too risky to carry out as a part of the active science mission and it was recommended to carry it out as an end of mission activity.
3. Estimates of the amount of remaining fuel in 2013 showed that we may run out of fuel mid 2014.
4. Being near the end of the mission it was decided to execute an experimental aerobraking in June/July 2014.

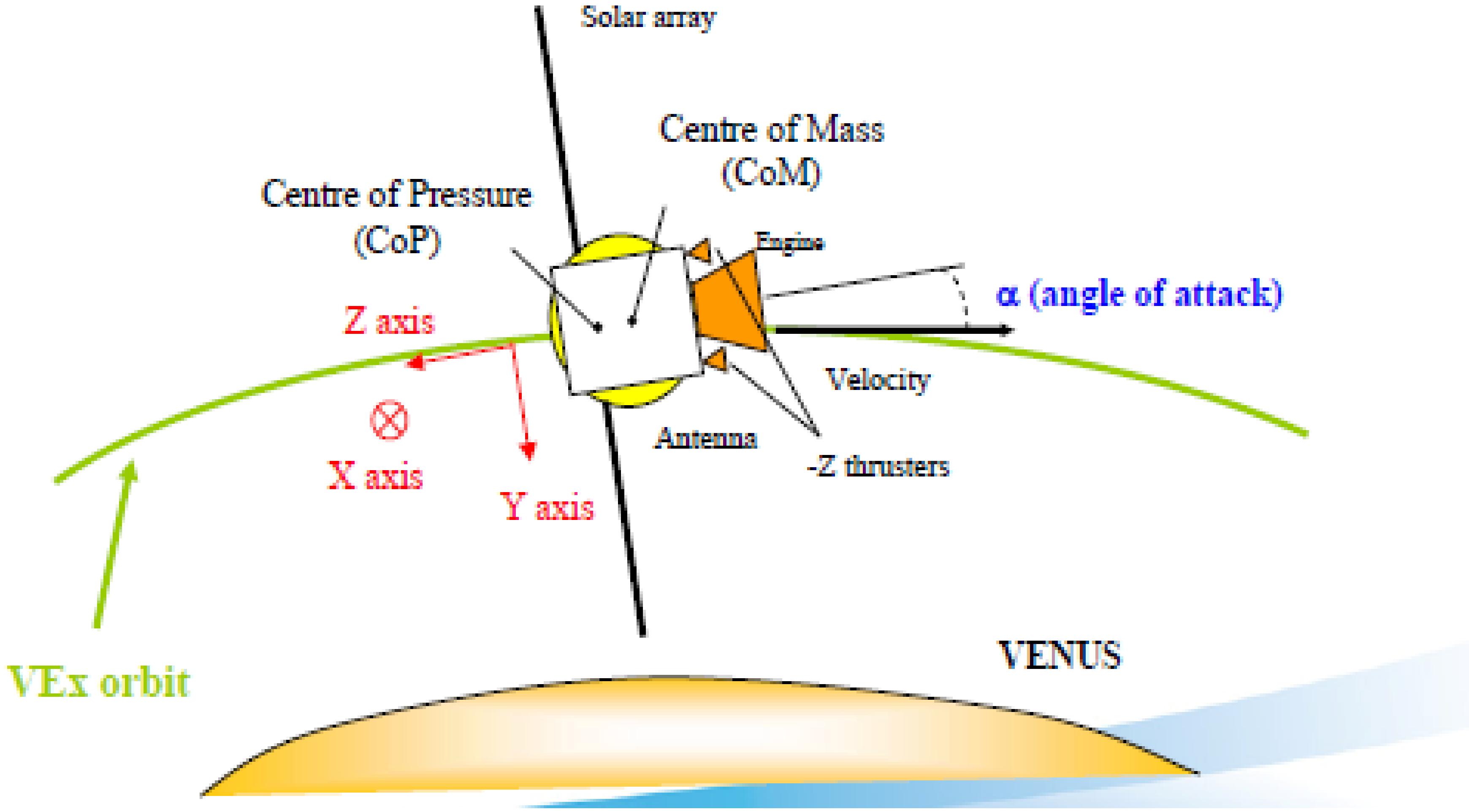
What about the fuel?

1. Why does VEX run out of fuel before MEX?
   a. The orbit of VEX takes the spacecraft out to 66000 km away from the planet. Here the orbit is only loosely bound to Venus and strongly affected by the gravity of the sun. At this phase of the mission this leads to a reduction of the pericentre altitude. MEX has a much lower apocentre distance and it much farther form the Sun and therefore do not suffer form this effect.
2. How is the amount of remaining fuel measured?
   a. By summing up the time the thrusters and the main engine have operated and multiplying by a factor. This number is then subtracted from the fuel mass at launch. - Uncertain!
   b. A special test, heating up the tanks and following the thermal response up and down, the thermal inertia of tank/fuel was estimated. Then the amount of fuel can be calculated.- Uncertain!

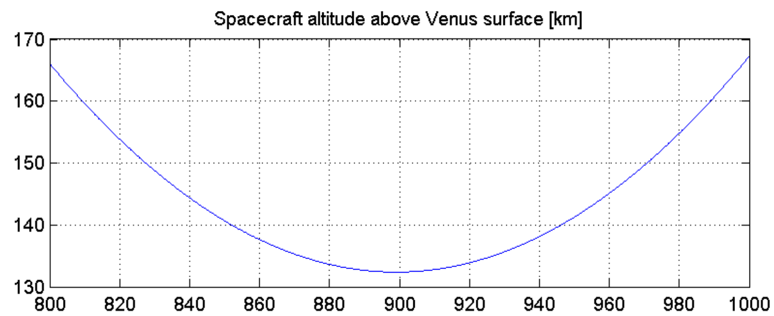
Pericentre altitude evolution

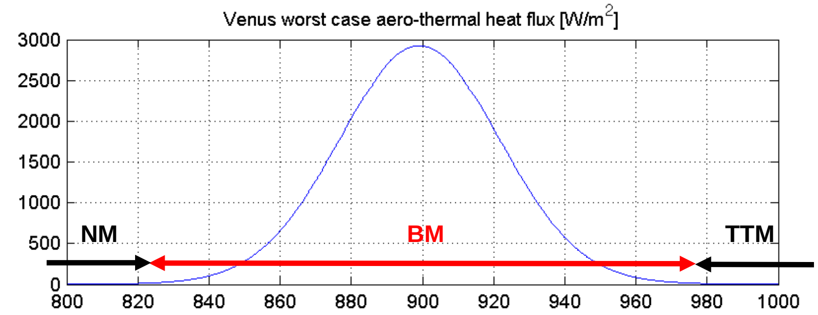


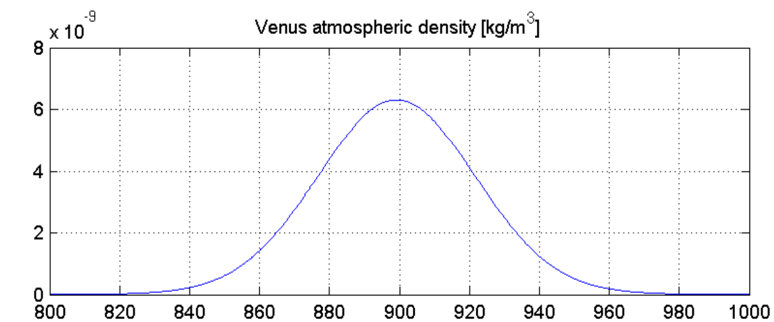
Aerobraking configuration

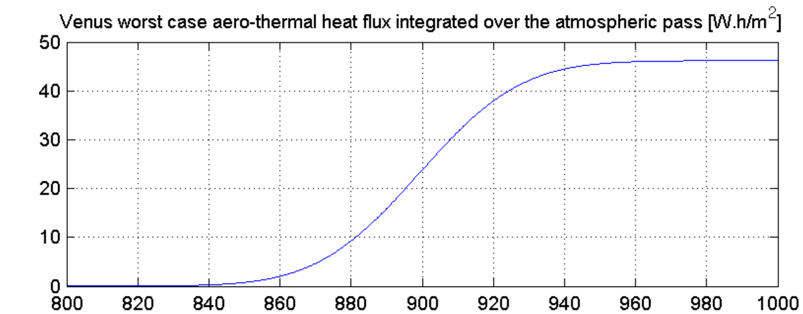


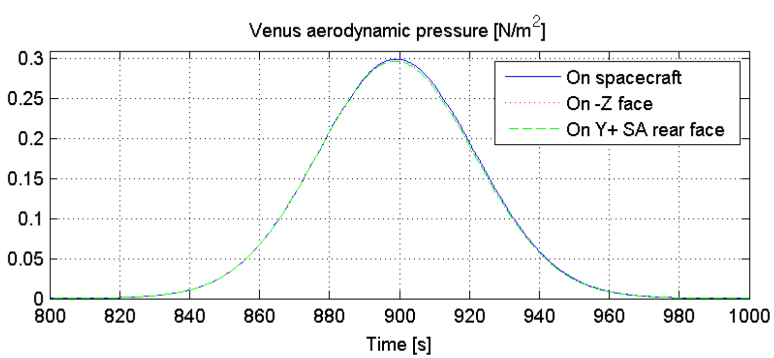
Parameters to consider

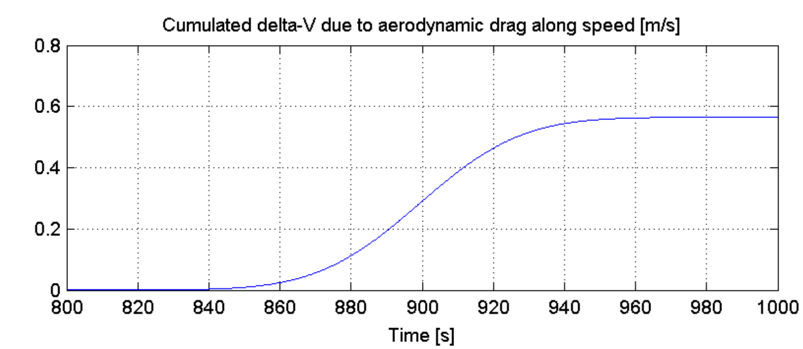








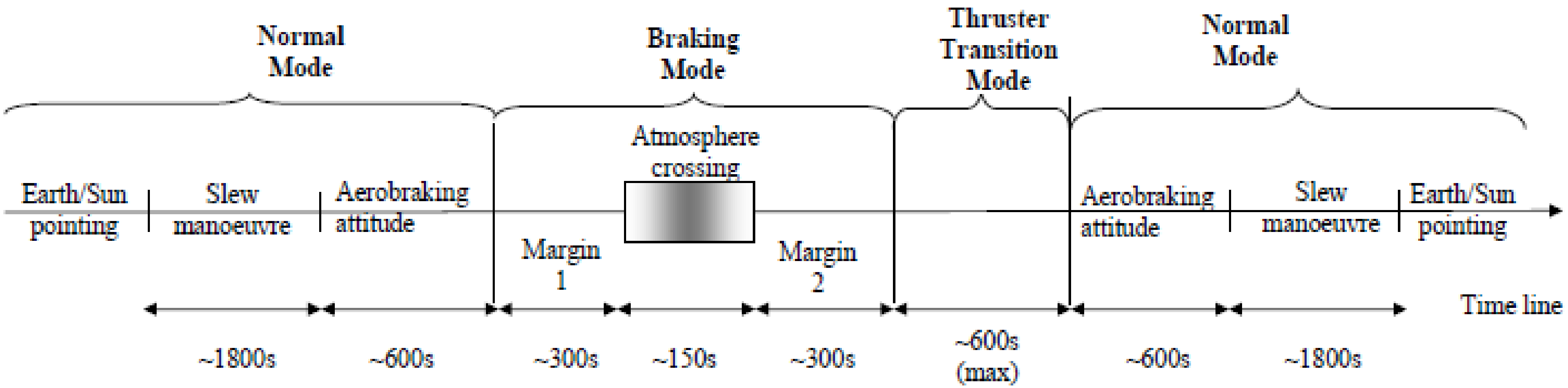




Relation of key parameters

Peak aerodynamic pressure		Aerodynamic delta-V (m/s)	Thruster delta-V in BM & TTM (m/s)	Delta-V over one plateau (m/s)
1	0.08 N/m²	0.16	0.007	5
2	0.20 N/m²	0.38	0.008	12
3	0.32 N/m²	0.60	0.007	18
4	0.40 N/m²	0.76	0.007	23
5	0.50 N/m²	0.95	0.006	29

Aerobraking sequence

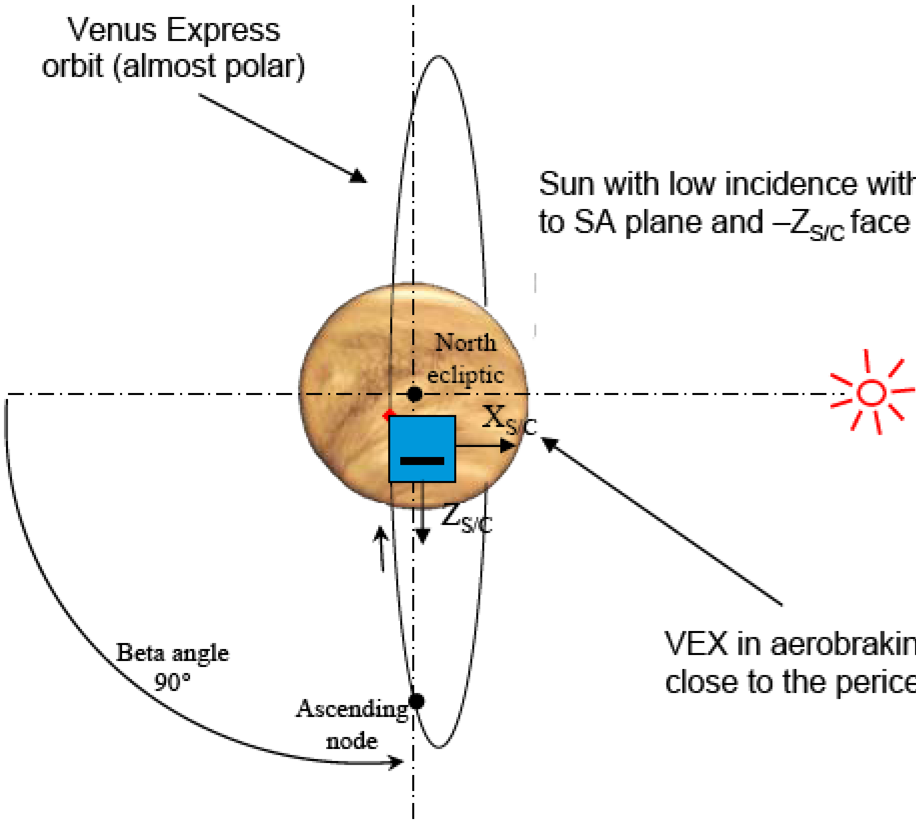


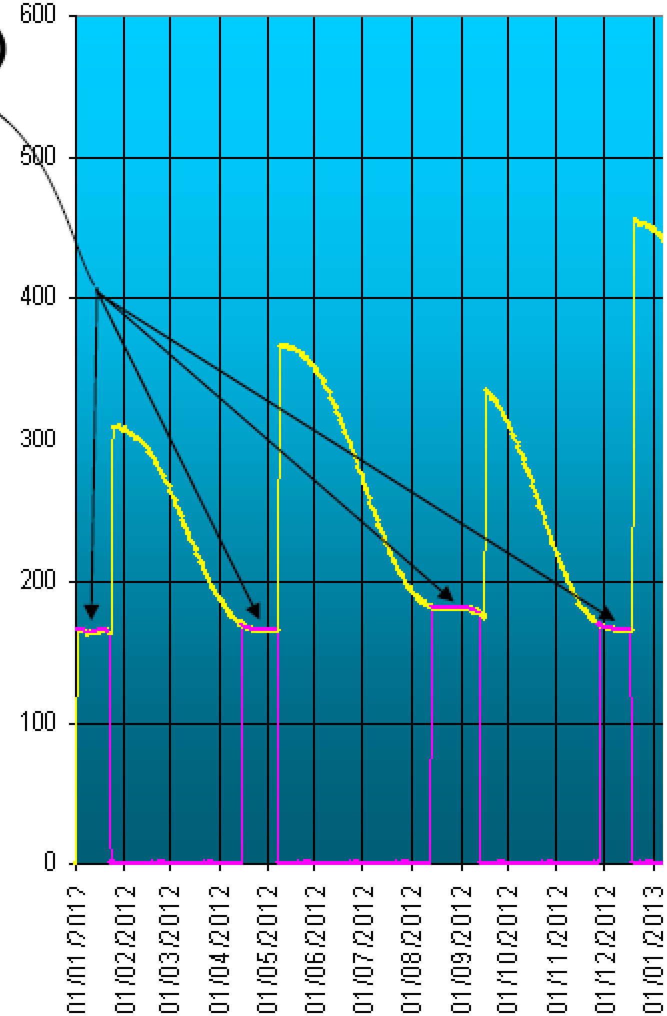
Optimum conditions for aerobraking at Venus

Reference case = most favourable conditions for Sun Aspect Angle allowing a Heat Flux of about 3000 W/m2 <> Dynamic Pressure of 0.3 N/m2.

