



Control Division, TEC-ECM

# ***Safety Analysis for Stage Reentry of VEGA LV***

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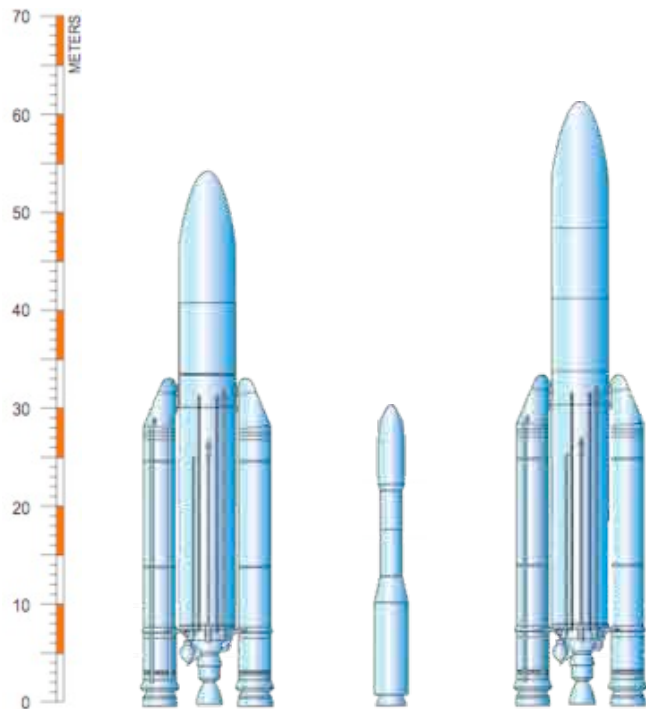
3rd IAASS Conference, October 21st-23rd, 2008

# Presentation guide

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-  VEGA missions
-  VEGA trajectory analysis
-  ASTOS as trajectory tool
-  Safety analysis
-  Way Forward
-  Conclusions

# What is VEGA?

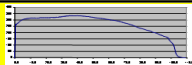


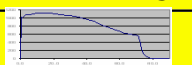
- Europe's answer to launch demand for small and medium spacecraft into low orbits
- Height: 30m
- Diameter: 3m
- Lift-off mass: 137 tons
- Launch from Kourou, French Guiana
- First flight scheduled for end of 2009

# VEGA Stages and Budget



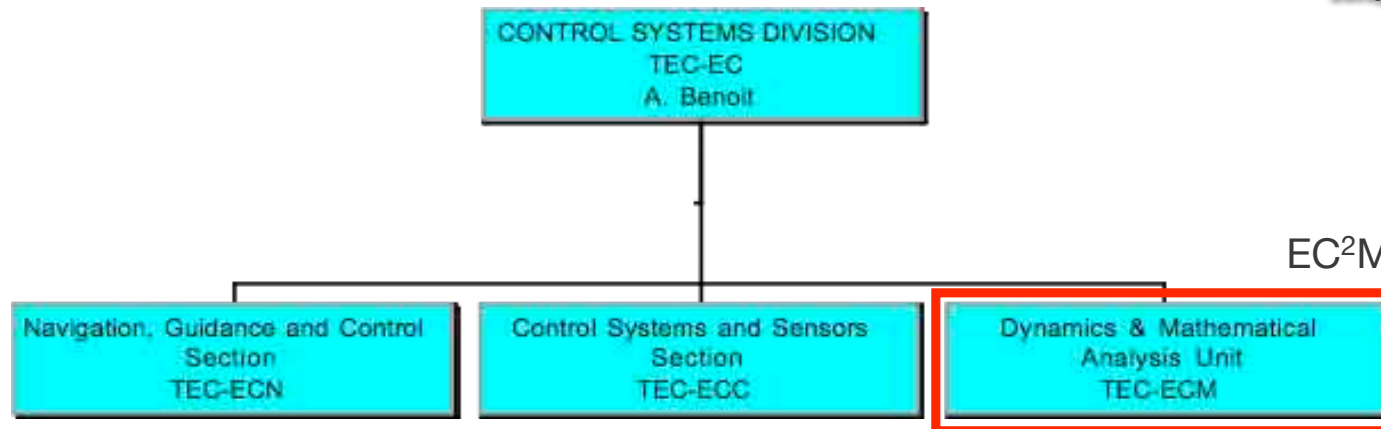
AVUM (*), Liquid	
Structural Mass	600 kg
Propellant	500 kg
Vacuum Isp	300 s

Third Stage Zefiro 9 (*), Solid	
Structural Mass	1400 kg
Propellant	10000 kg
Thrust	

Second Stage Zefiro 23 (*), Solid	
Structural Mass	2500 kg
Propellant	24000 kg
Thrust	

FirstStage P 80FW (*), Solid	
Structural Mass	8000 kg
Propellant	85000 kg
Thrust	Profile of N12

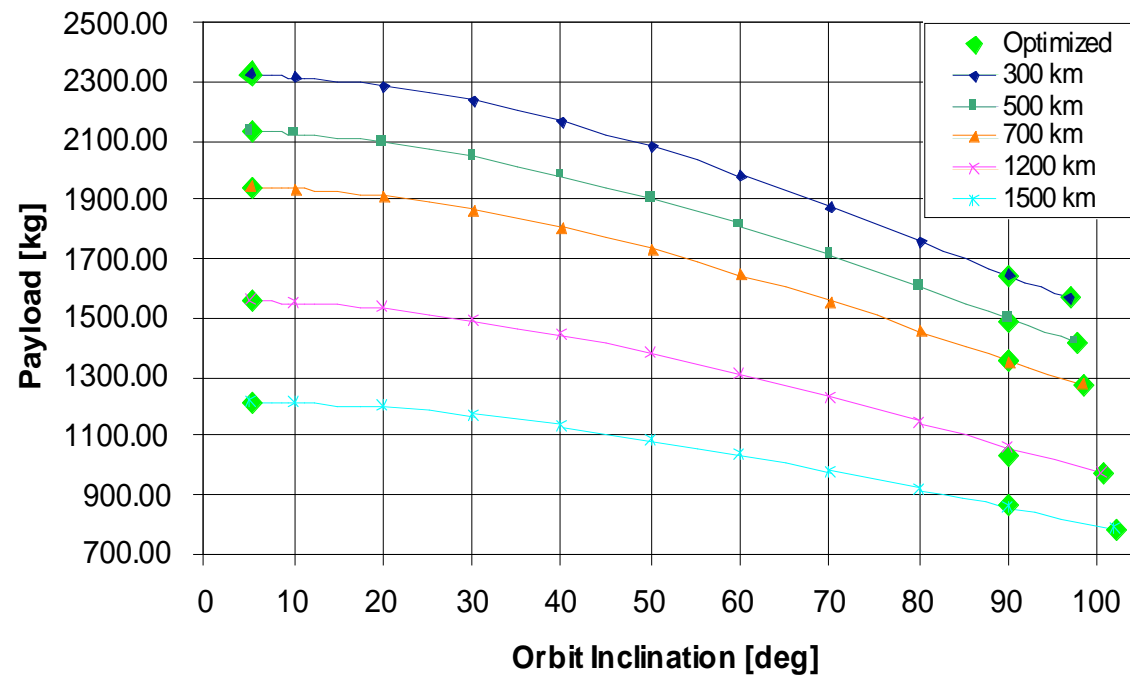
# ESTEC TEC-ECM team



- The Control Division has been supporting VEGA since 1998 i.e. for 10 years (Div. Heads: J.C. Degavre, R. Creasey, and A. Benoit)
- Support to the SDR review and after (1999-2005)
- Support to the CDR review (2006-2007)
- Independent assessments for Vega regularly since 1998
- Support to ELV on cross check of trajectory optimization

# ESTEC TEC-ECM support to ESRIN IPT

- ESTEC TEC-ECM supports ESA-IPT ESRIN computing optimal ascent trajectories using the ASTOS optimization software suite
- Performance maps