→ Sun at 90° from the VEX orbit plane **(Beta Angle)**

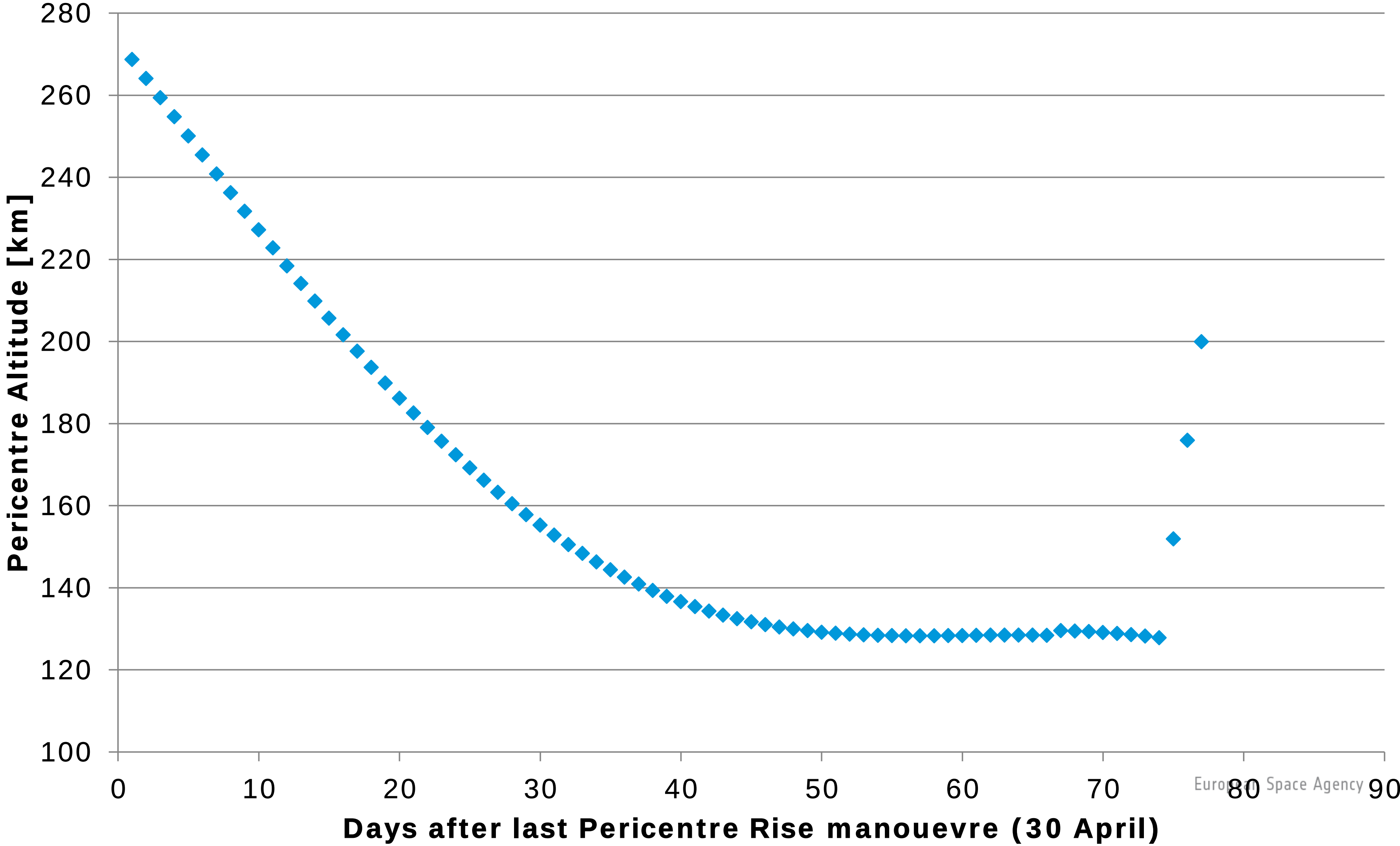
→ ß= 90° <> Middle of Plateaus



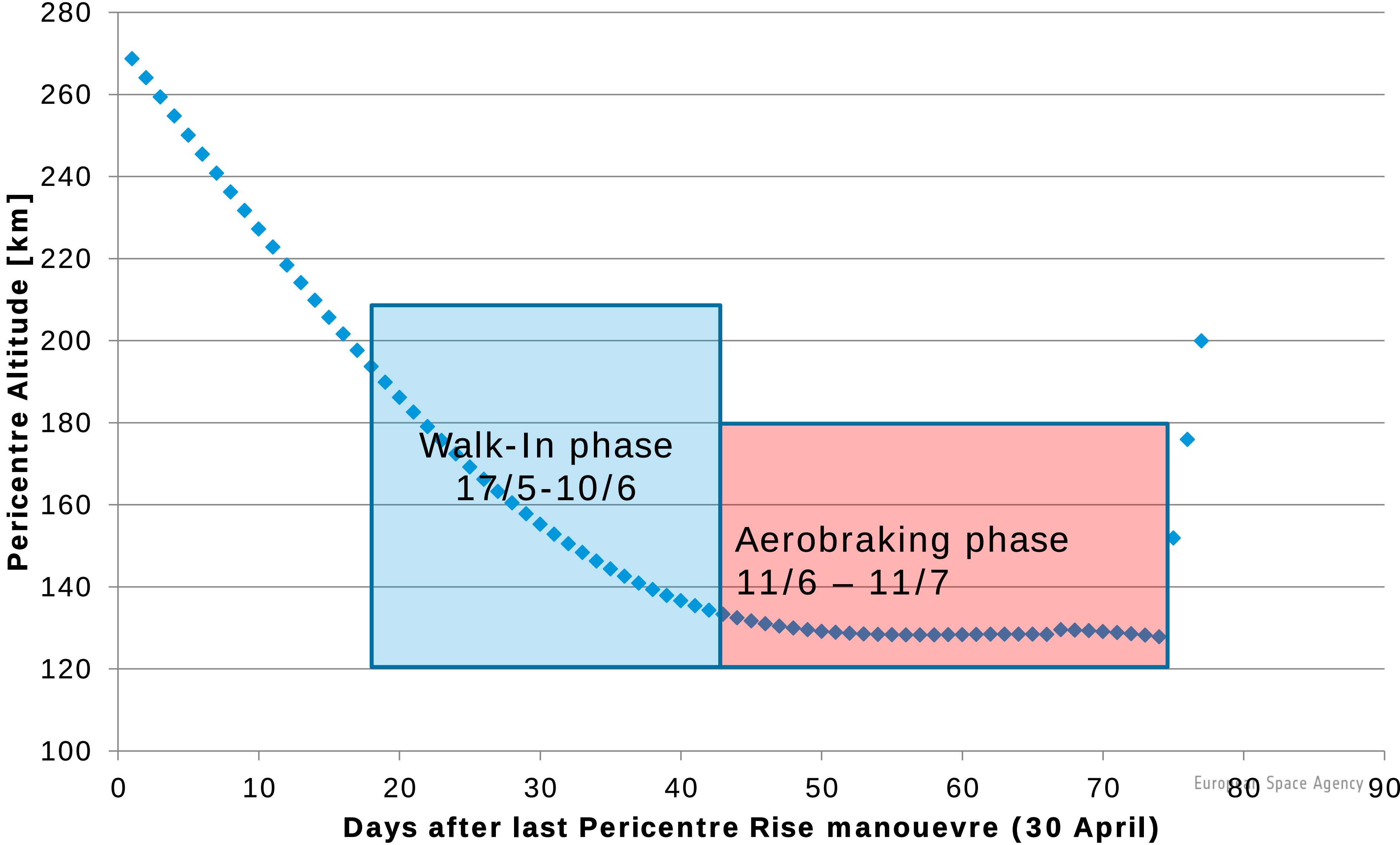


View from above Venus orbit plane

Pericentre Altitude [km]



Pericentre Altitude [km]



Preparation for aerobraking

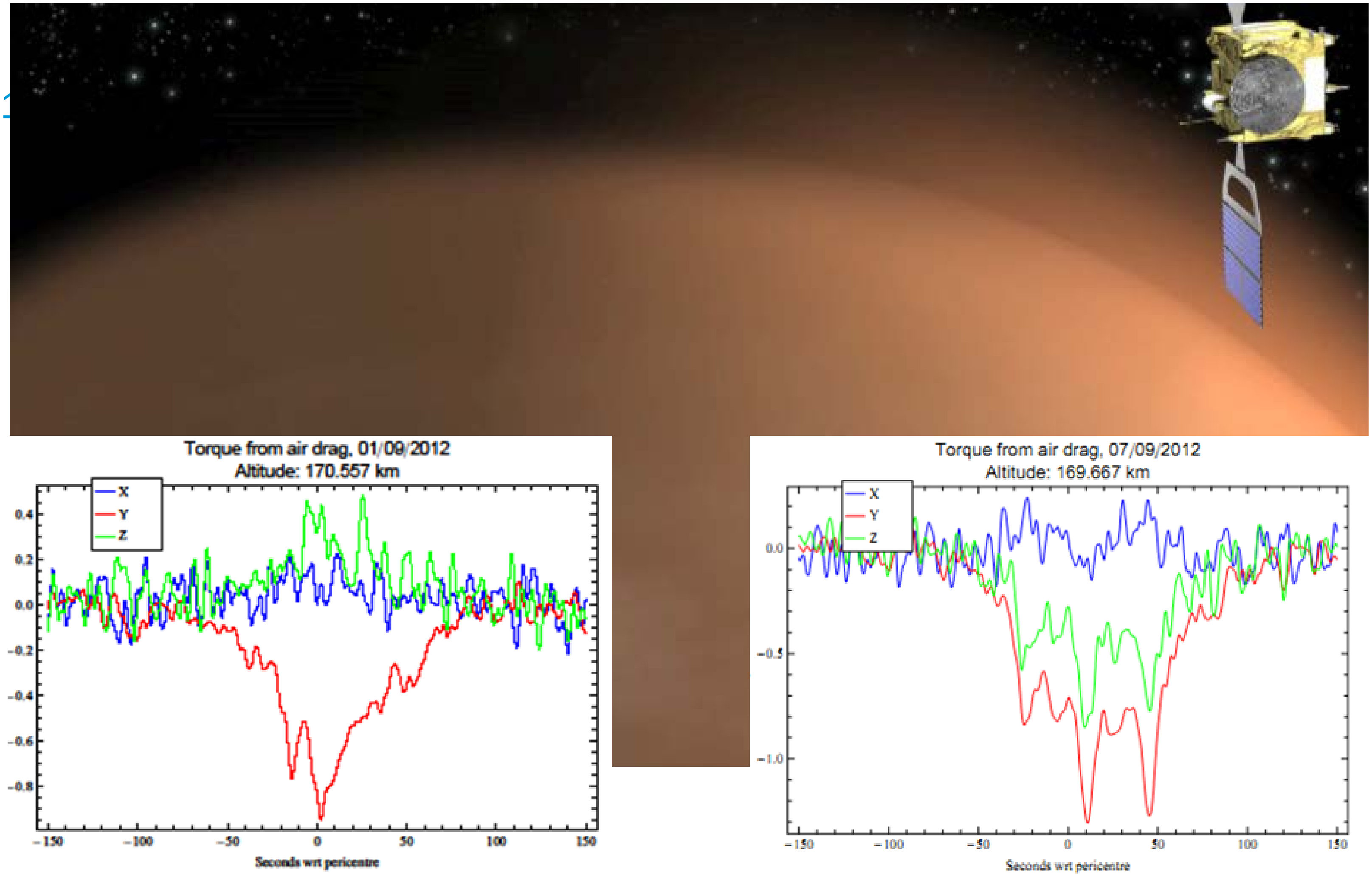
1. A full test of the aerobraking mode at high altitude (well outside the atmosphere) was carried out 19 Nov 2013.
2. A series of event simulations was been carried out by ESOC during March-April 2014 in order to prepare the ground system for the planned activities.
3. All activities have been carried out on an experimantal basis as manpower is very limited at this late stage of the mission
4. Several campigns with Drag.Torque measurments have taken place to as good as possible estimate the expected atmospheric density in the region concerned.

Science of Aerobraking

1. Using on board accelerometers, atmospheric density can be estimated at any point along the track through the atmosphere.
    a. $m\, a_z = \frac{1}{2}\, \rho\, S\, v^2\, C_z$
    b. Sensitive to about 10^{-11} kg/m^3 corresponding to about 155 km

2. Measurements will be taken as low as at 130 km altitude
3. Measuring total density in a region not accessible by other methods
4. Collecting information across the terminator region where the density gradient can be very steep
5. Collecting information in the high latitude region around 75 deg North
6. Searching and characterising atmospheric waves, and possibly winds
7. Carrying out magnetic field measurements at very low altitude

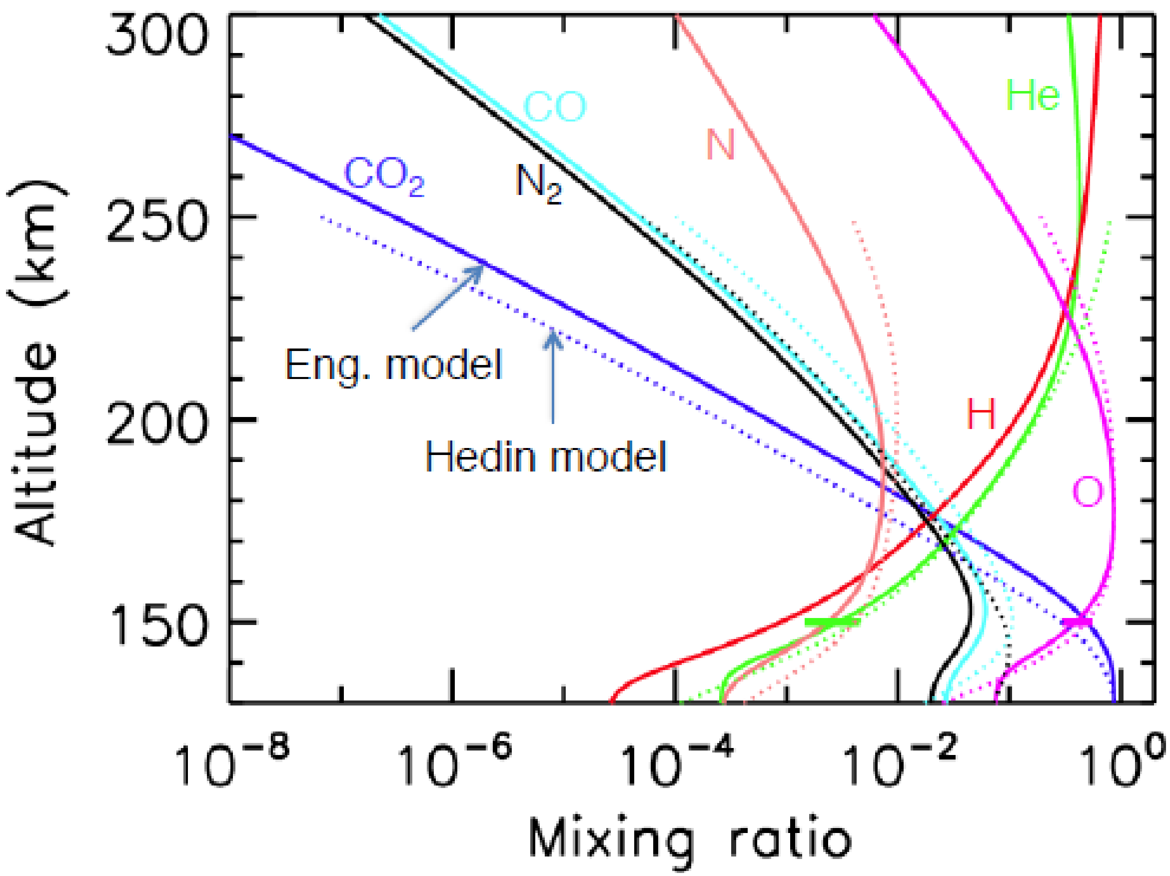
Preparation for aerobraking: Torque technique for measuring atmospheric density at low altitudes



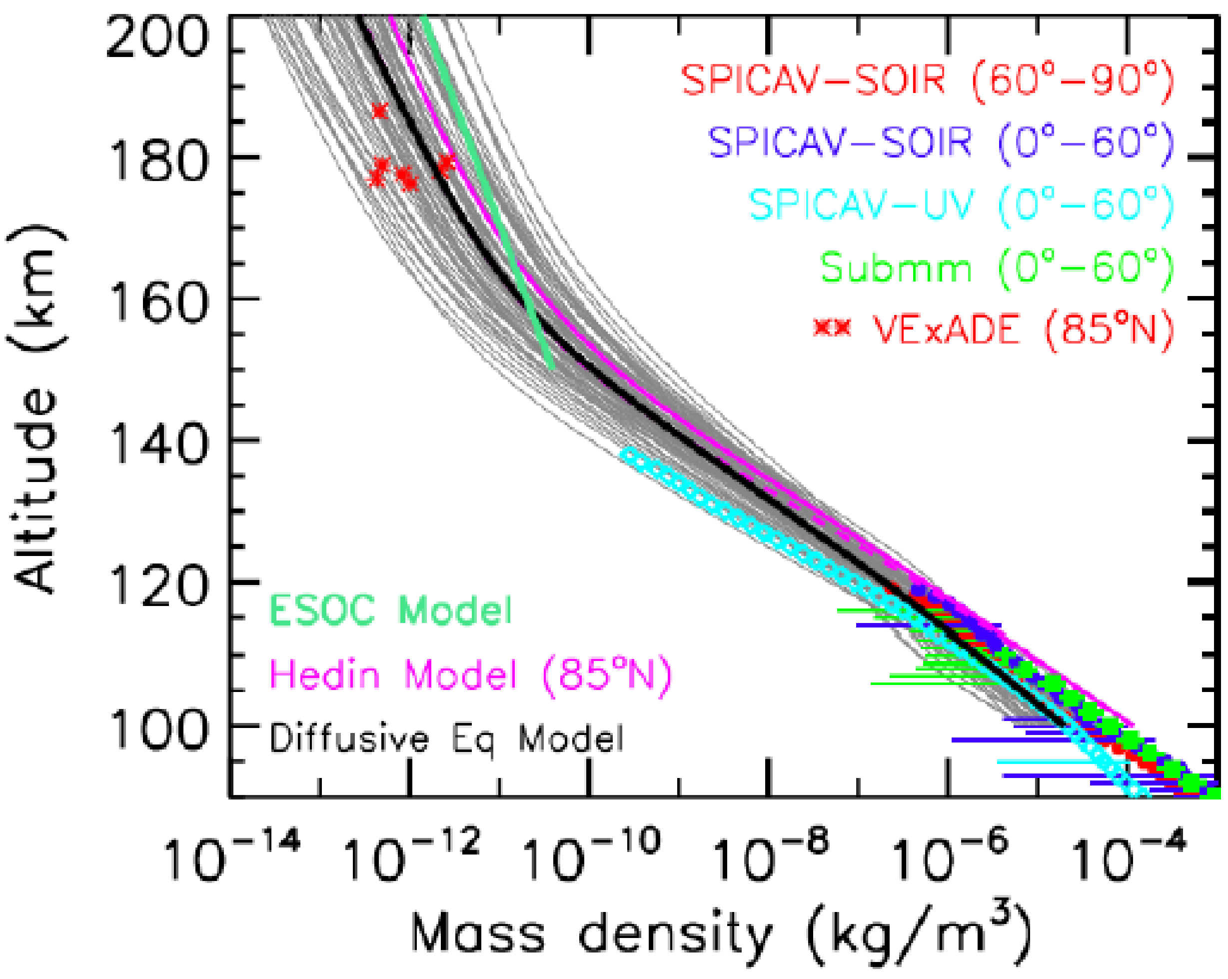
Models and measurements of density and temperature

- VIRA (Venus International Reference Model), Hedin model, VTS3 model
- Measurements on Venus Express
  - Spicav, up to 130 km (only CO_2)
  - SOIR, up to 150 km (only CO_2)
  - VeRa, up to 95 km
  - Drag, by radio tracking, 165-180 km
  - Torque, 165-200 km

Gas Mixing Ratios



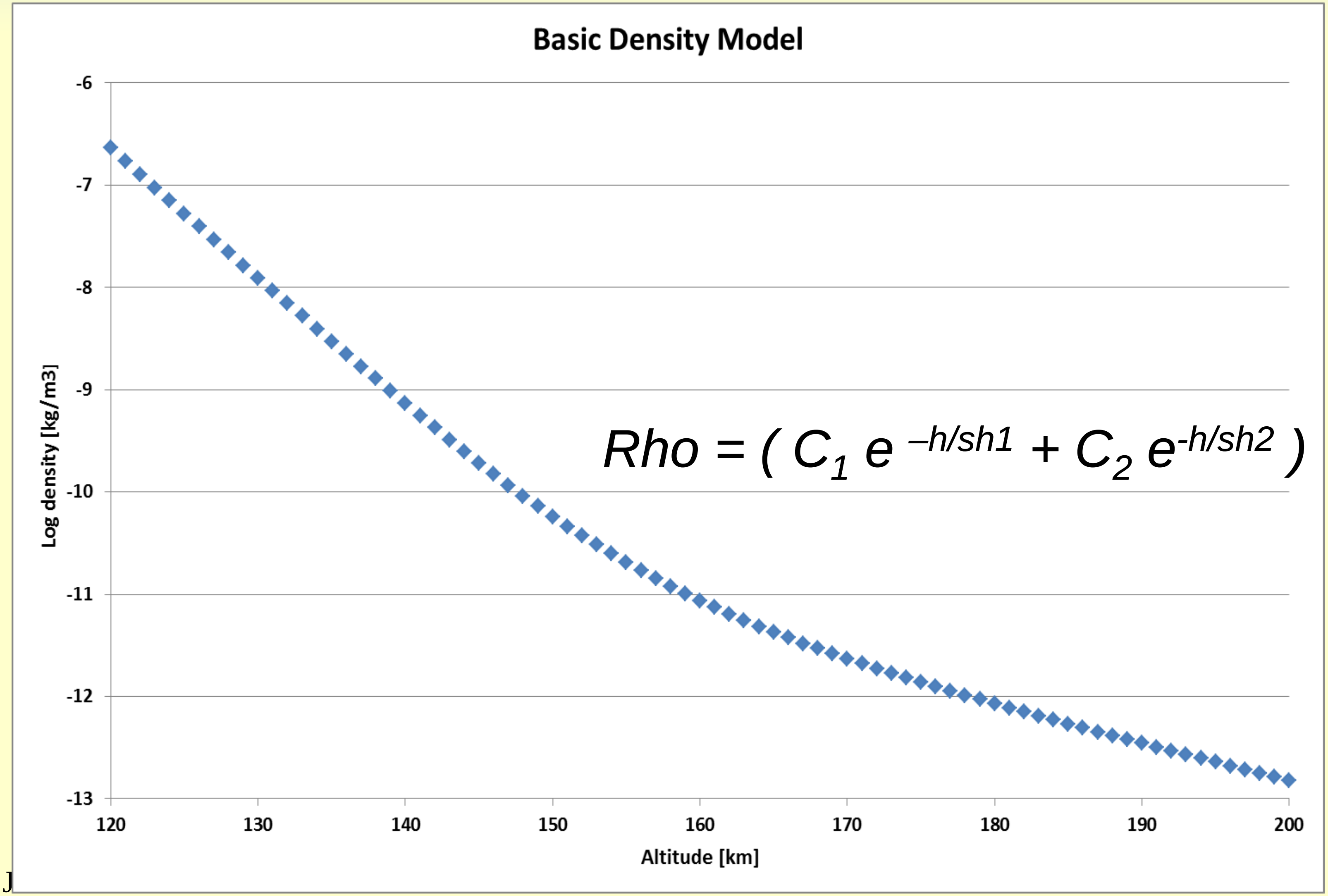
Making a one-dimensional model



JMCT Submm data
Courtesy of T. Clancy

SPICAV-UV data
Courtesy of F. Montmessin

SPICAV-SOIR data
Courtesy of A-C. Vandaele

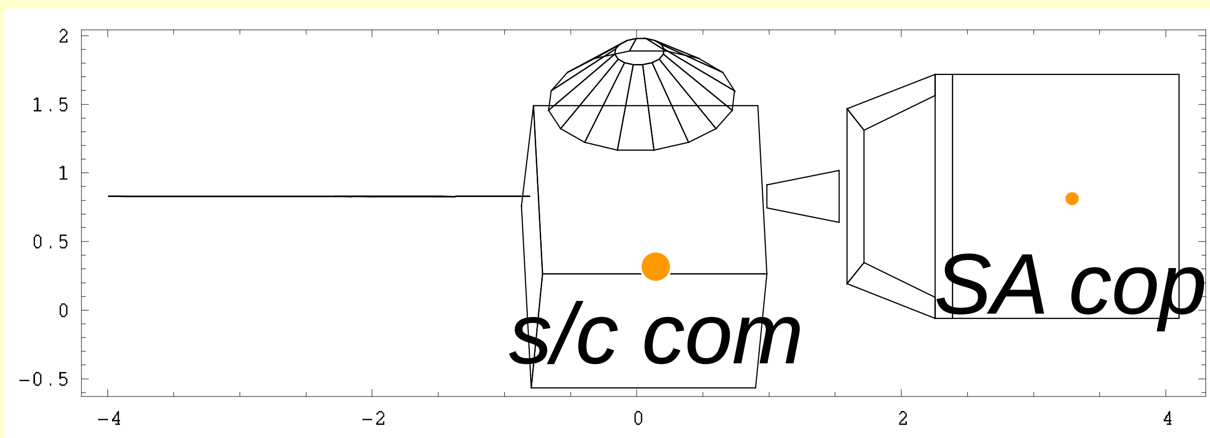


$$Rho = (C_1 \, e^{-h/sh1} + C_2 \, e^{-h/sh2})$$

J

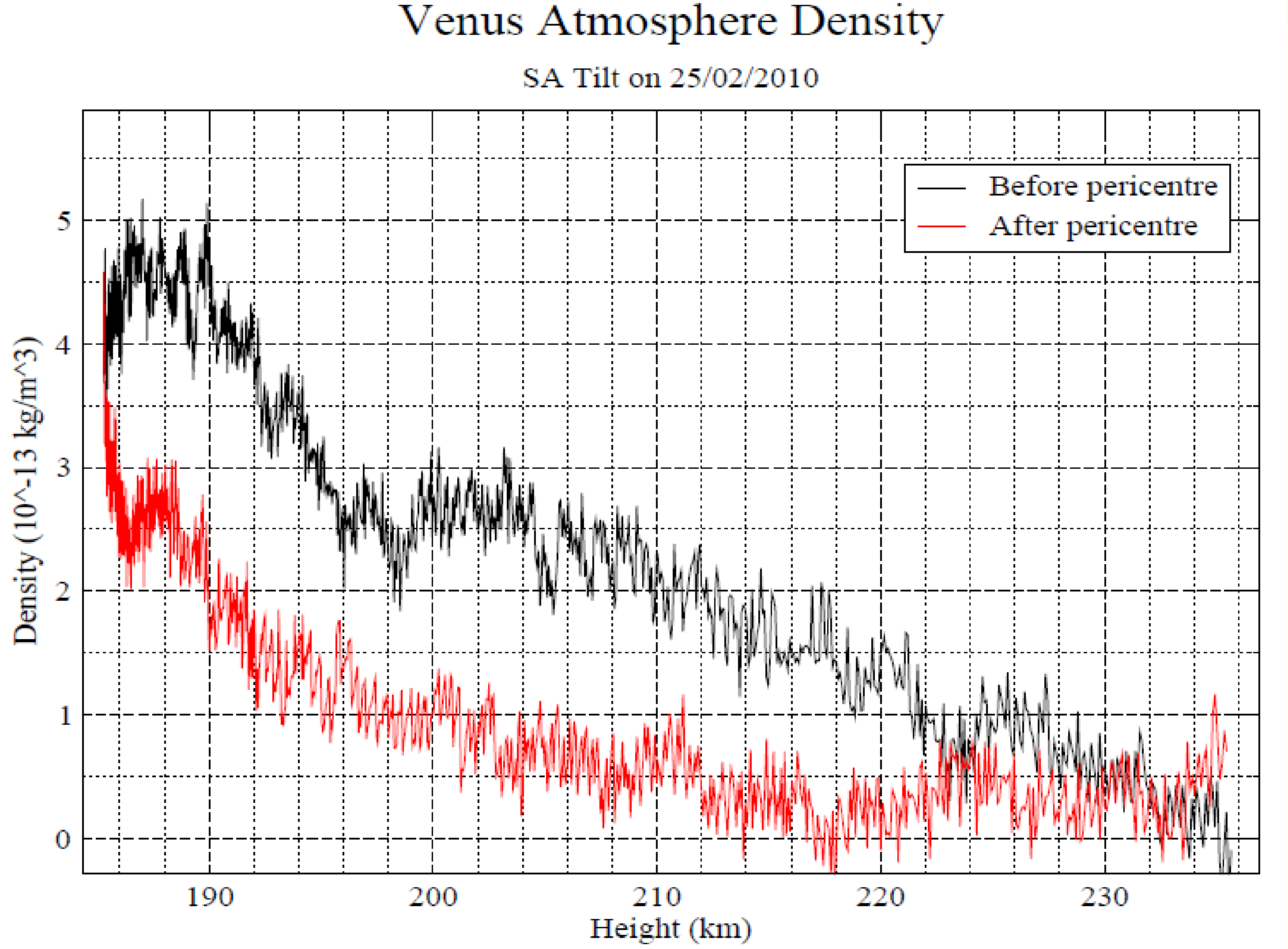
Torque measurement

$$T = \frac{1}{2} c_D \rho A_{eff} v^2 (r_{SA-cop} - r_{SC-com})$$

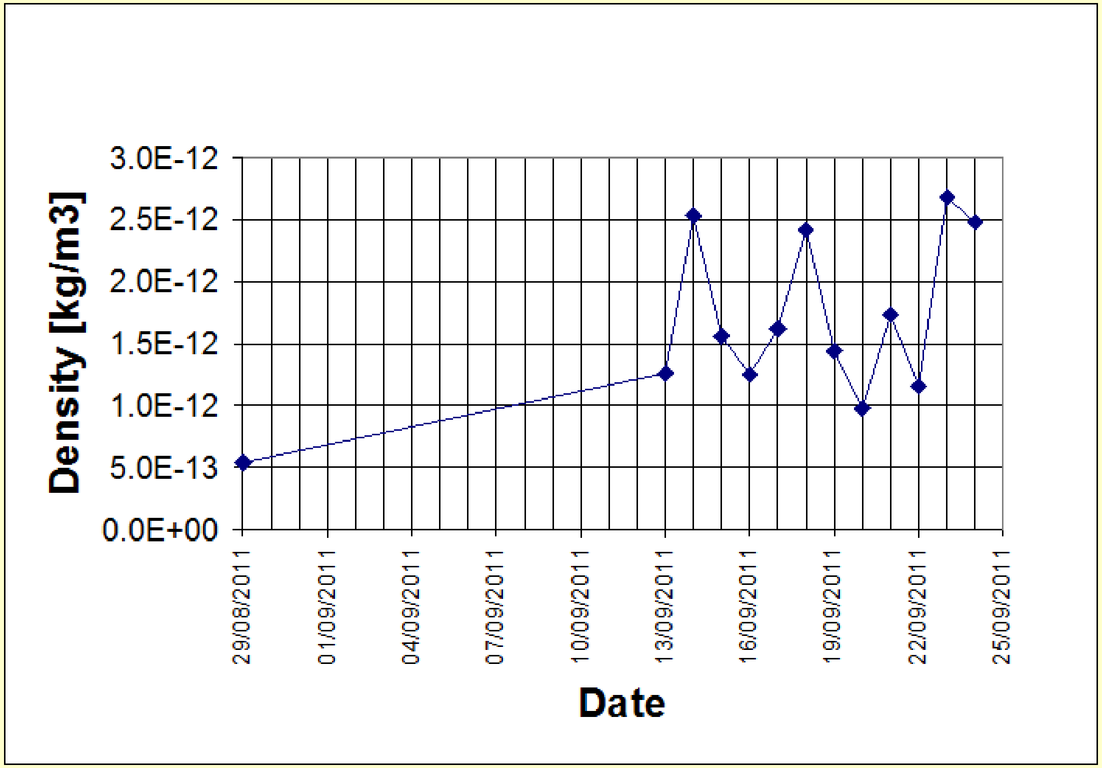


Dominating error: C_D (~15%)