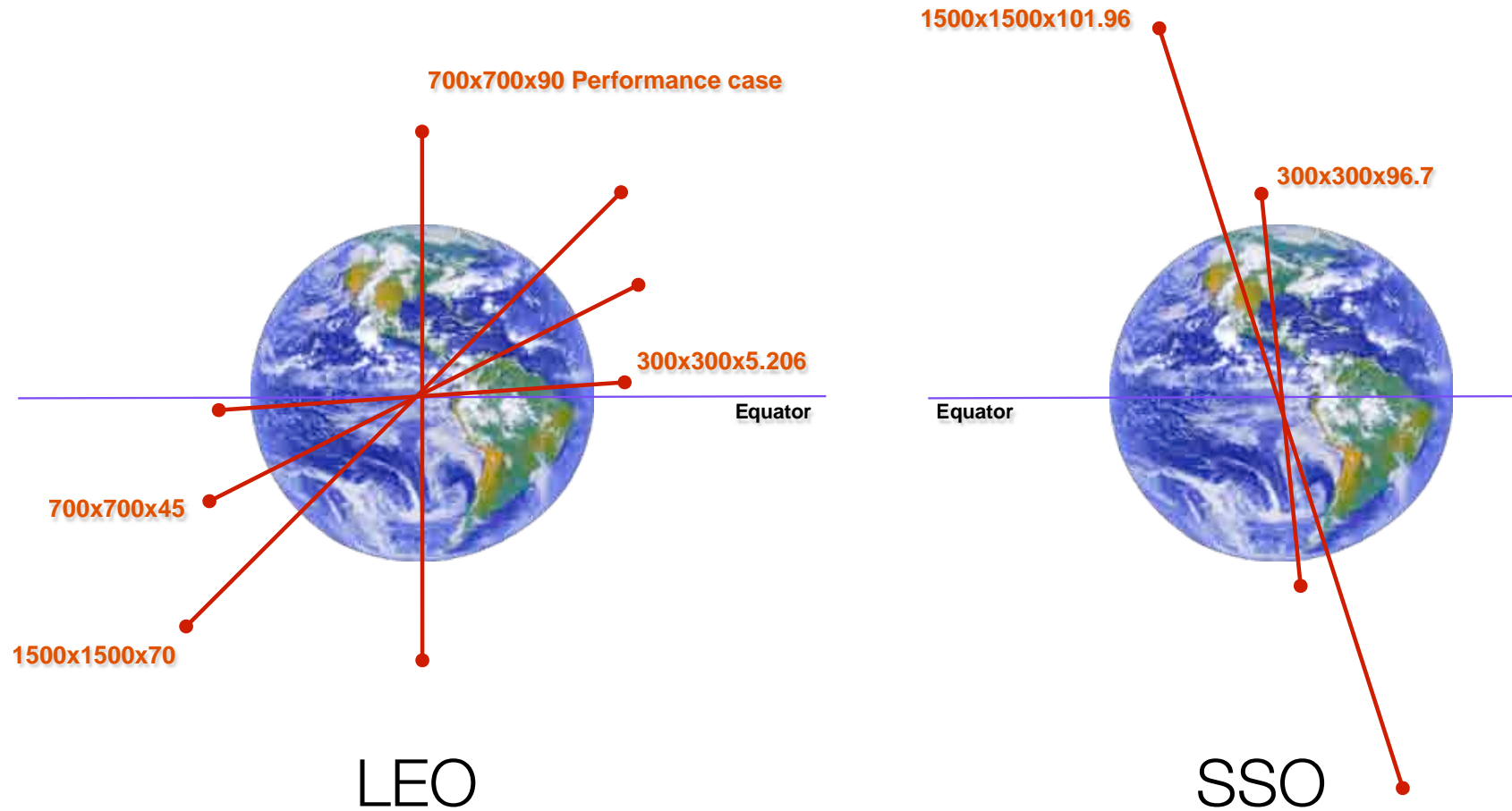
# Two types of performance maps

- Optimization of launcher's trajectories are performed using initial and final boundary conditions, and path constraints
- A launcher uses two types of performance maps: Un-constrained and Constrained
- Un-constrained maps do NOT take into account the complete set of path constraints and boundary conditions like ground station visibility
- Constrained maps take into account the complete set of path constraints and boundary conditions like SAFETY
  - Constrained performance maps deliver (most of the times) less payload mass than Un-constrained ones

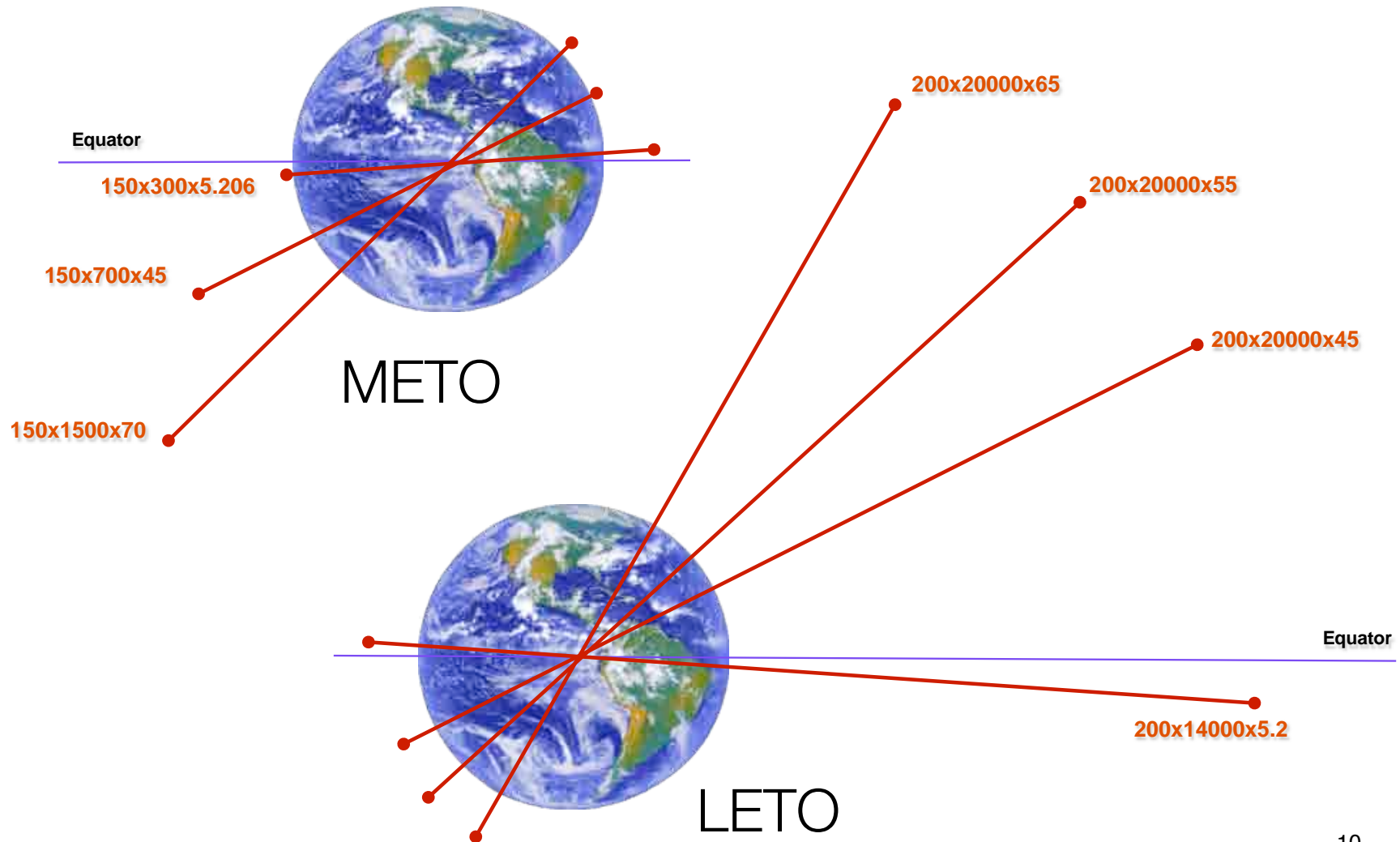
# VEGA performance maps family

- 📌 VEGA family of maps are as follows:
  - 📌 LEO (Low Earth Orbit): orbits with altitudes from 300 Km to 1500 Km with all inclinations except SSO
  - 📌 METO (Medium Earth and Transfer Orbit): “escape” orbits with apogee of 20000 Km and inclinations between 45 and 70 deg
  - 📌 LETO (Low Earth and Transfer Orbit): escape elliptic orbits, having perigee at 150 km with apogee from 300 Km to 1500 Km with all inclinations except SSO
  - 📌 SSO (Sun Synchronous Orbit): orbits with altitudes from 300 Km to 1500 Km SSO inclinations