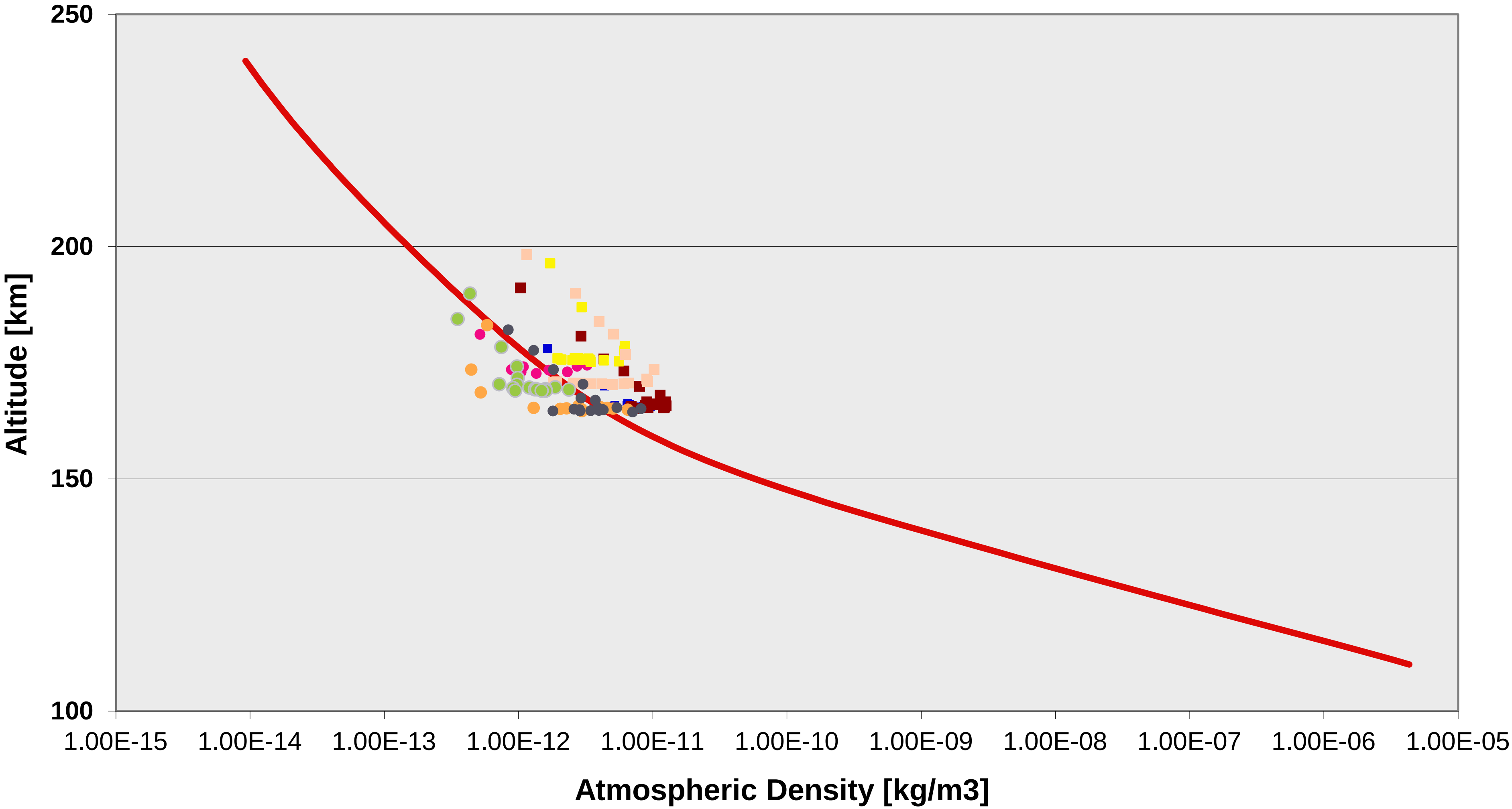
Day - Night variability



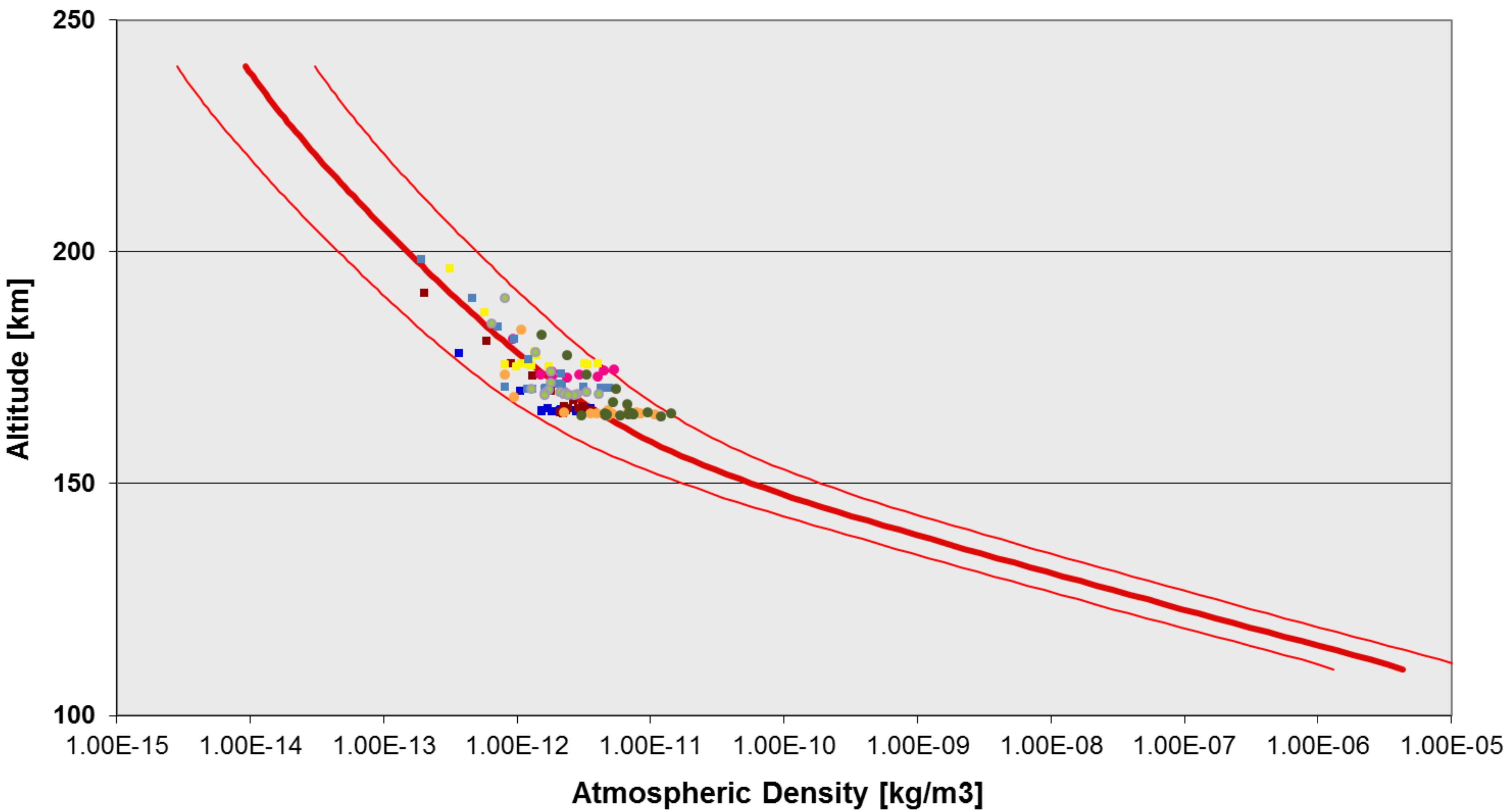
High day to Day variablity from Drag/Torque measurements at 165km



Polar density, raw torque data



Polar density, normalised to 90 deg SZA

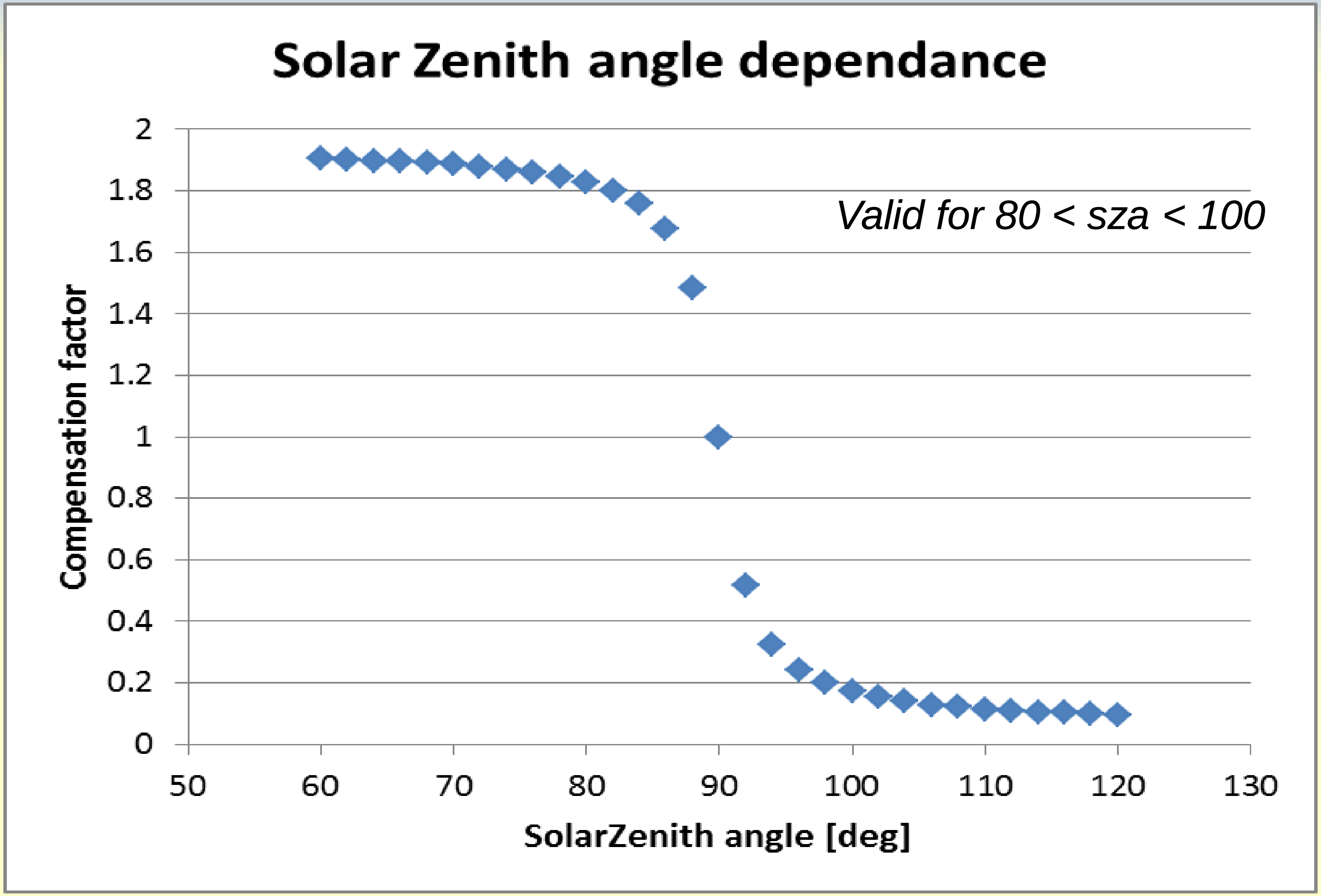


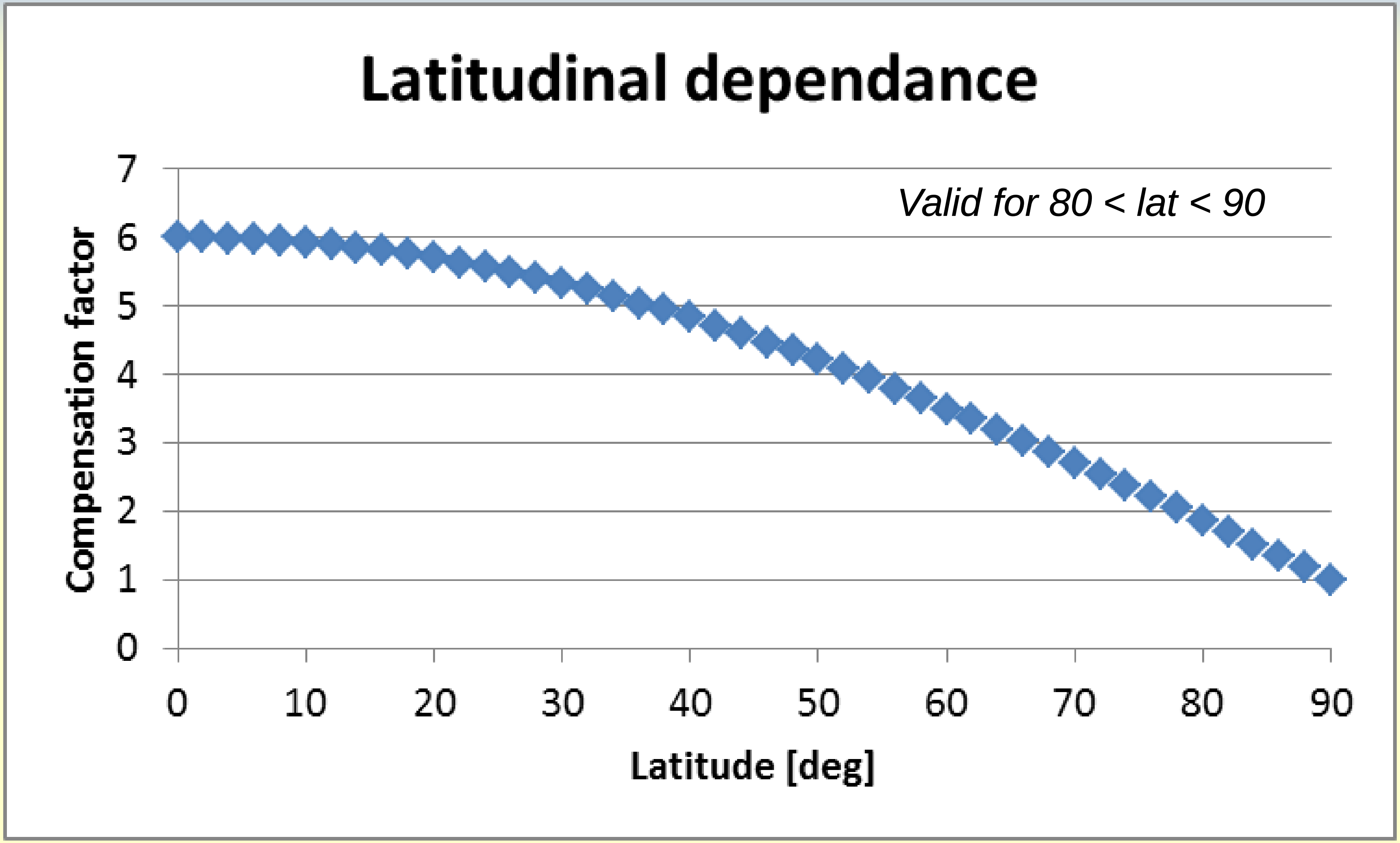
$$Rho_{new} = Rho(h) \cdot F(sza) \cdot G(lat)$$

$$Rho = (C_1\, e^{-h/sh1} + C_2\, e^{-h/sh2})$$

$$F(sza) = (1 - C_6\, Atan\, (C_5\, (sza - 90))$$

$$G(lat) = (1 + C_4\, Cos\ lat)$$


Solar Zenith angle dependance
Valid for 80 < sza < 100
Compensation factor
SolarZenith angle [deg]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
50
60
70
80
90
100
110
120
130


Latitudinal dependance
Valid for 80 < lat < 90
Compensation factor
0
1
2
3
4
5
6
7
0 10 20 30 40 50 60 70 80 90
Latitude [deg]

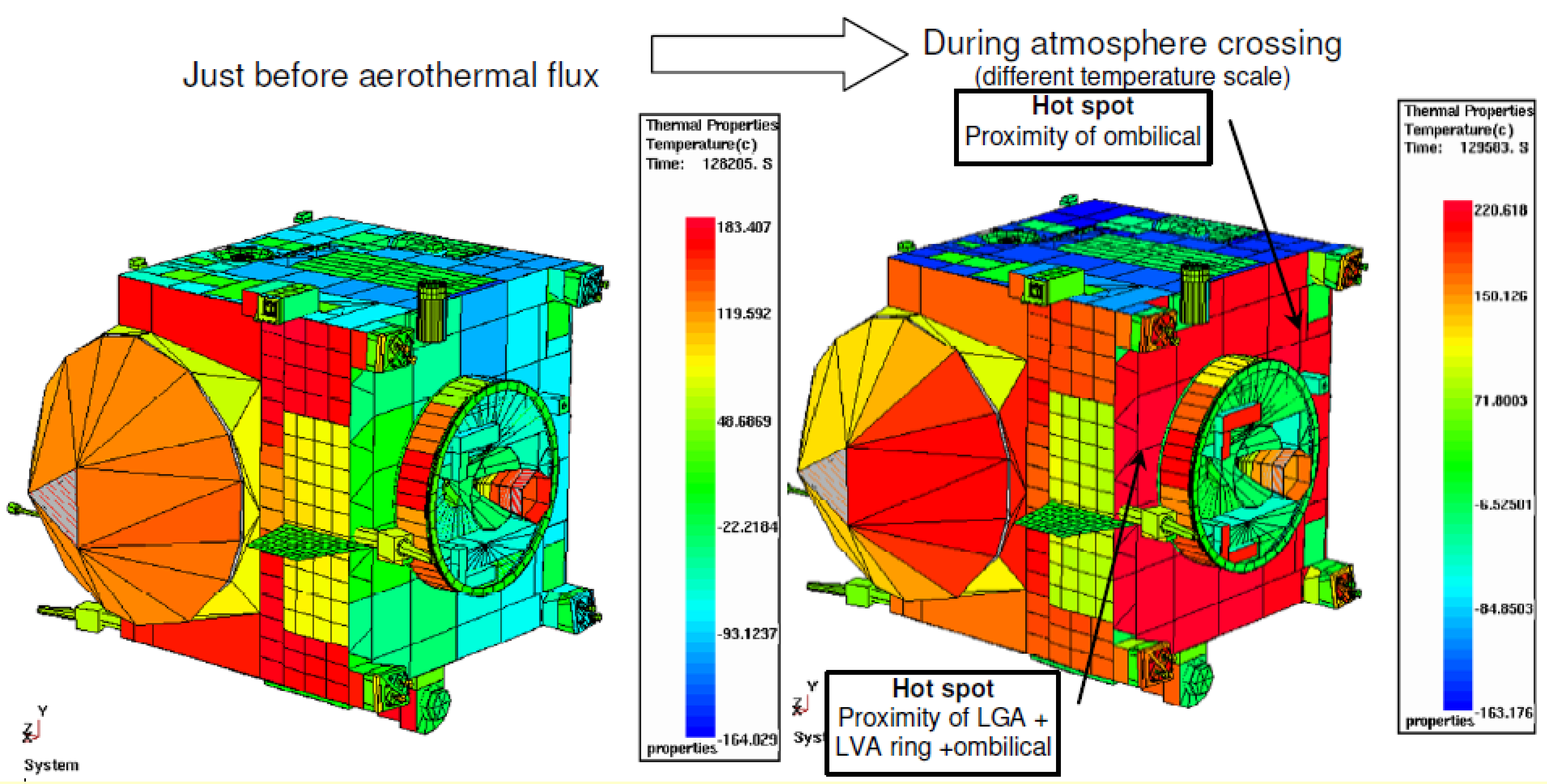
A spacecraft designed for aerobraking

- Is has often been mentioned that the VEX spacecraft was not designed to perform aerobraking. This is not correct. The contract with Astrium included as a requirement compliancy with aerobraking to a level of 0.3 N/m^2, including all required margins that apply in the beginning of the mission. This was a heritage from MEX and the intension was to use aerobraking as a back-up in case the orbit insertion would not work as planned. Some examples of specific design issues are:
  - Dynamically stable spacecraft due to high mounted solar panels leading to a centre of pressure well behind the centre of mass
  - Additional tests at high temperatures of the solar panels
  - Using stand-offs and clips to ensure fixation of MLI in case of weakened MLI adhesive tape
  - Inclusion of a s/c software Braking Mode
  - Solar panels exposed to excess thermal tests, multiple cycling to 170 deg.
- In addition in a later study (finished 2010), Astrium confirmed the validity of the aerobraking even during the nominal mission.