# VEGA nominal performance cases: LEO and SSO




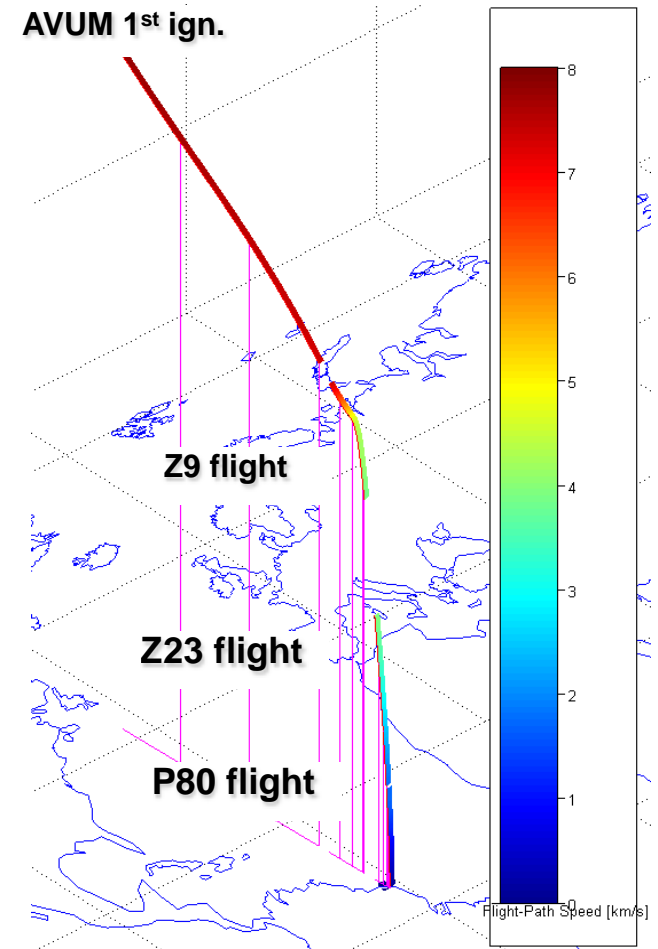
# VEGA nominal performance cases: METO and LETO



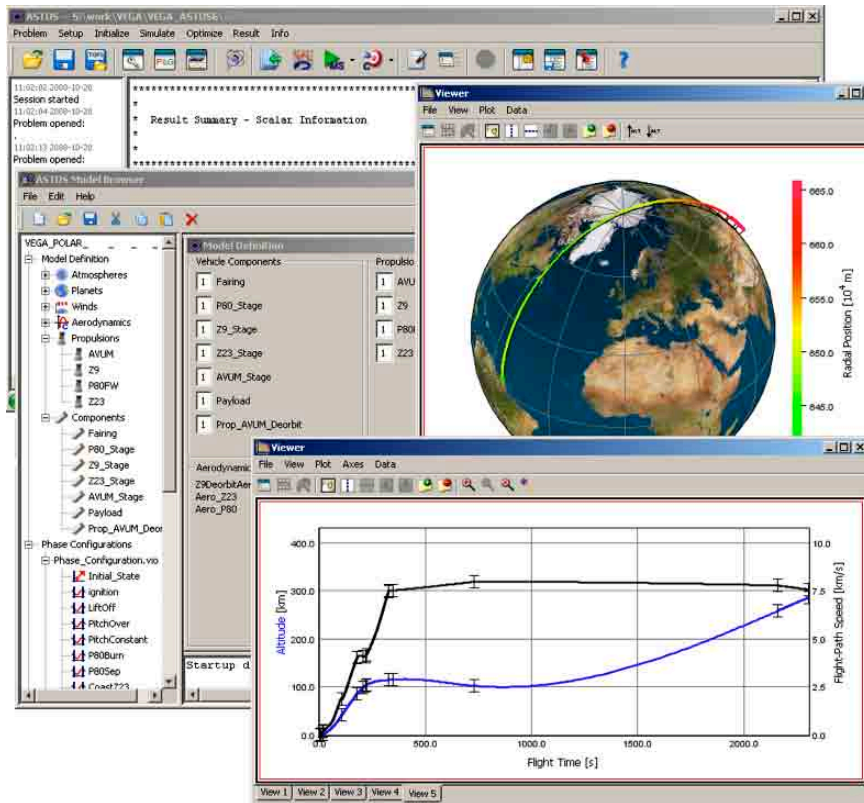
# Computation of performance maps by TEC-ECM

- Computation of trajectories in all maps
- Un-constrained and constrained cases
- Results are delivered in a spreadsheet
  - Number of parameters per each state vector is 191
  - Simulation data every 0.01 seconds

 <b>VEGA launcher trajectory analysis</b>																		
Normalized Flight Time [s]	Radial position [m]	Geometric longitude [rad]	Declination [rad]	Inertial radial velocity [m/s]	Inertial longitudinal velocity [m/s]	Inertial latitudinal velocity [m/s]	Propellant mass of tank in stage P00_Stage	Station_Visibility constraint	Station_Visibility constraint	Station_Visibility constraint	Station_Visibility constraint	Station_Visibility constraint	Station_Visibility constraint	Time [s]	Flight Time [s]			
9	0.00E+00	0.30E+06	-0.21E-01	0.50E-02	1.00E-03	4.83E-02	0.00E+00	0.85E+04	-4.34E-02	-1.72E-01	-1.43E+00	-1.37E+00	-2.98E-01	0.00E+00	0.00E+00			
10	1.00E-02	0.30E+06	-0.21E-01	0.50E-02	2.79E-01	4.83E-02	-2.14E-04	0.85E+04	-4.34E-02	-1.72E-01	-1.43E+00	-1.37E+00	-2.98E-01	3.00E-02	3.00E-02			
11	2.00E-02	0.30E+06	-0.21E-01	0.50E-02	5.59E-01	4.83E-02	-4.27E-04	0.85E+04	-4.34E-02	-1.72E-01	-1.43E+00	-1.37E+00	-2.98E-01	7.20E-02	7.20E-02			
12	3.00E-02	0.30E+06	-0.21E-01	0.50E-02	8.29E-01	4.83E-02	-6.41E-04	0.85E+04	-4.34E-02	-1.72E-01	-1.43E+00	-1.37E+00	-2.98E-01	1.08E-01	1.08E-01			
13	4.00E-02	0.30E+06	-0.21E-01	0.50E-02	1.10E+00	4.83E-02	-8.55E-04	0.85E+04	-4.34E-02	-1.72E-01	-1.43E+00	-1.37E+00	-2.98E-01	1.44E-01	1.44E-01			
14	5.00E-02	0.30E+06	-0.21E-01	0.50E-02	1.38E+00	4.83E-02	-1.07E-03	0.85E+04	-4.34E-02	-1.72E-01	-1.43E+00	-1.37E+00	-2.98E-01	1.80E-01	1.80E-01			
15	6.00E-02	0.30E+06	-0.21E-01	0.50E-02	1.66E+00	4.83E-02	-1.29E-03	0.85E+04	-4.34E-02	-1.72E-01	-1.43E+00	-1.37E+00	-2.98E-01	2.16E-01	2.16E-01			
16	7.00E-02	0.30E+06	-0.21E-01	0.50E-02	1.94E+00	4.83E-02	-1.50E-03	0.85E+04	-4.34E-02	-1.72E-01	-1.43E+00	-1.37E+00	-2.98E-01	2.52E-01	2.52E-01			
17	8.00E-02	0.30E+06	-0.21E-01	0.50E-02	2.22E+00	4.83E-02	-1.71E-03	0.85E+04	-4.34E-02	-1.72E-01	-1.43E+00	-1.37E+00	-2.98E-01	2.88E-01	2.88E-01			
18	9.00E-02	0.30E+06	-0.21E-01	0.50E-02	2.50E+00	4.83E-02	-1.92E-03	0.85E+04	-4.34E-02	-1.72E-01	-1.43E+00	-1.37E+00	-2.98E-01	3.24E-01	3.24E-01			
19	1.00E-01	0.30E+06	-0.21E-01	0.50E-02	2.78E+00	4.83E-02	-2.14E-03	0.85E+04	-4.34E-02	-1.72E-01	-1.43E+00	-1.37E+00	-2.98E-01	3.60E-01	3.60E-01			
20	1.10E-01	0.30E+06	-0.21E-01	0.50E-02	3.06E+00	4.83E-02	-2.35E-03	0.79E+04	-4.34E-02	-1.72E-01	-1.43E+00	-1.37E+00	-2.98E-01	3.96E-01	3.96E-01			
21	1.20E-01	0.30E+06	-0.21E-01	0.50E-02	3.34E+00	4.83E-02	-2.56E-03	0.73E+04	-4.34E-02	-1.72E-01	-1.43E+00	-1.37E+00	-2.98E-01	4.32E-01	4.32E-01			
22	1.30E-01	0.30E+06	-0.21E-01	0.50E-02	3.62E+00	4.83E-02	-2.78E-03	0.67E+04	-4.34E-02	-1.72E-01	-1.43E+00	-1.37E+00	-2.98E-01	4.68E-01	4.68E-01			



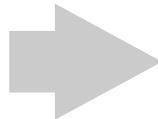
# ASTOS for Trajectory Optimization



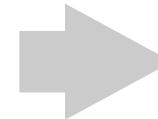
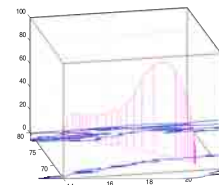
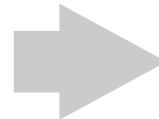
- Reference tool for ascent, re-entry and transfer trajectory optimization,
- Direct access to multiple optimal solvers (SLSQP, SNOPT, SOCS),
- Drag-and-drop scenario, model and mission description,
- Initial guess generator with vast set of guidance schemes,
- Precise simulation of end-to-end trajectories,
- Monitoring and visualization.