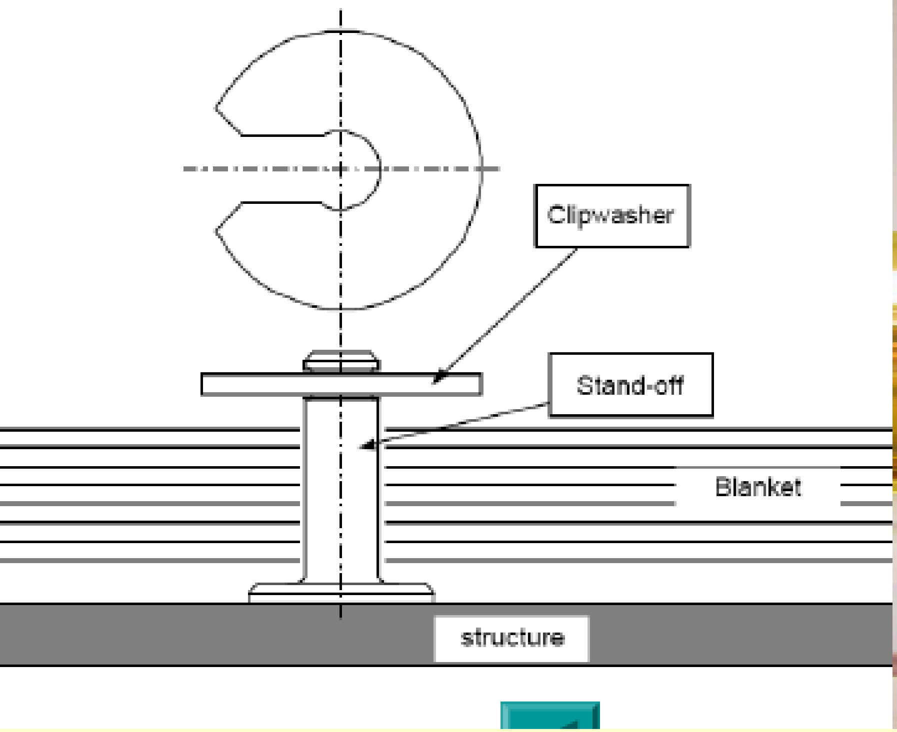
Mechanical and Thermal considerations

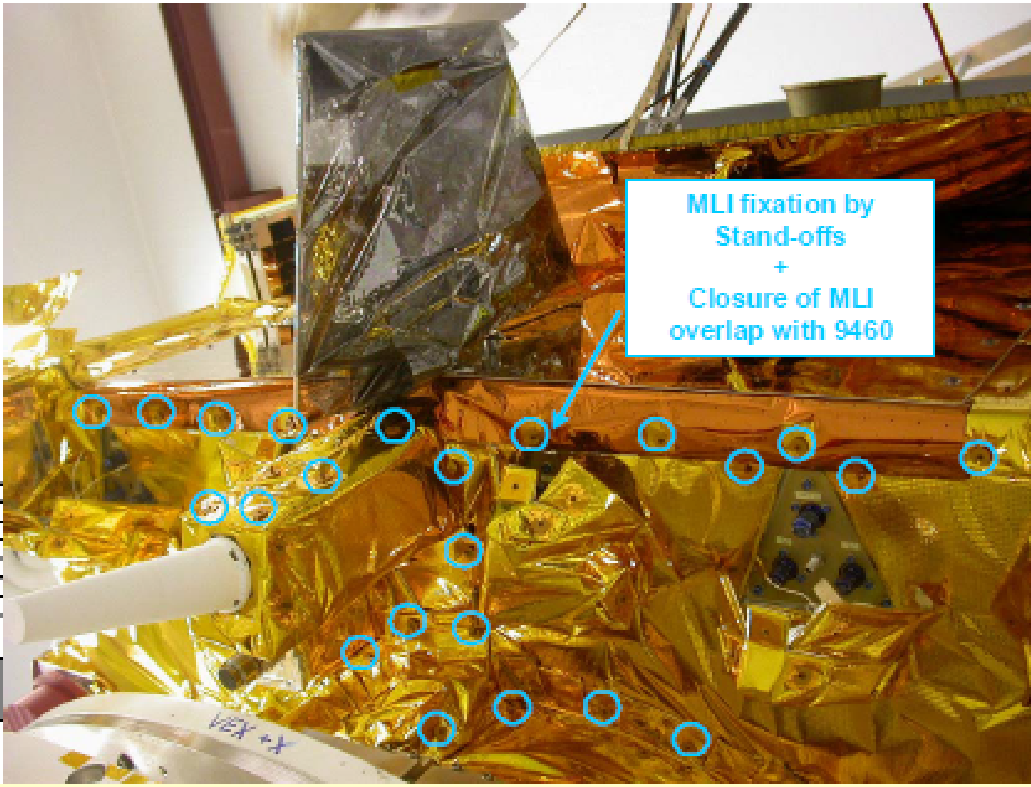
- The dynamic pressure of 0.6 N/m^2 is less than what is required to keep a single sheet of paper in the air. ASTRIUM considers this well within the capabilities of the spacecraft, both with respect to direct mechanical forces and torques (on SADE etc.) and with respect to tearing off MLI even in case of weakened tape adhesive (stand offs and clips will retain the MLI in place).
- For the thermal model ASTRIUM uses as a general rule a 10 degree margin on all material qualification limits and an additional 10 degree margin on the thermal model.
- The solar panels have a fairly high thermal inertia and therefore respond slowly to the thermal flux. Cooling down of the panels before entering into aerobraking will assure that the temperature will stay within limits.
- The base material in the MLI is Kaptone (du Pont). Kaptone is used in several applications at temperatures up to 400 deg C for extended duration. Kaptone does not melt but decomposes at temperatures above 520 deg C.
- The MLI qualification temperature in the ASTRIUM study concerns continuous operation. During aerobraking the effective time at high temperature is about one minute per pass. Possibly some effect will be noticed on the thermo-optical properties (α and ε) of the MLI on the –Z platform. The influence of this on the s/c should however be small as this side is never facing the Sun (for extended periods) and the heat exchange is dominated by the large area of the main engine and launch adapter.

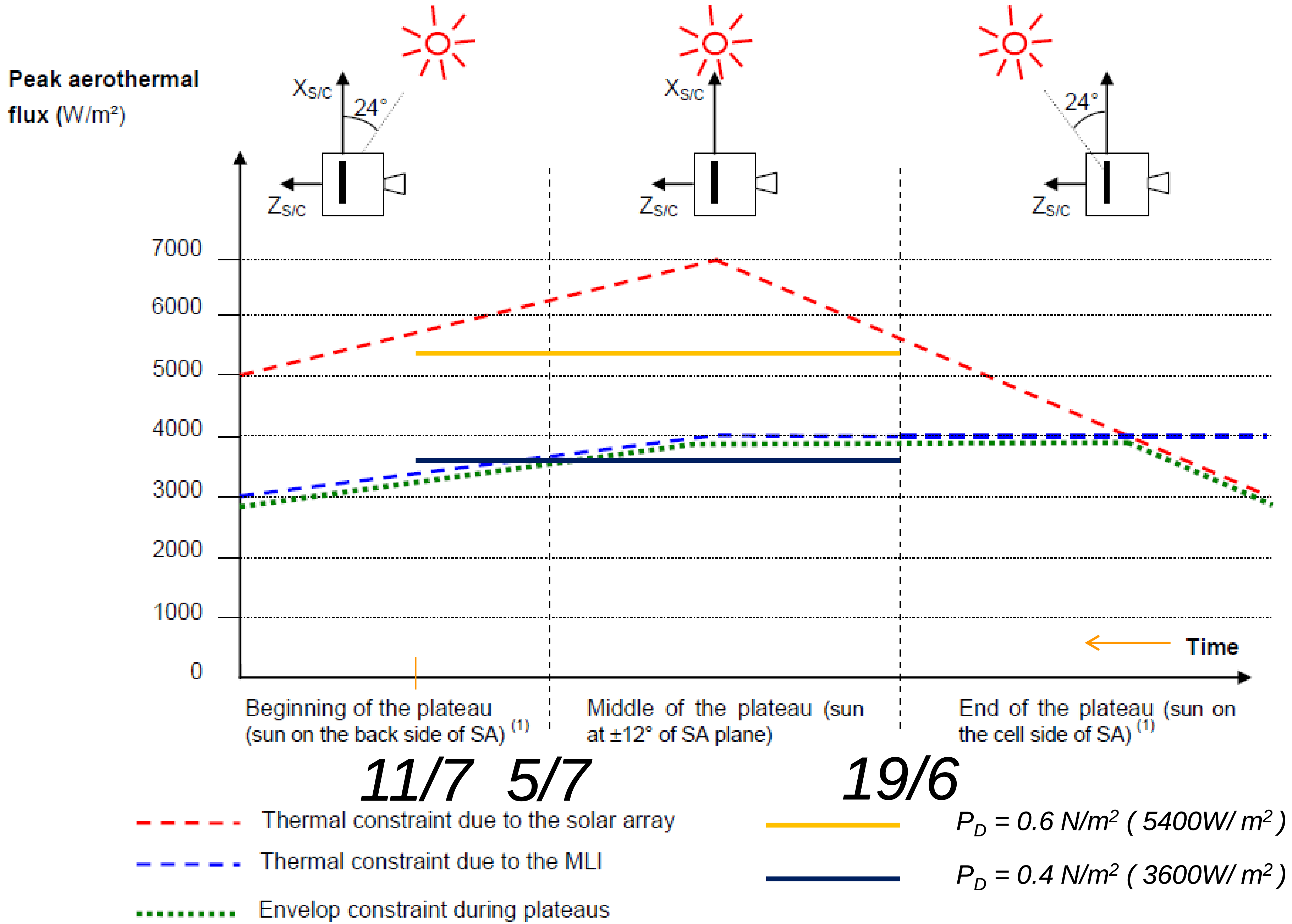
Thermal modelling



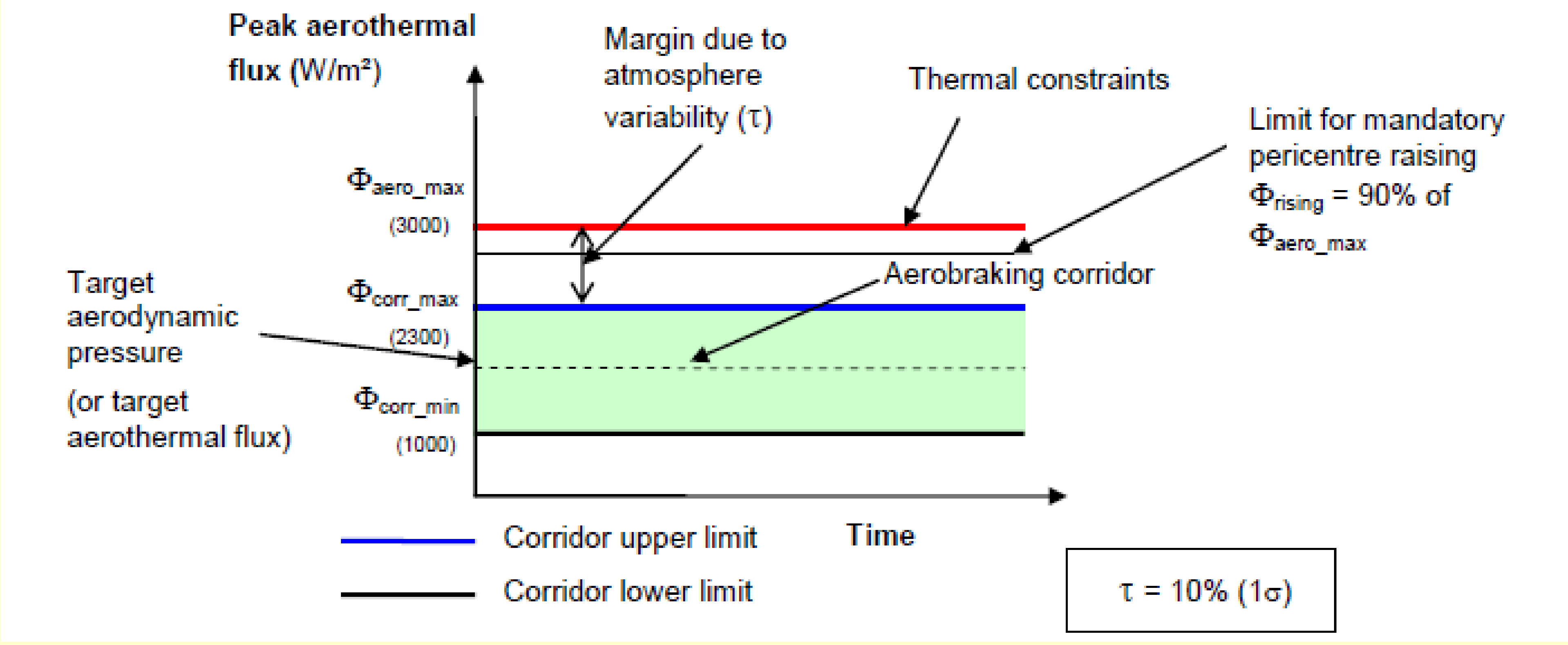
MLI attachment points



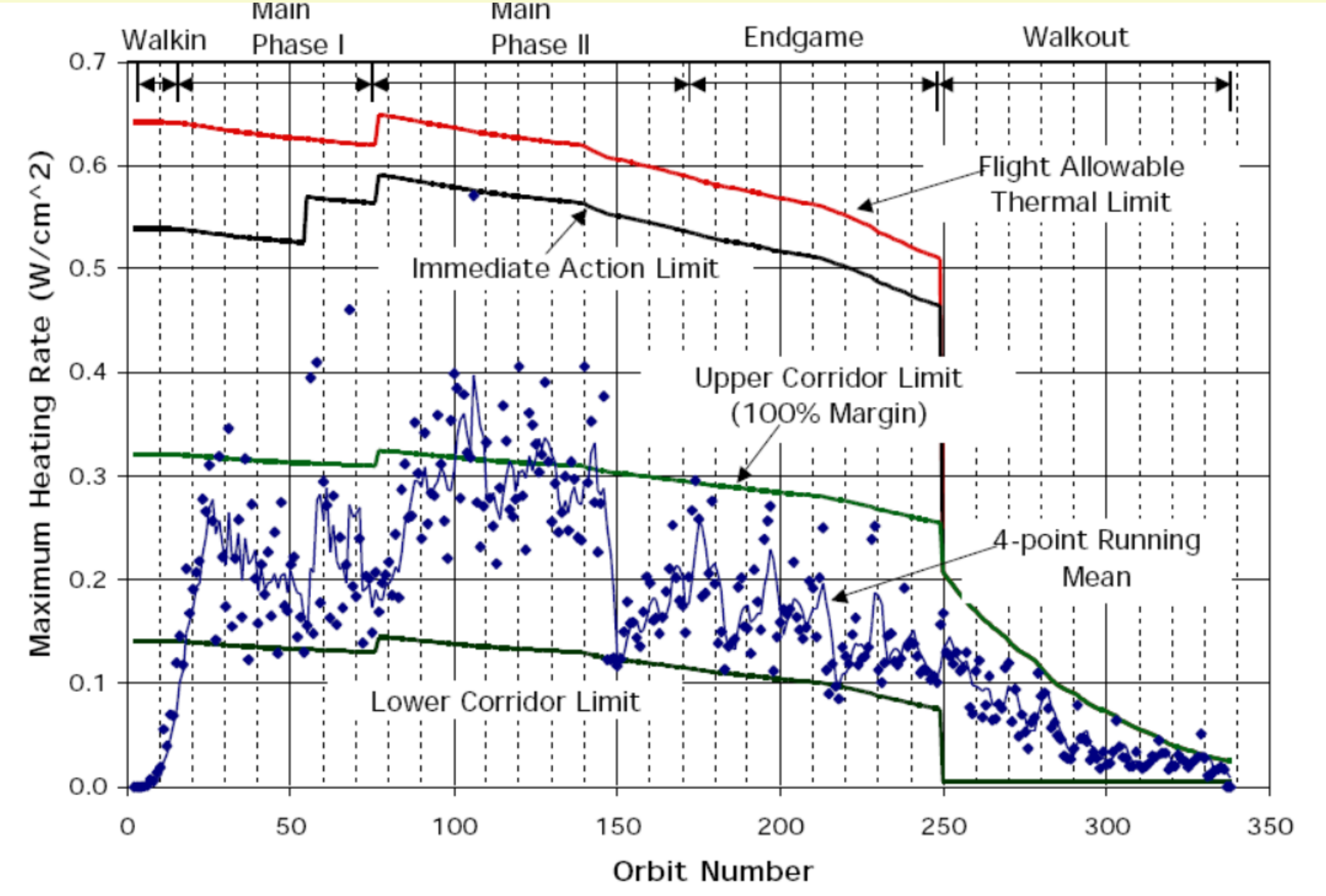




Note (1) : Depending on the plateau the sun will be illuminating the back side of the SA either at the beginning or at the end of the plateau