# Trajectory Safety Analysis: HOWTO

Input data



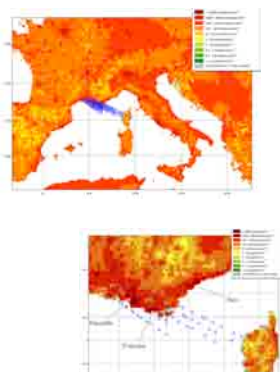
**Entry Analysis**



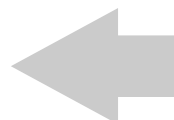
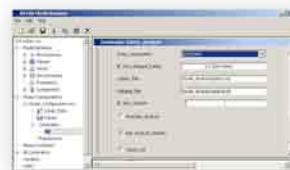
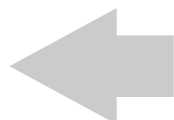
**Safety Analysis**



**DARS, DIA**



**Risk Assessment Analysis**







**RAM**



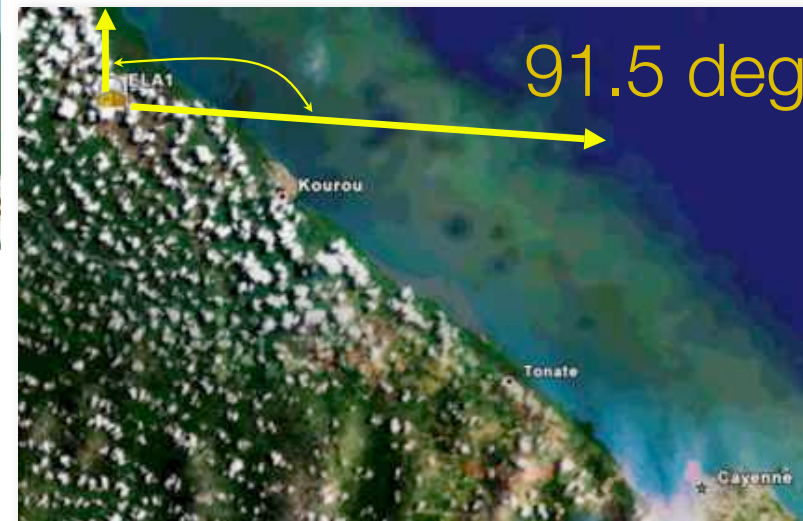
# TEC-ECM independent performance verification

- 📌 Optimizable trajectory has been set up in precise 17-phase configuration
- 📌 Model description has been extracted from VEGA documentation
- 📌 Ascent guidance profile
- 📌 Uses initial and final boundary conditions and path constraints
- 📌 All rocket data needed, such as
  - 📌 Mass budget
  - 📌 Propulsion performance profiles
  - 📌 Aerodynamic coefficients
  - 📌 Stage separation procedures

## Example of flight constraints

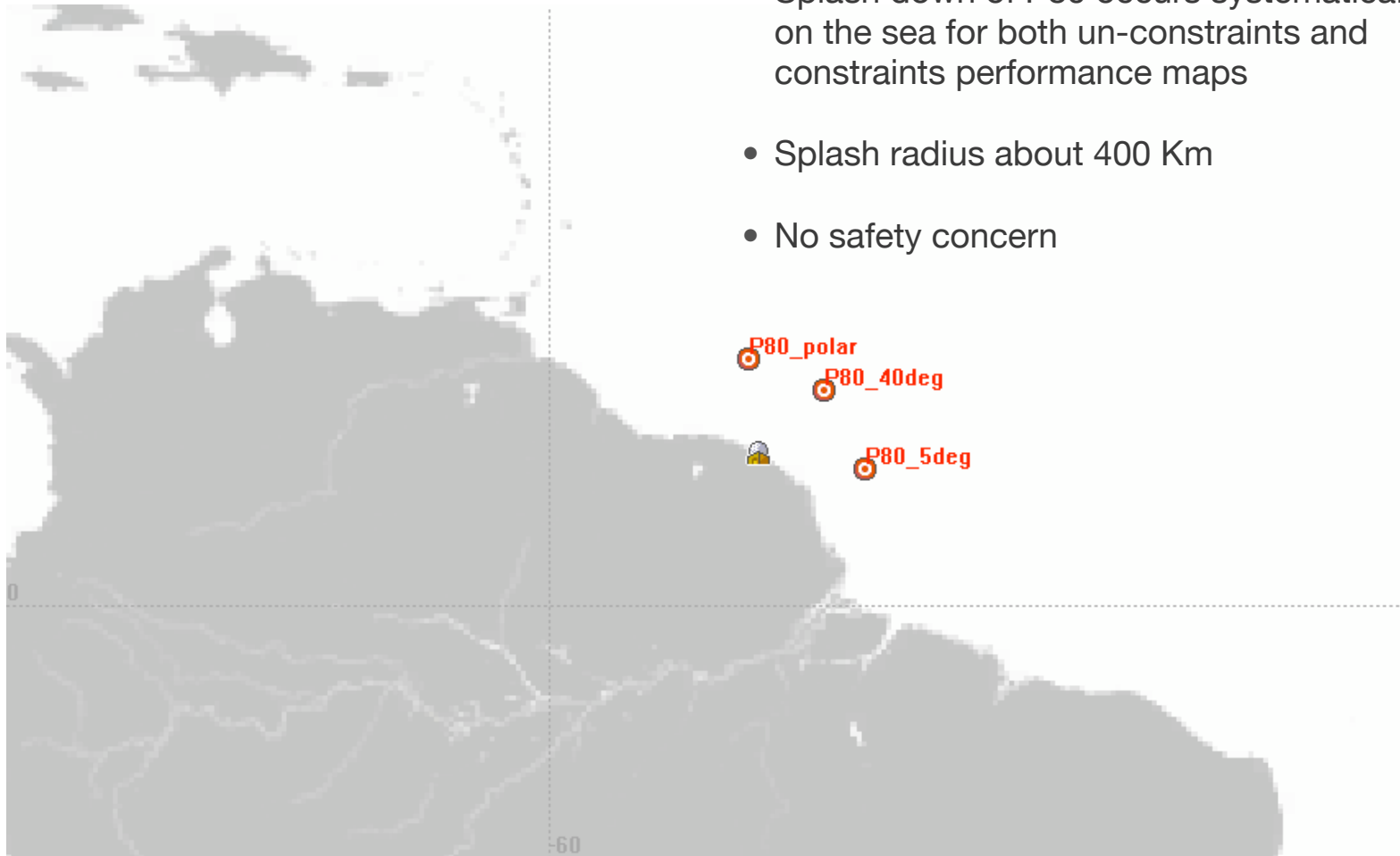
-  Launch pad clearance: the minimum altitude for initiating the pitch-over maneuver is A m
-  Heat flux: the heat flux on the PL, evaluated in free-molecular flow regime ( $Q_w = 1/2\rho u^3$ ), shall be lower than B W/m<sup>2</sup>.
-  Telecommand: the flight path shall be visible from Kourou ground station up to 3rd stage motor burn-out; elevation of the LV above the ground station horizon shall be at all times greater than C°
-  Telemetry: the flight path shall be visible from suitable ground stations during all the powered phases and at P/L release; elevation of the LV above the ground stations horizon shall be at all times greater than D°

# Kourou range flight space



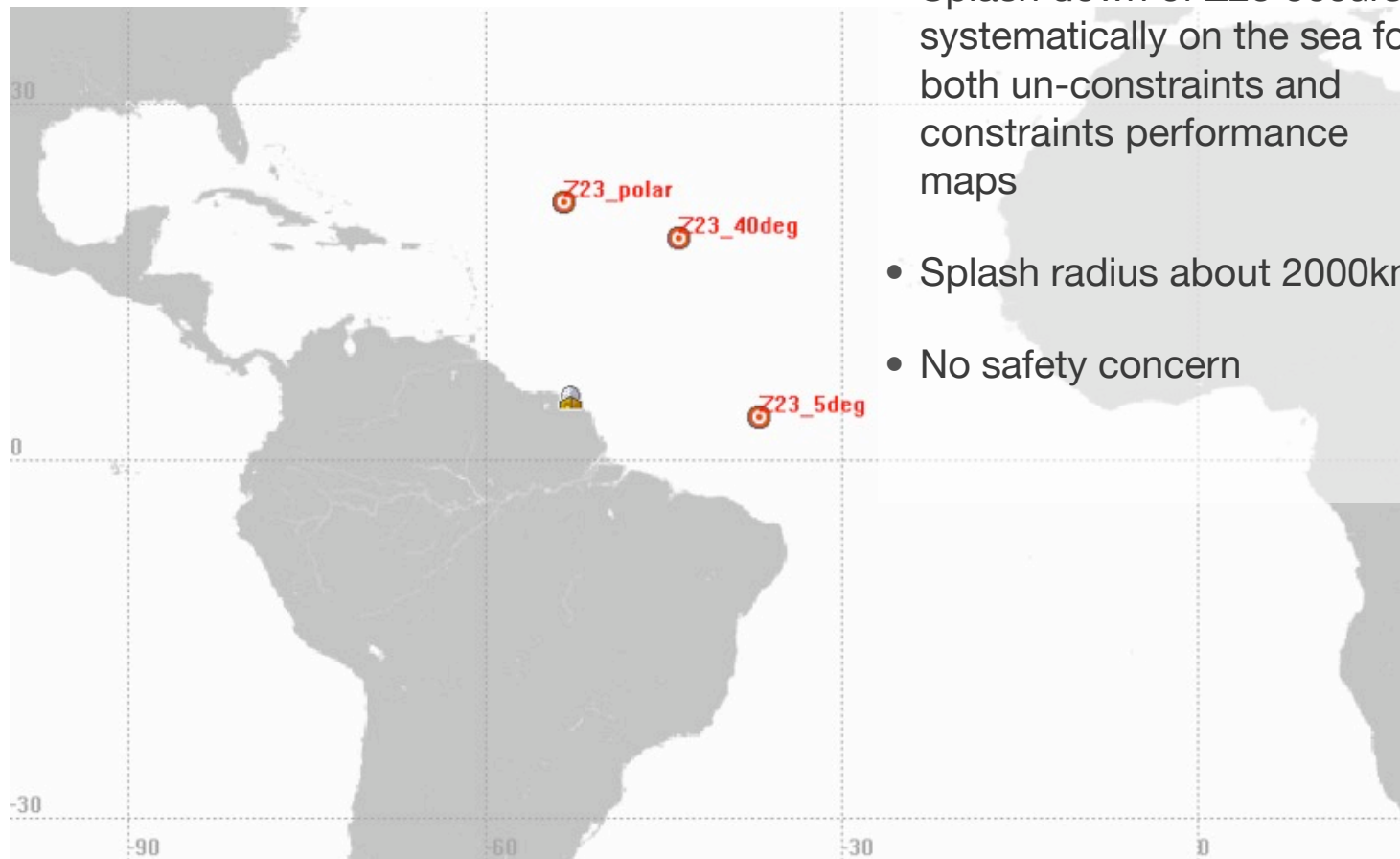
- Safety rules require not to fly over populated areas (i.e. Kourou city, Tonate, and Cayene)

# P80 Splash down



- Splash down of P80 occurs systematically on the sea for both un-constraints and constraints performance maps
- Splash radius about 400 Km
- No safety concern

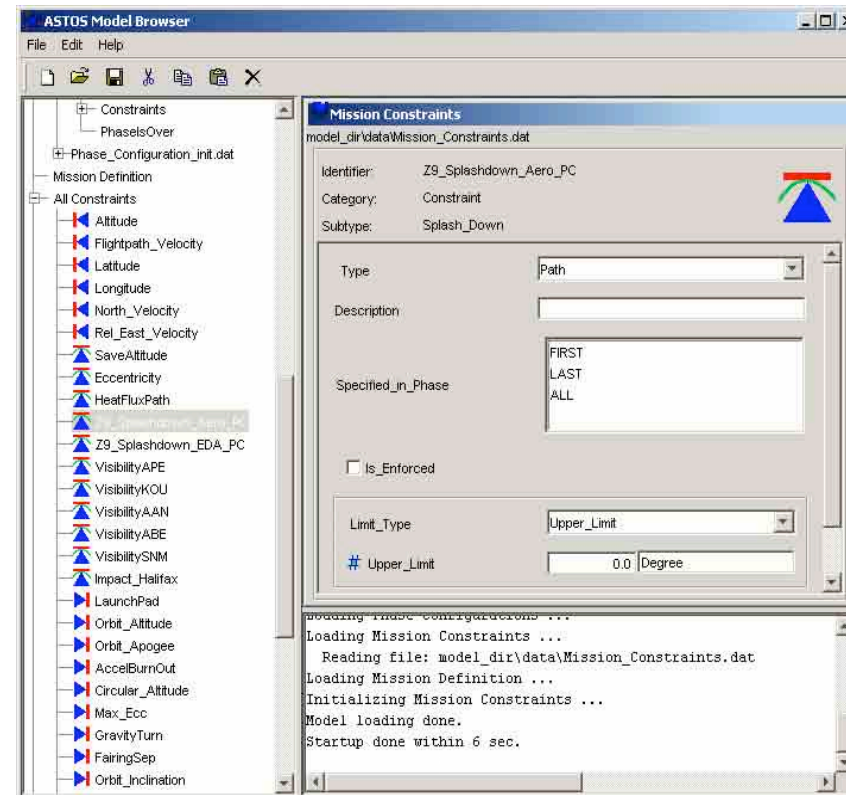
# Z23 Splash Down



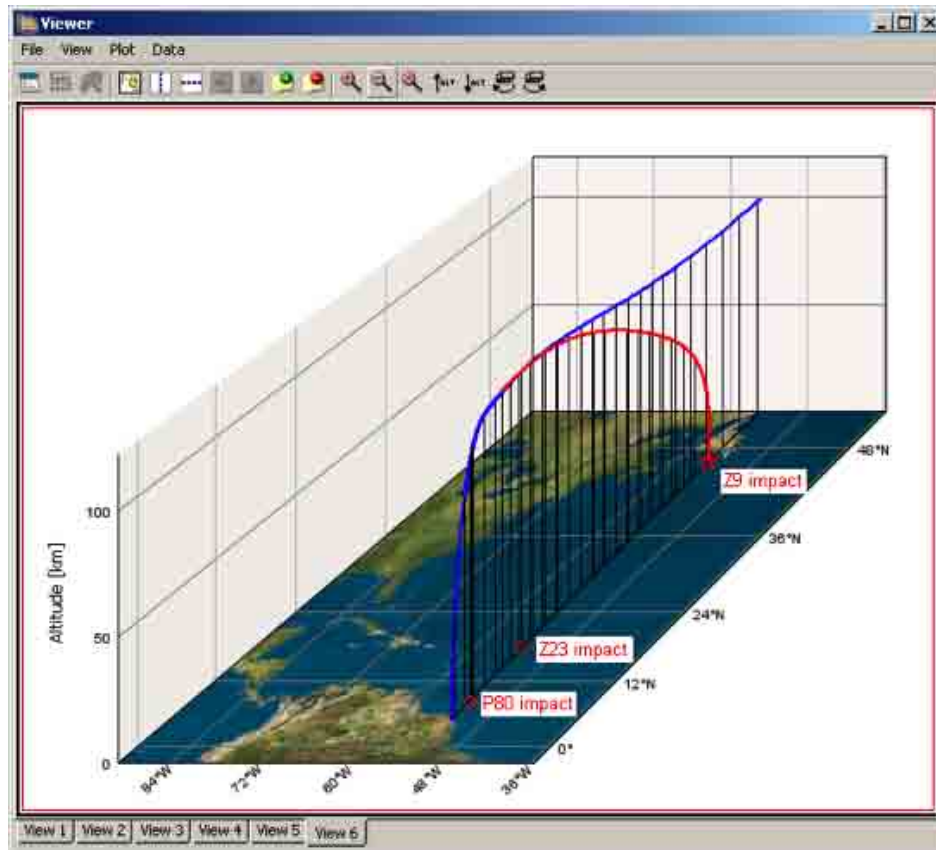
- Splash down of Z23 occurs systematically on the sea for both un-constraints and constraints performance maps
- Splash radius about 2000km
- No safety concern