Peak aerothermal flux (W/m²)
Margin due to atmosphere variability (τ)
Thermal constraints
Limit for mandatory pericentre raising
Φrising = 90% of Φaero_max
Φaero_max
(3000)
Φcorr_max
(2300)
Φcorr_min
(1000)
Aerobraking corridor
Target aerodynamic pressure
(or target aerothermal flux)
Time
Corridor upper limit
Corridor lower limit
τ = 10% (1σ)

Example from Mars Odessey

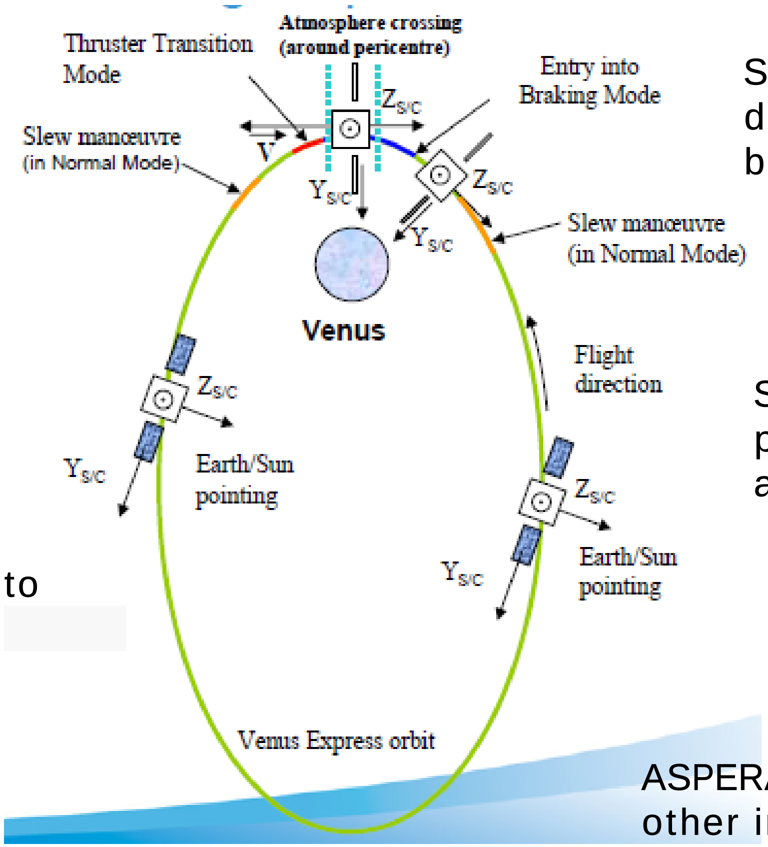


Overview of Aerobraking Operations

S-band transmitter on as beacon

Braking mode duration is 6700 seconds

Some heaters OFF to reduce power consumption

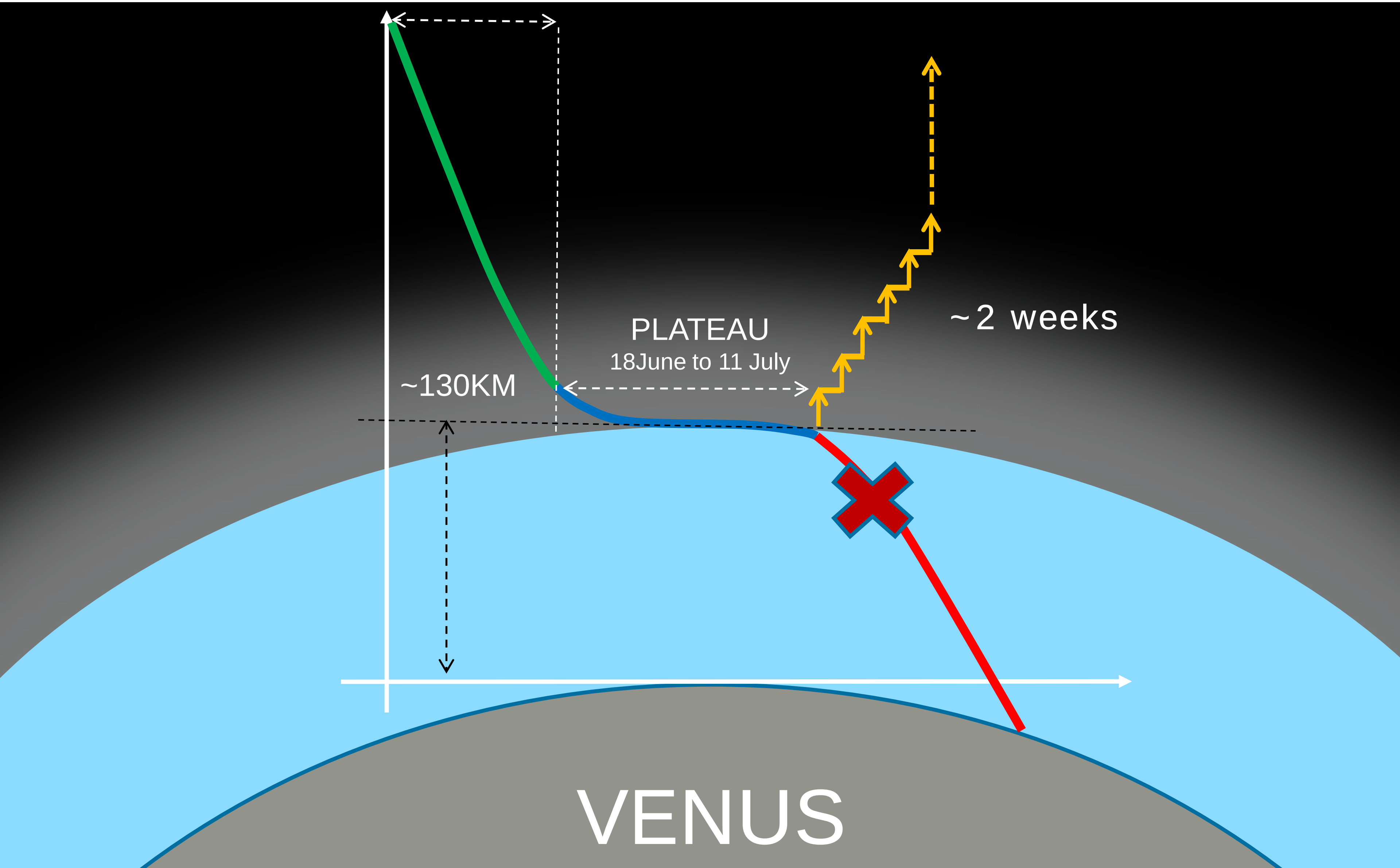


Solar arrays are stepped during slews to/from braking mode attitude

Spacecraft is earth-pointing except during aerobraking

ASPERA and MAG are ON, other instruments are OFF

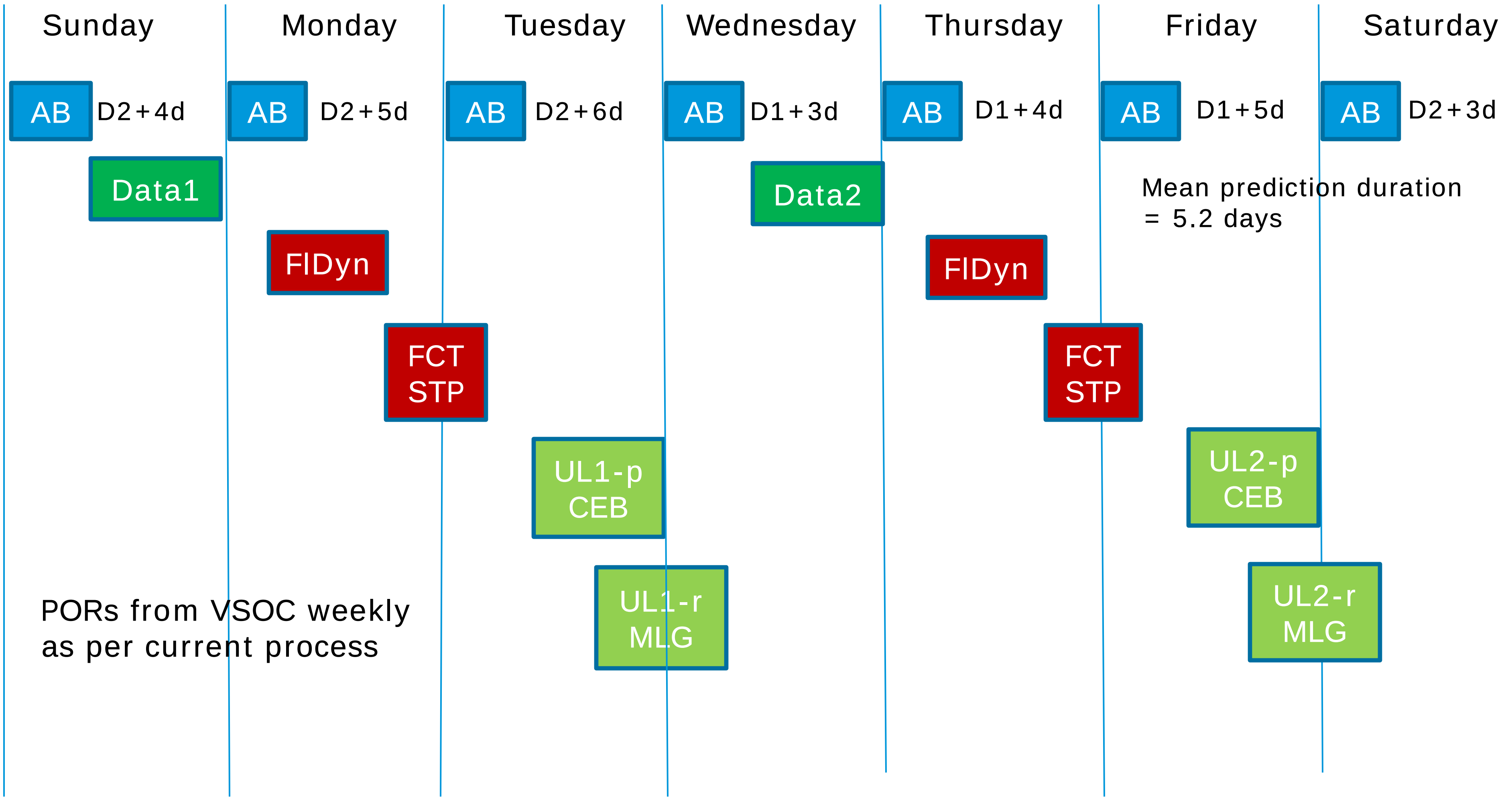
17 May to 18 June 2014



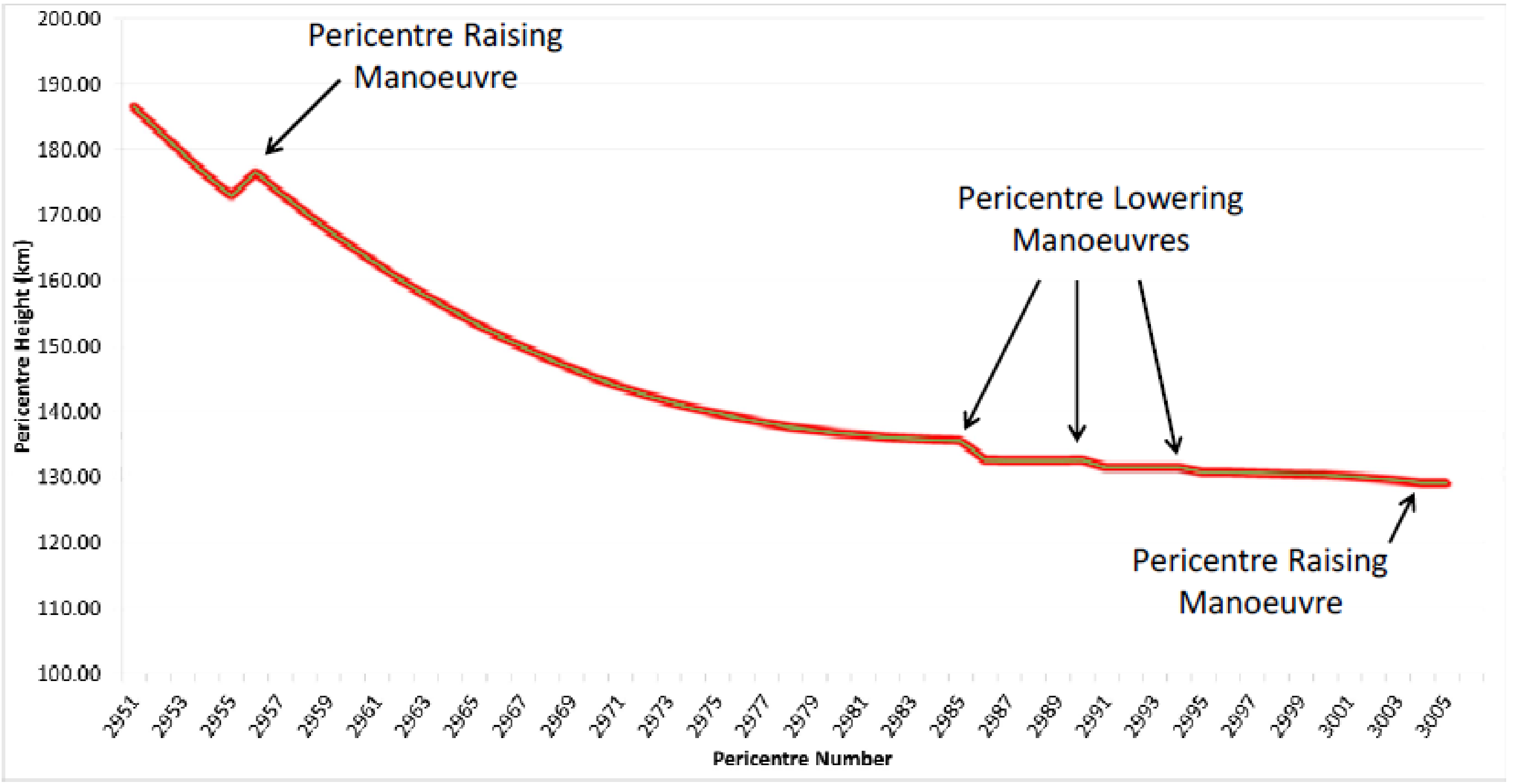
Venus Express AB & EOM Schedule

6 Mar – 8 May	Operational validation (mini sims campaign)
8 May	End of Routine Science Planning
9-12 May	Mission Planning Reconfiguration
12 May	FOP 5.9 (Aerobraking) Release
13 May	Start of Aerobraking Planning
17 May	End of Routine Science Ops / Spacecraft reconfiguration for AB
17 May – 18 Jun	Walk-in (occasional OCMs to tune dynamic pressue)
18 Jun – 11 Jul	Aerobraking (with OCMs as necessary to tune dynamic pressure)
11 Jul – 25 Jul	Pericentre Raising Manouevre (series of daily OCMs)
14 Jul – 18 Jul	Check of platform health status / reconfigure spacecraft + MPS
21 Jul – 25 Jul	Check of payload health status / possible pointing test (TBC)
29 Jul	Venus Express Post-AB Review – definition of reduced science ops
11 Aug	Post-AB orbit file available