# Z9 constrained flight: Splash Down

- In order to improve safety, Z9 splash down can be **CONSTRAINED** to fall in the sea, far away from populated areas
- This new constraint...
  - modifies the orbital arguments of the Z9 stage
  - changes the trajectory of VEGA
  - impacts the performance of the launcher

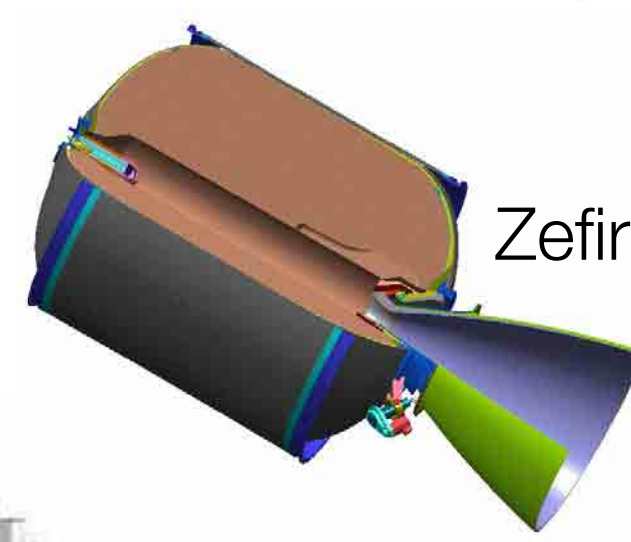


# Z9 constrained flight: Splash Down



- Safety constraints studied:
  - Z9 splash down not to pose potential harm to humans or property
  - No-fly zones directly above densely populated areas
  - Accompanying constraints on ground station visibility
  - Casting error in Zefiro production
- Results in max payload reduction

# Details of Zefiro-9 and AVUM stages



Zefiro-9

AVUM



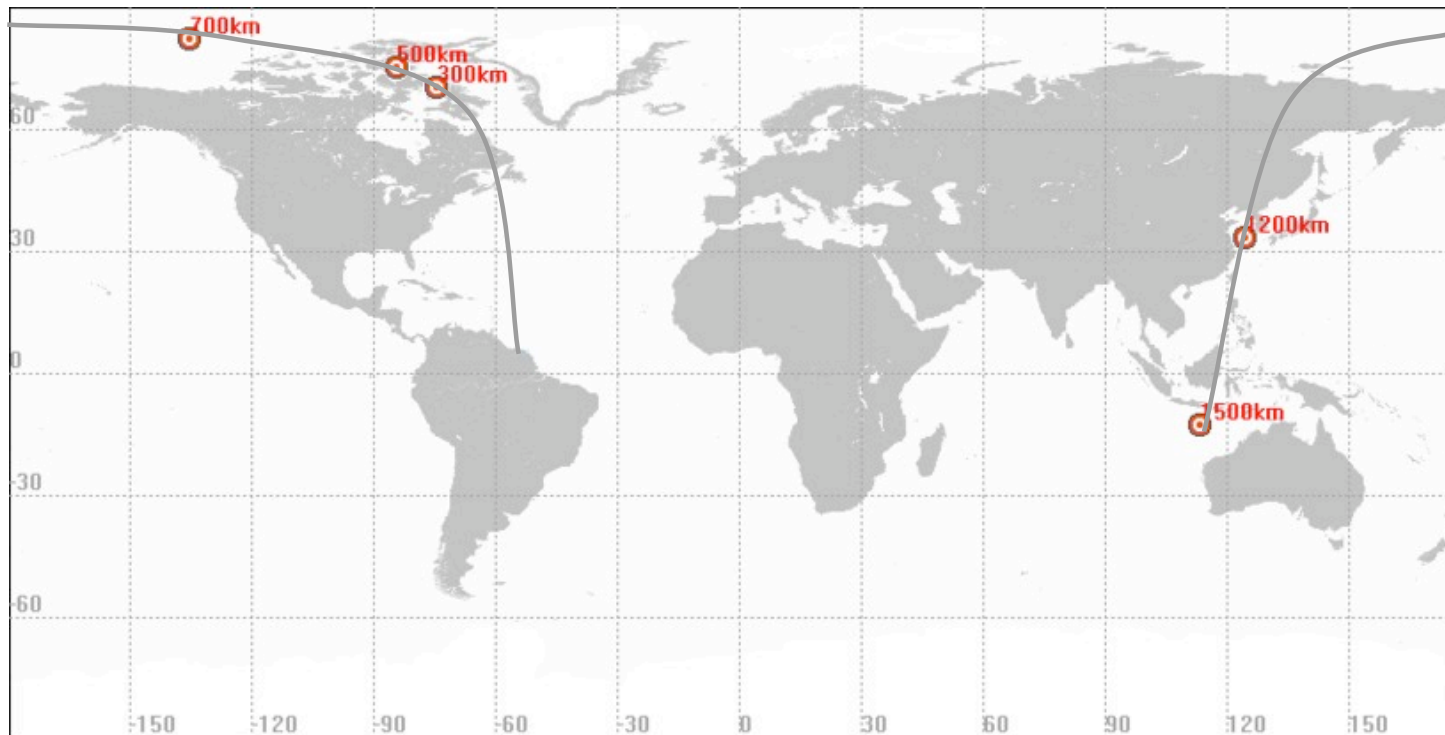
# Z9 Splash Down: POLAR (un-constrained)

- Un-constrained, maximum payload is assumed:
- At low altitudes, Z9 splashes from the Labrador Sea to the North Pole
- At medium altitudes, Z9 splashes in Siberia, Russia, Mongolia, China, Indonesia, and Java
- At high altitudes, Z9 splashes in West Australia, Indic Ocean, and Antarctica



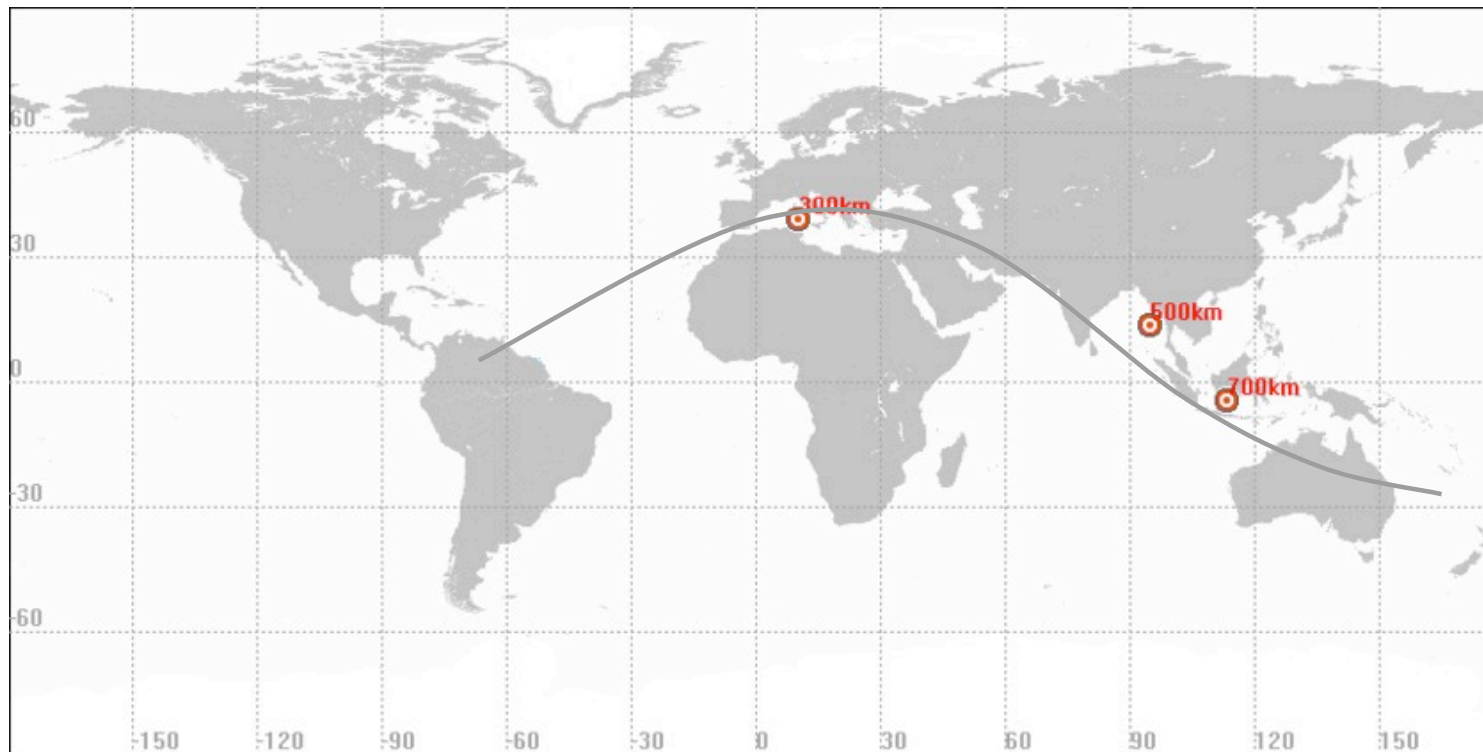
# Z9 Splash Down: SSO (un-constrained)

- Un-constrained, maximum payload is assumed:
- At low altitudes, Z9 splashes in the Baffin and Victoria islands
- At medium altitudes, Z9 splashes North pole
- At high altitudes, Z9 splashes in Siberia, Russia, Korea, Philippines, Indonesia, and Antarctica



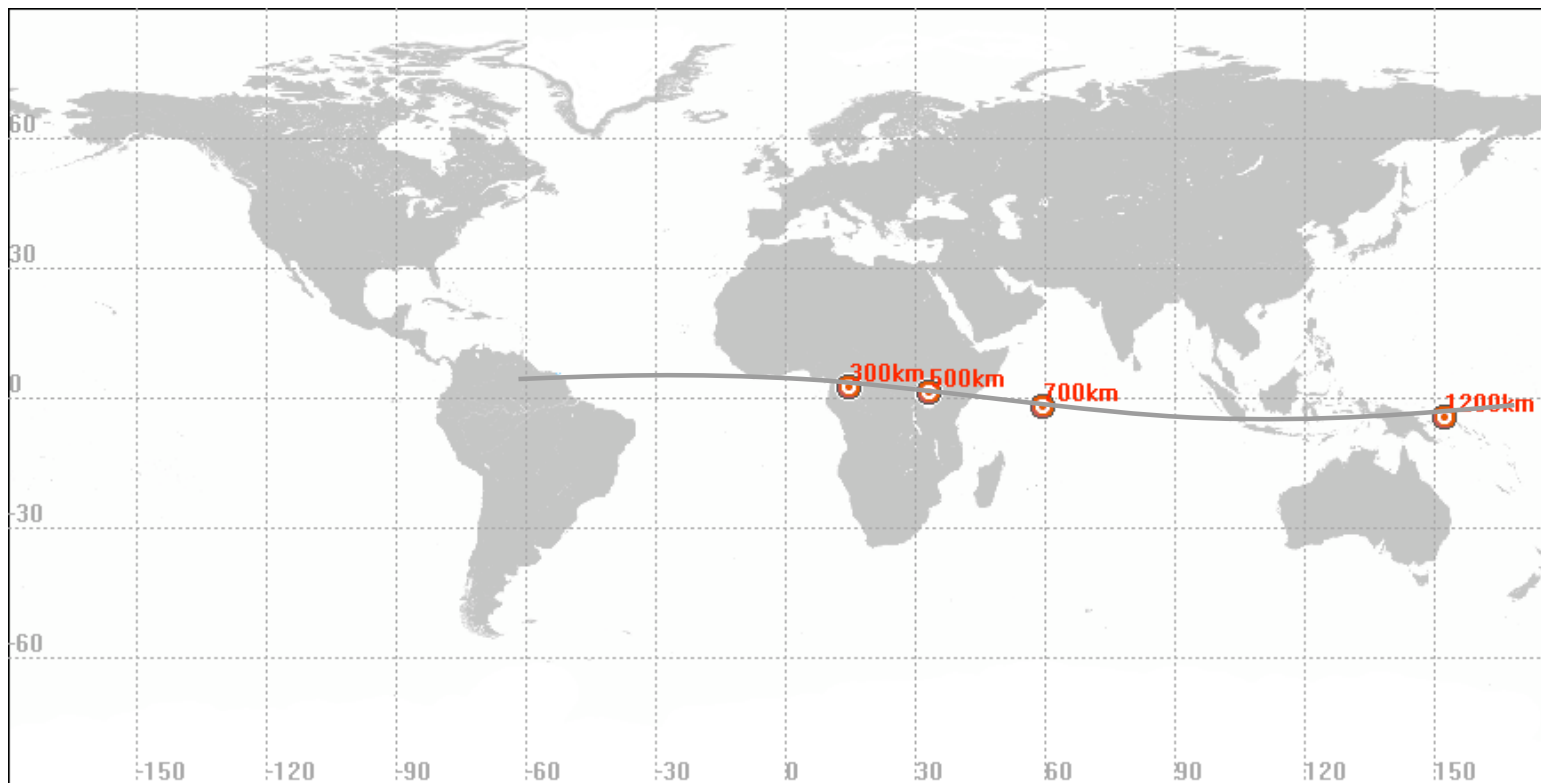
# Z9 Splash Down: 40 Deg (un-constrained)

- Un-constrained, maximum payload is assumed:
- At low altitudes, Z9 splashes in Malta, Lebanon, India
- At medium altitudes, Z9 splashes in Malaysia, Indonesia
- At high altitudes, Z9 splashes in the Pacific Ocean