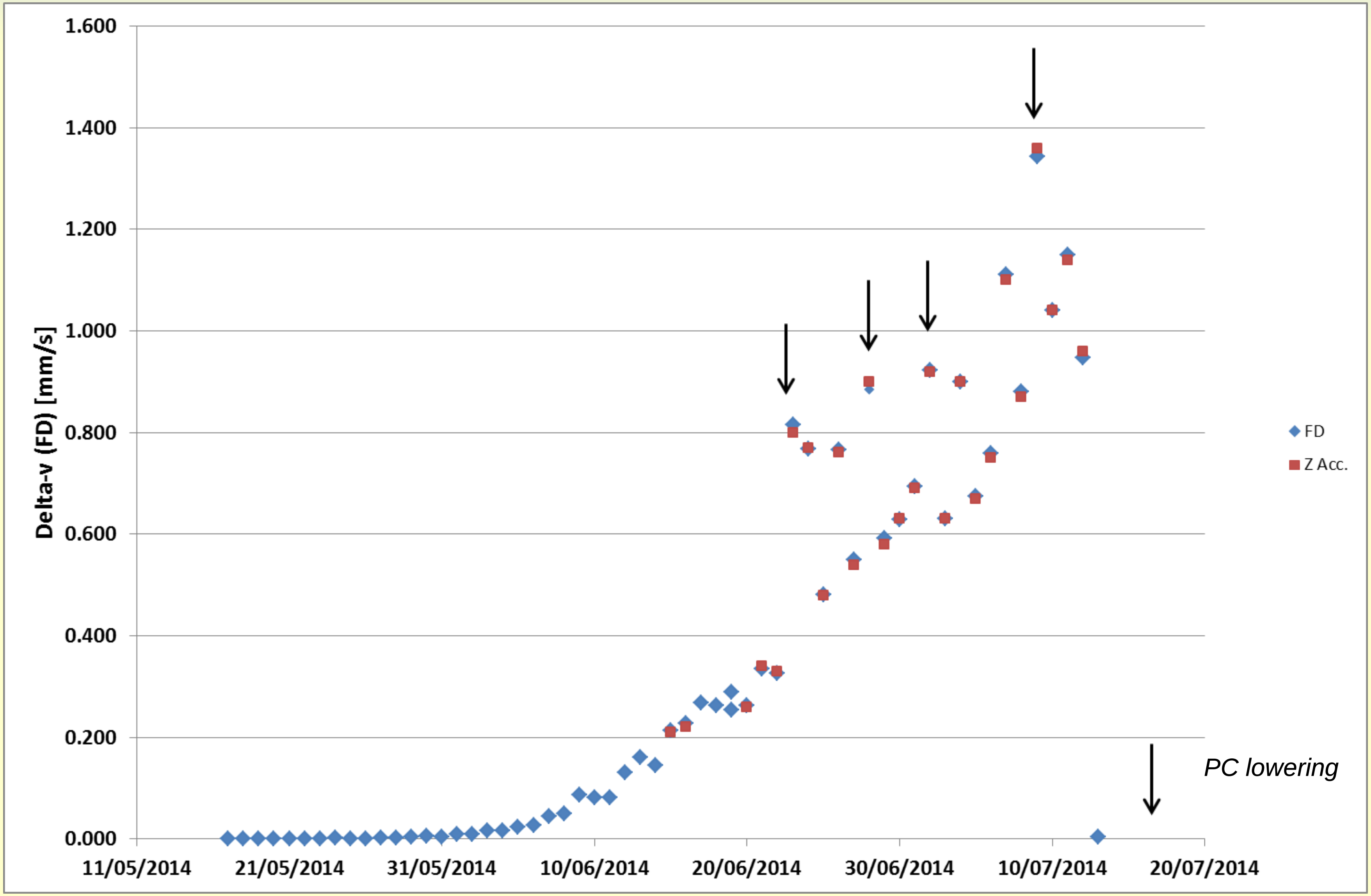
Schematic of Aerobraking Operations



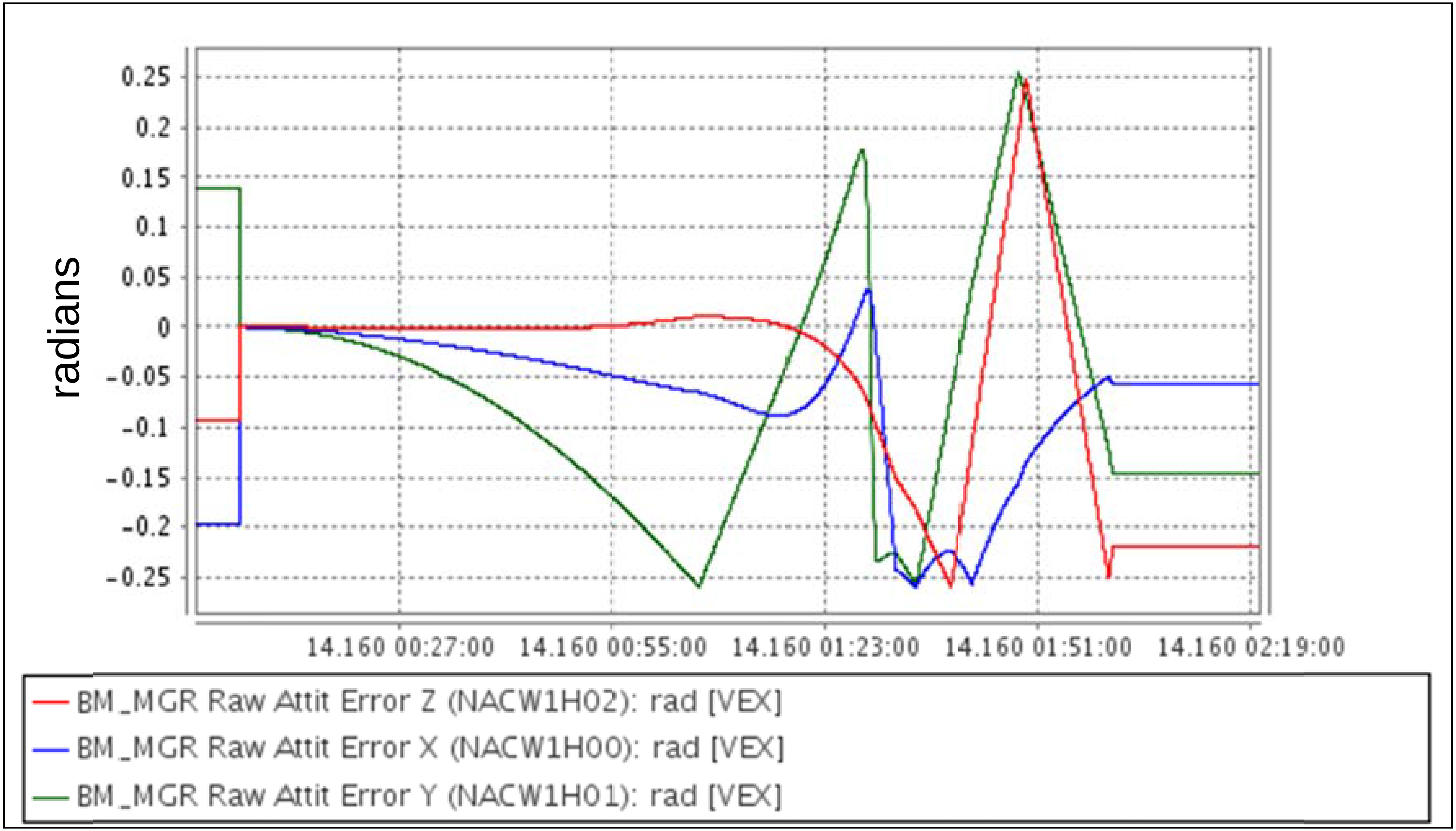
Pericentre Altitude evolution



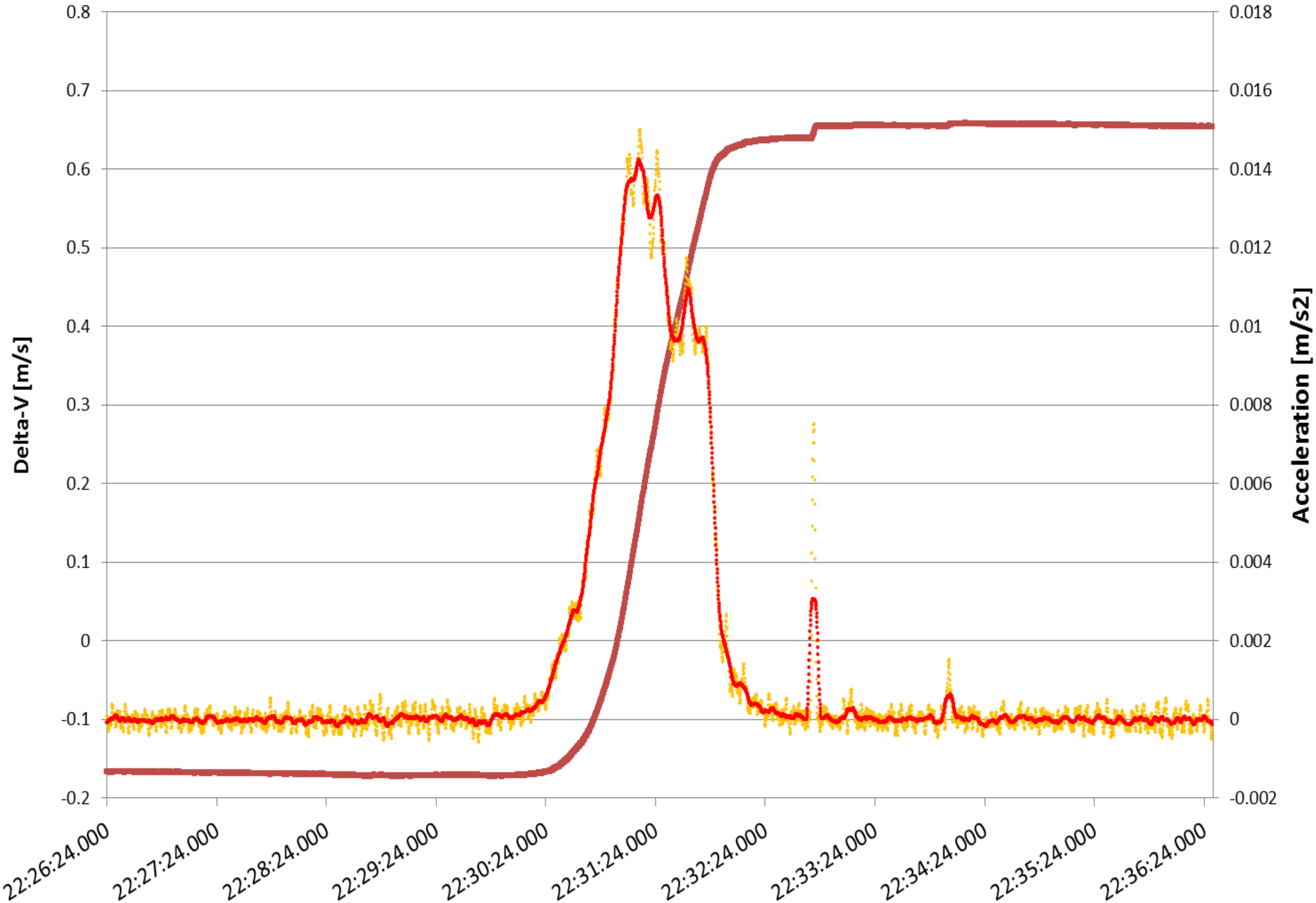
Delta-v vs date



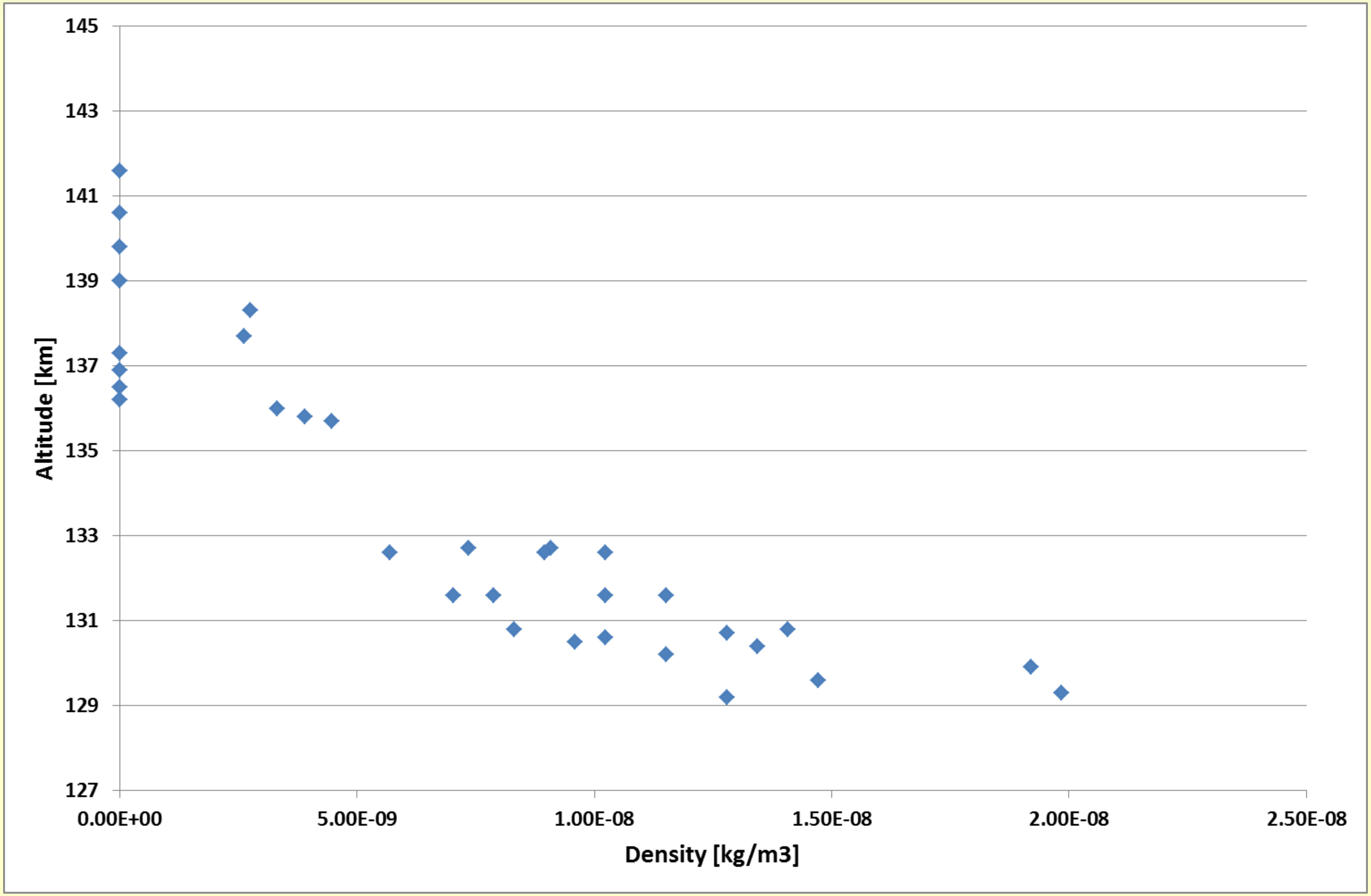
Attitude error during Braking Mode



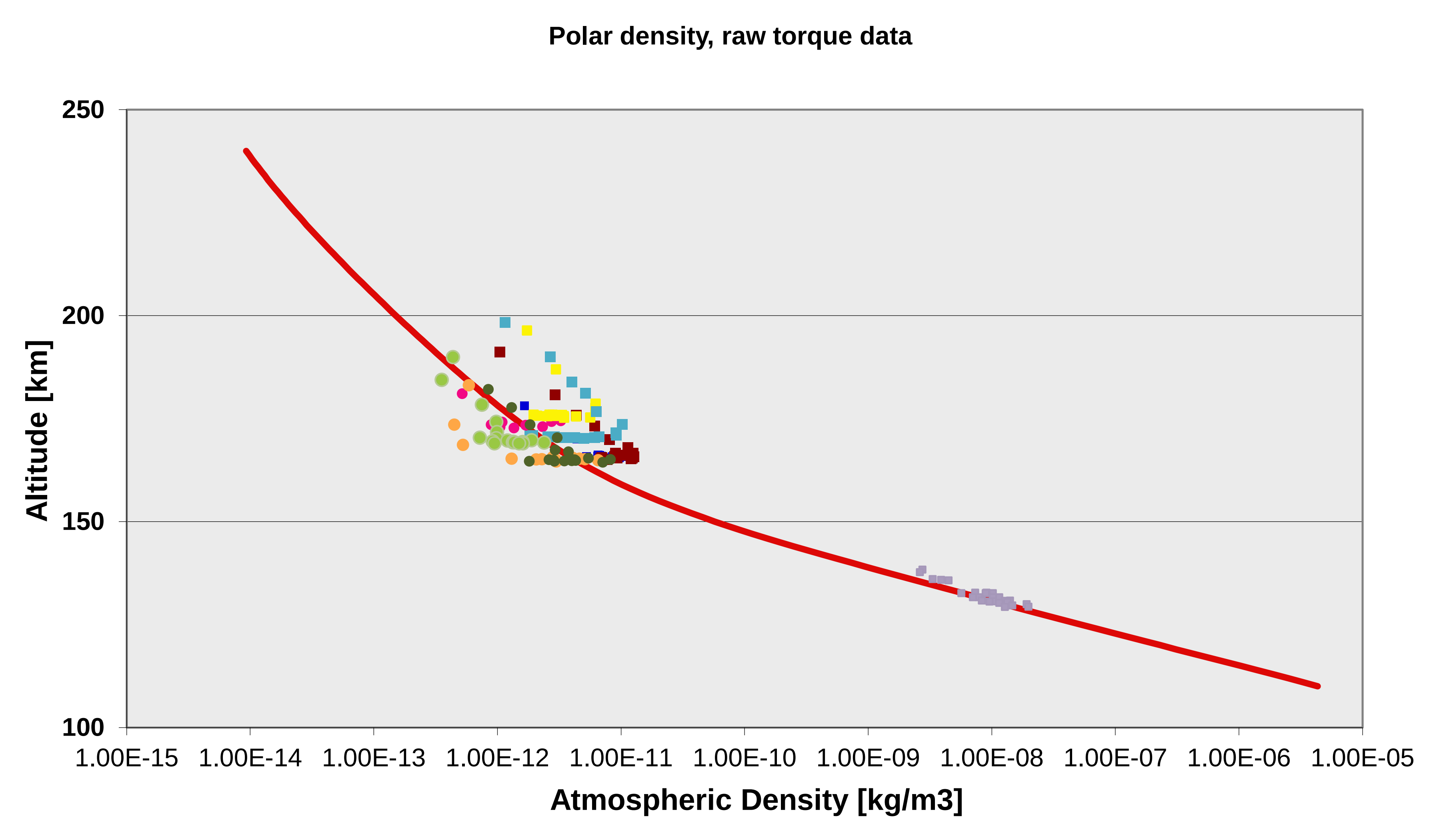
Aerobraking pass #2986, 23 June



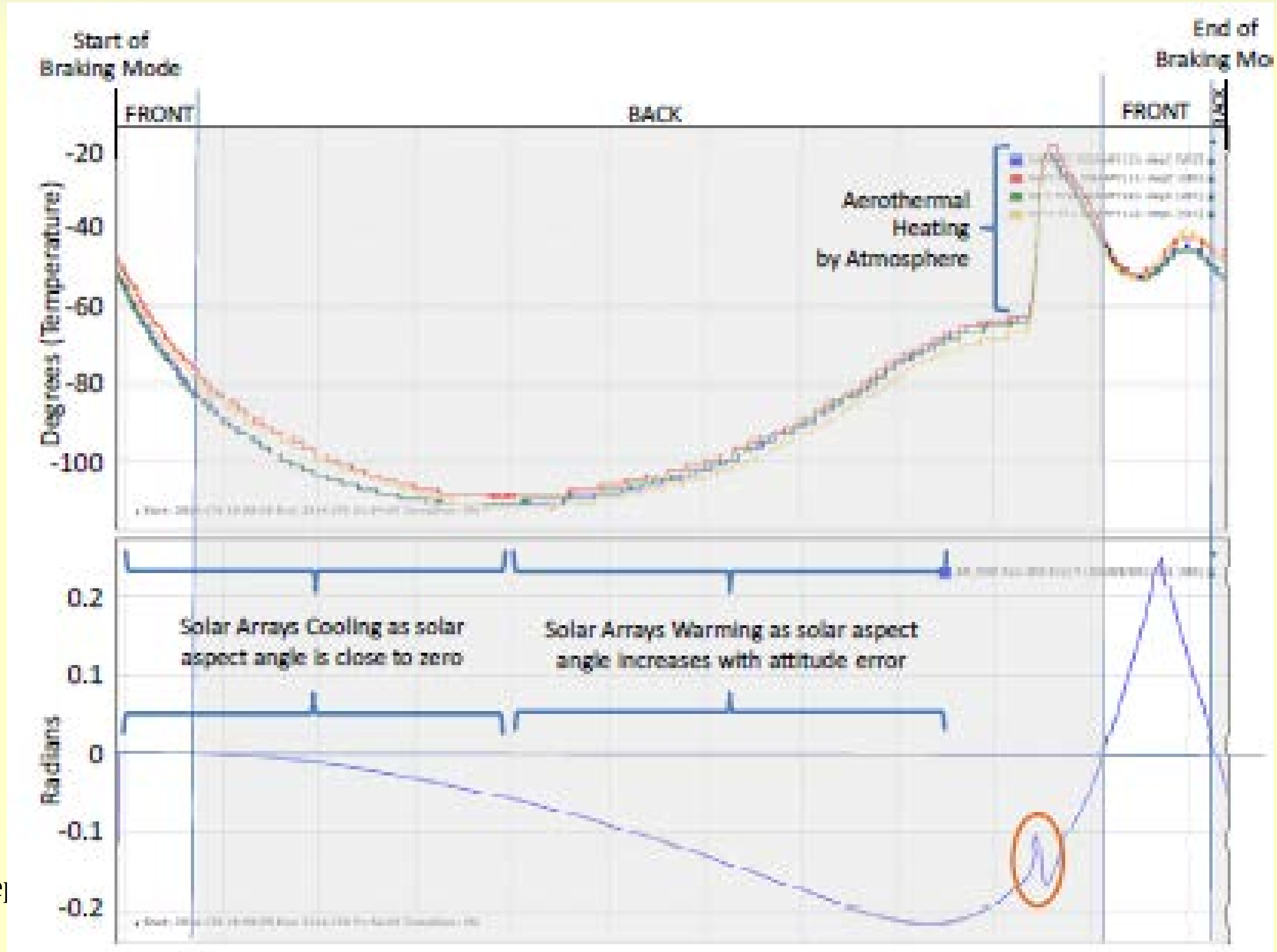
Atmospheric Density



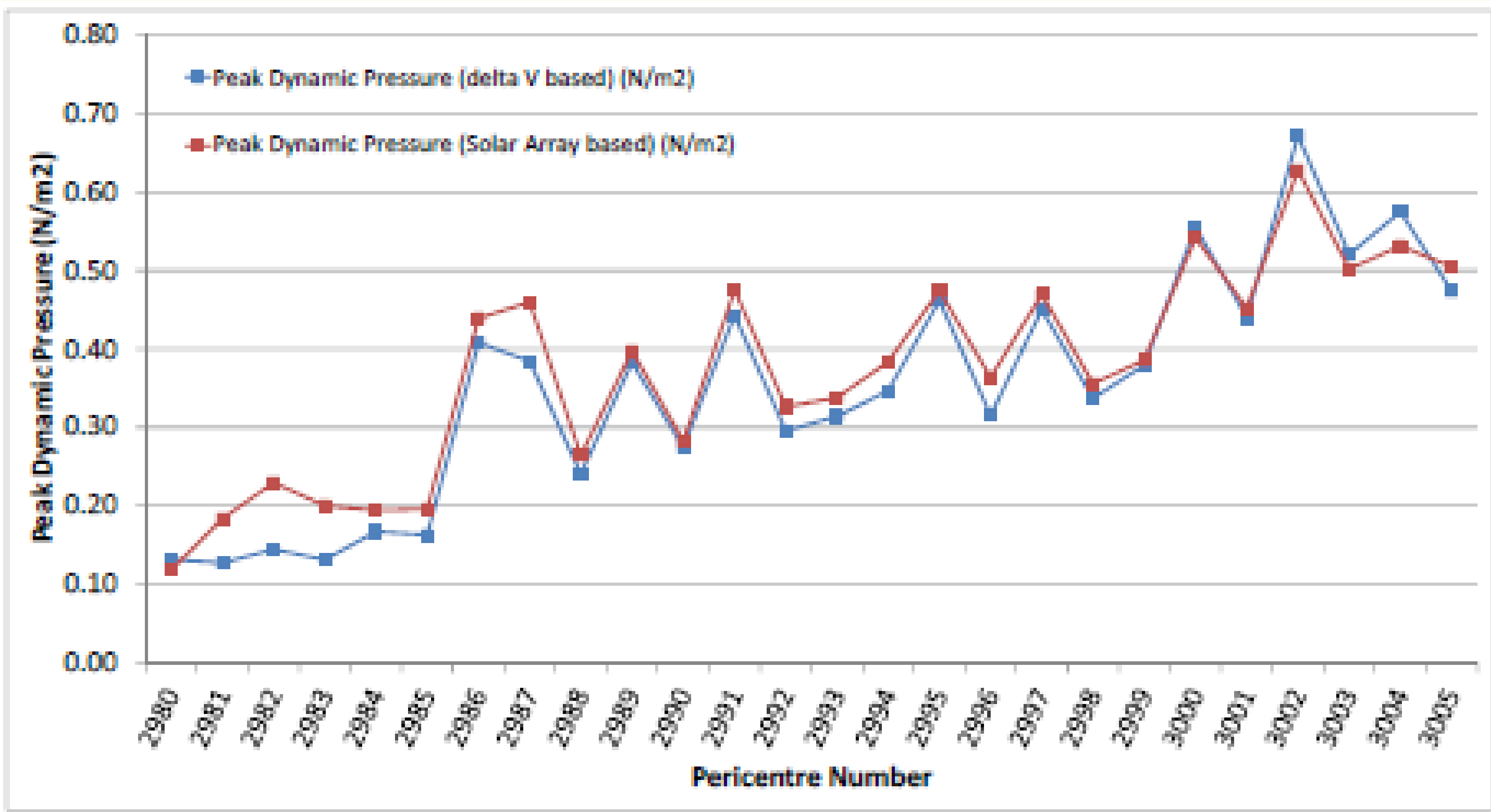
Measurements vs. Model results



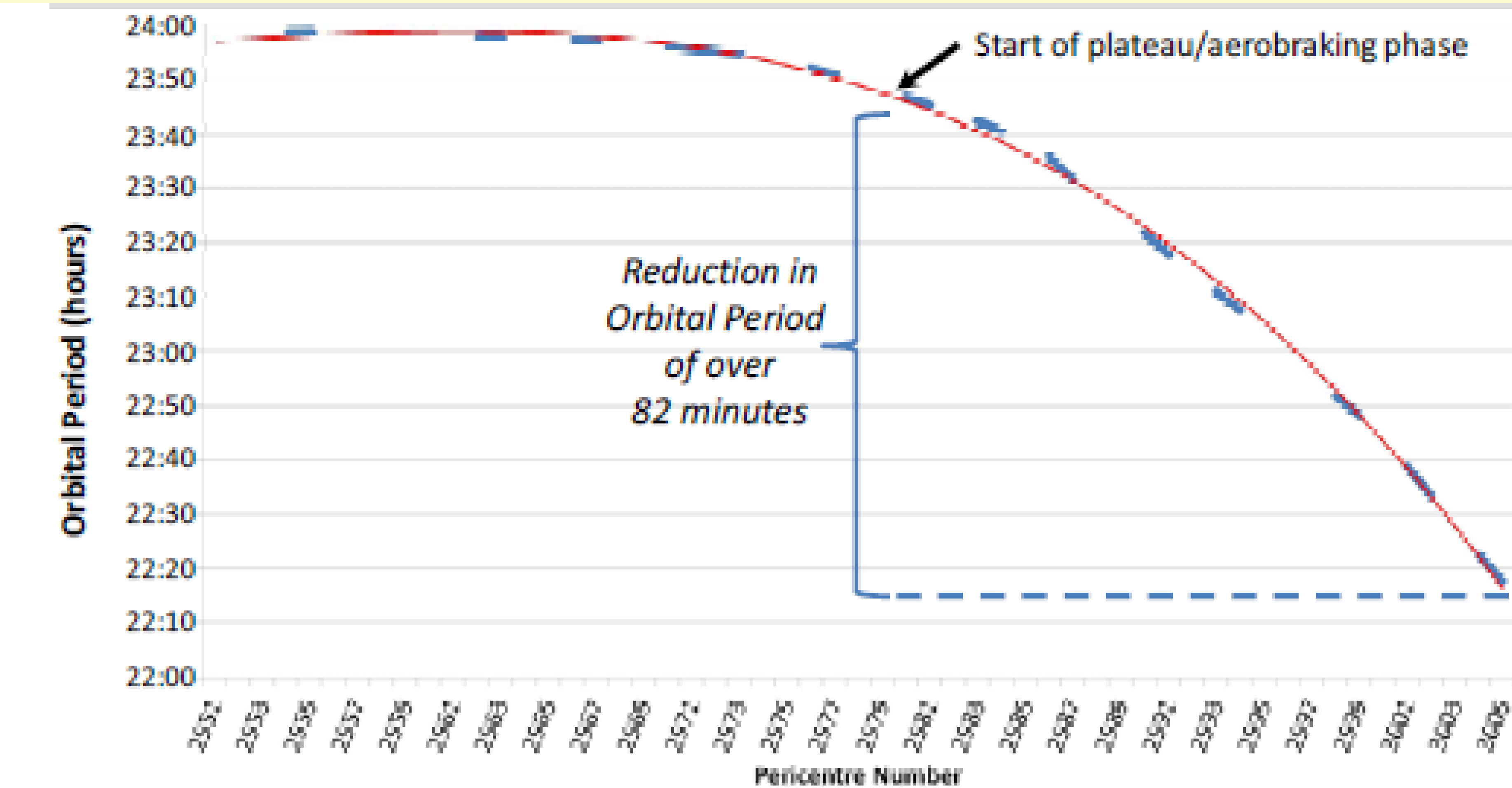
Solar Array response to aerobraking



Using Solar Array temperature as a proxy for Dynamic Pressure



Evolution of Orbital Period



Future operations, post A/B

- Pericentre was lifted to above 450 km
- Limited support by ESOC due to Rosetta
- Limited but sufficient support by VSOC
- At a post A/B review 29 July the s/c and instrument status was assess and accepted for continued operations
- No damages or degraded performances of any kind have been found.
- As long as fuel lasts, operations will continue into 2015, pending an agreement by SPC in November 2014.
- Operations will continue following the same principles and methods as before the aerobraking with the (slight) complication of being in a non 24 h orbit, but with a reduced workforce in MOC and SOC.

Success criteria for Venus Express aerobraking experiment 18/5 - 11/7 2014

- Scientific criteria
  - S1. Record accelerometer data of the maximum density at a signal to noise ratio of at least 5 for a minimum of 20 pericentre passes below 150 km altitude, to enable new models and studies of the atmospheric structure at these altitudes.

    DONE
  - S2. Record traces of the full accelerometer signal below 150 km for at least ten pericentre passes where the pericentre altitude is below 140 km, to study spatial variability and wave phenomena in the atmosphere.