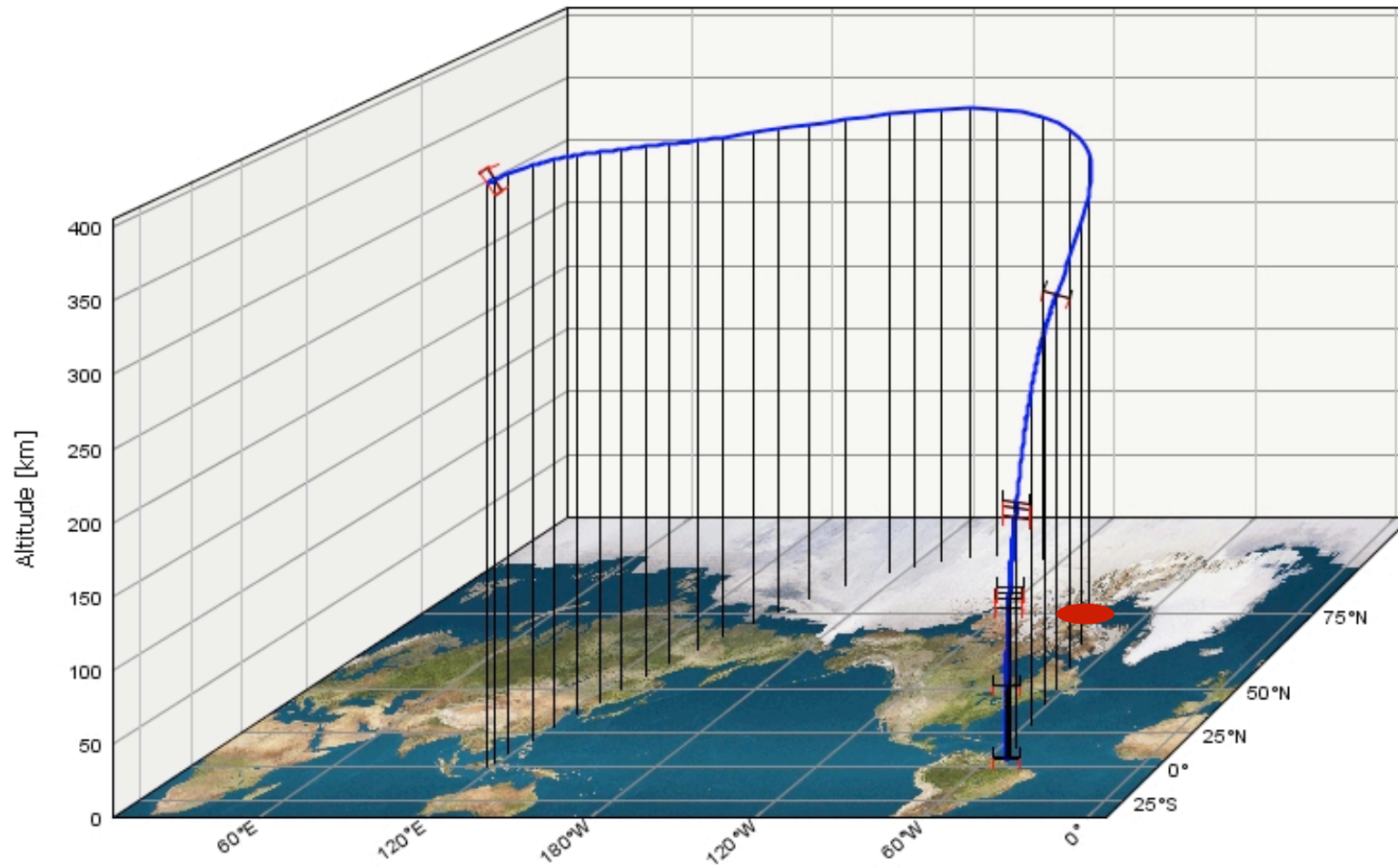


# Z9 Splash Down: 5.2 deg (un-constrained)

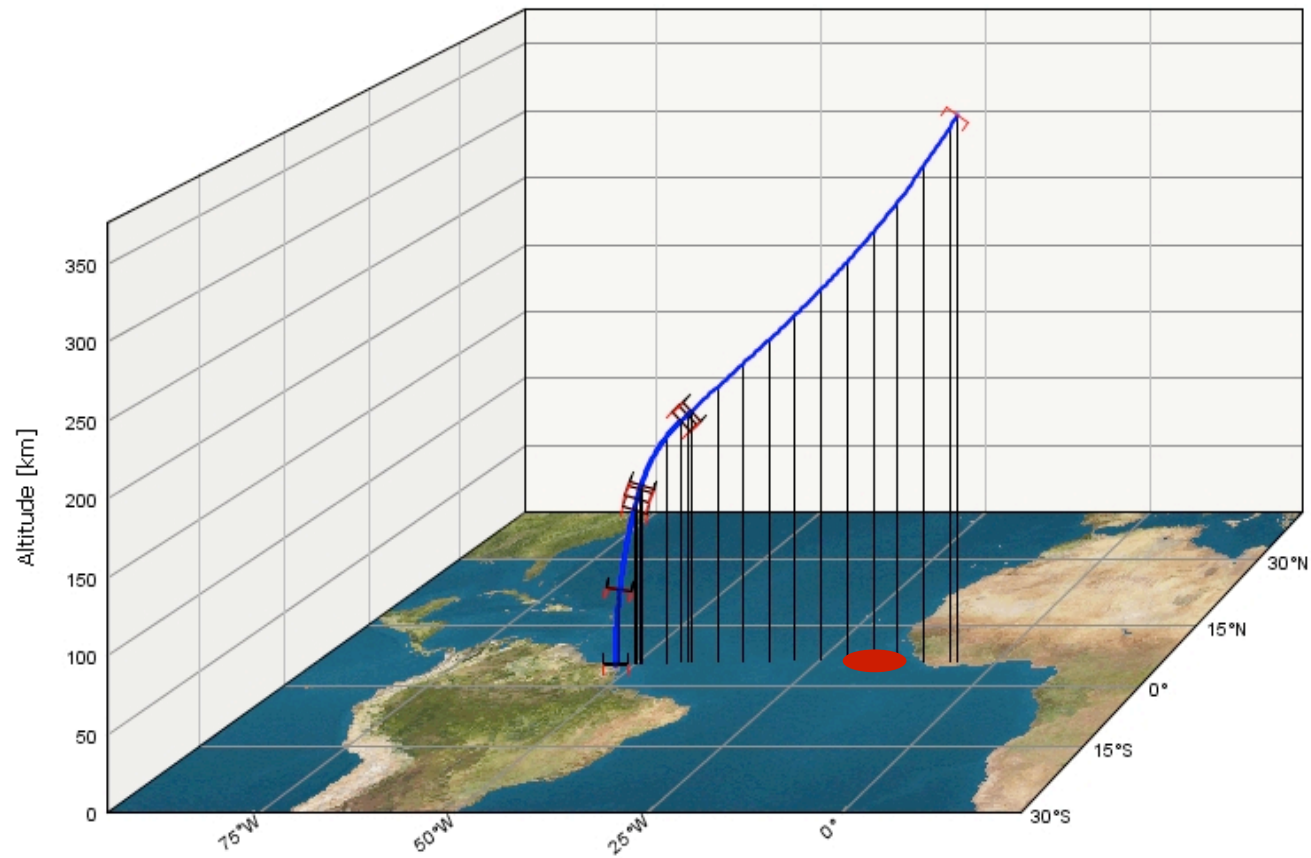
- Un-constrained, maximum payload is assumed:
- At low altitudes, Z9 splashes in Congo, Kenya
- At medium altitudes, Z9 splashes in the Indic Ocean
- At high altitudes, Z9 splashes in Papua New Guinea, and the Pacific Ocean



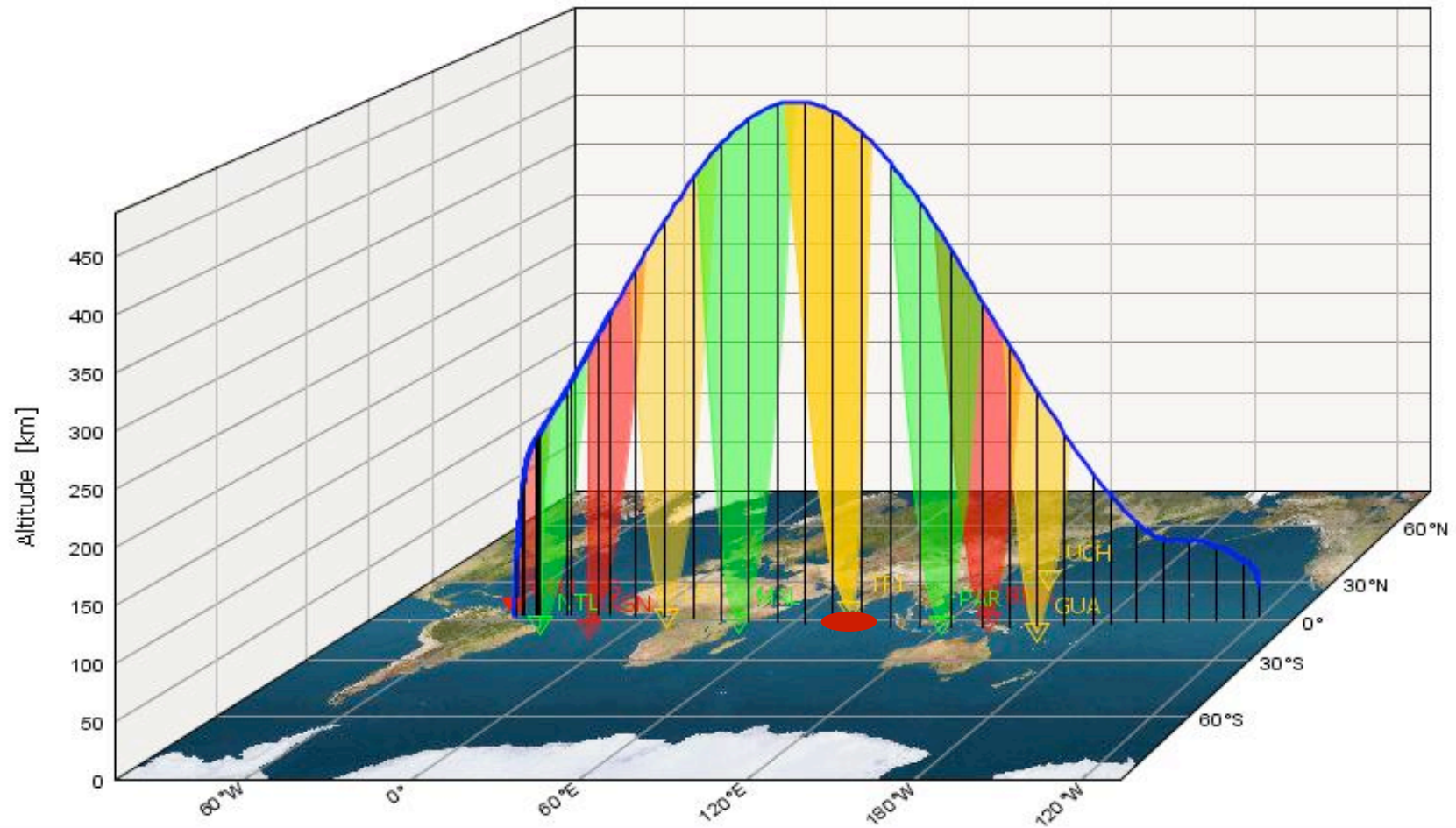
# Aeolus trajectory



# LISA Pathfinder Trajectory






# IXV trajectory



## Conclusions

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-  Under D/LAU request, ESTEC performs independent analysis and verification of VEGA performance with safety constraints
-  ECM computes optimal ascent trajectories using the ASTOS optimization software suite
-  All constraints were taken into account, including safety