    DONE
  - S3. Record ground station tracking data (off pericentre) for orbital arcs sufficient to allow calculation of orbital decay, for at least 25 orbits with pericentre passes below 165 km altitude, in order to determine the integrated delta-v per pass, to investigate the time variability of the atmosphere.

    DONE

Success criteria for Venus Express aerobraking experiment 18/5 - 11/7 2014

- Technical criteria
  - T1. Achieve a reduction of the orbital period of at least 0.5 hour during the plateau between 18 June and 11 July, to demonstrate the efficiency of aerobraking. **DONE**
  - T2. Make at least six pericentre passes at a dynamic pressure of at least 0.4 N/m^2 including at least 3 passes at a dynamic pressure of at least 0.5 N/m^2, to demonstrate the robustness of the s/c. **DONE**
  - T3. Record temperatures of the solar panel thermal sensors of at least ten pericentre passes below 140 km altitude, in order to evaluate the thermal effects of aerobraking on the solar panels and to verify existing models. **DONE**

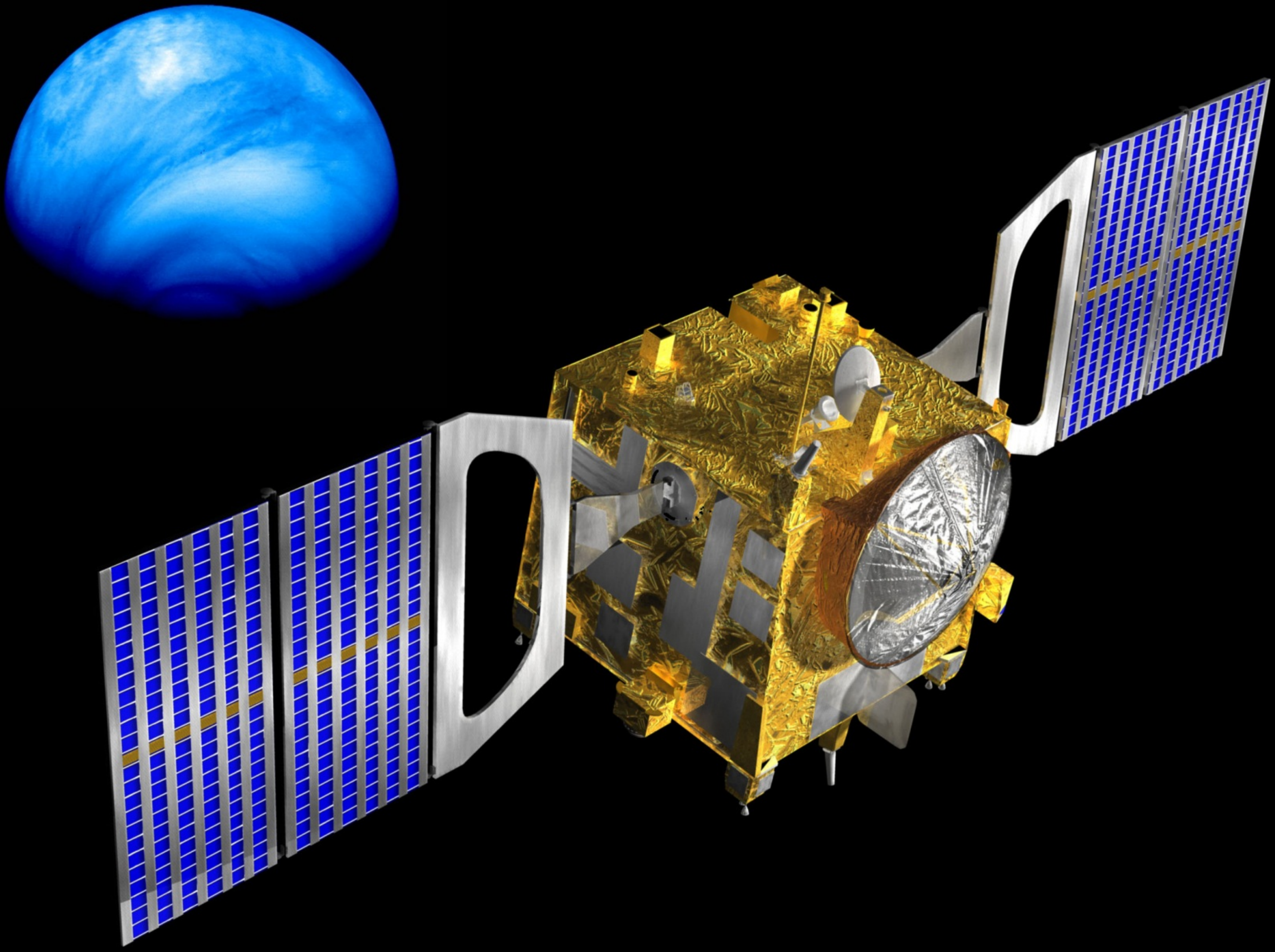
Success criteria for Venus Express aerobraking experiment 18/5 - 11/7 2014

- Technical criteria (cont.)
  - T4. Record data on s/c attitude and thruster firing during Braking Mode of at least ten pericentre passes below 140 km altitude, to analyse s/c dynamic stability.
  - T5. Record temperatures of –Z platform sensors before, during and after aerobraking in order to evaluate possible damage and/or deterioration of MLI.
  - T6. Record data on the electrical performance of the solar panels, to enable comparison of charging characteristics before and after aerobraking and to evaluate possible damage and/or deterioration of the solar panels.

DONE

DONE

DONE



Venus Express – still going strong!