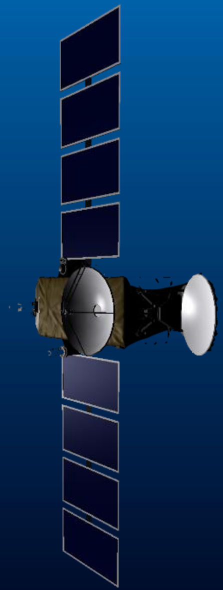
International GNSS Service (IGS): Orbit Dynamics, Modeling and Timing

IGS Advances and Future Applications



Professor Marek Ziebart

Chair, IGS Satellite Vehicle Orbit Dynamics Working Group

IGS Governing Board Member

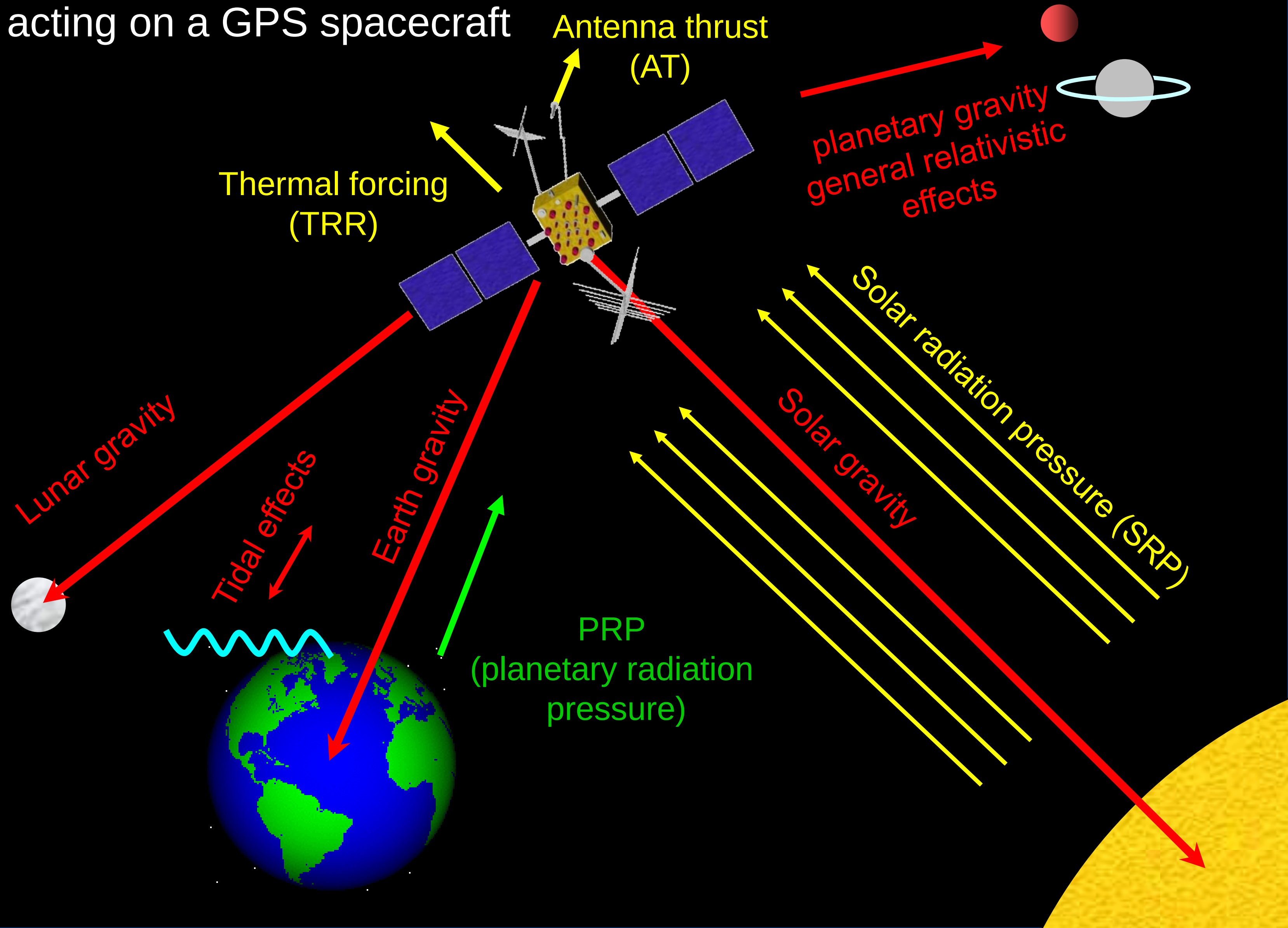
Director, Space Geodesy and Navigation Laboratory

University College London

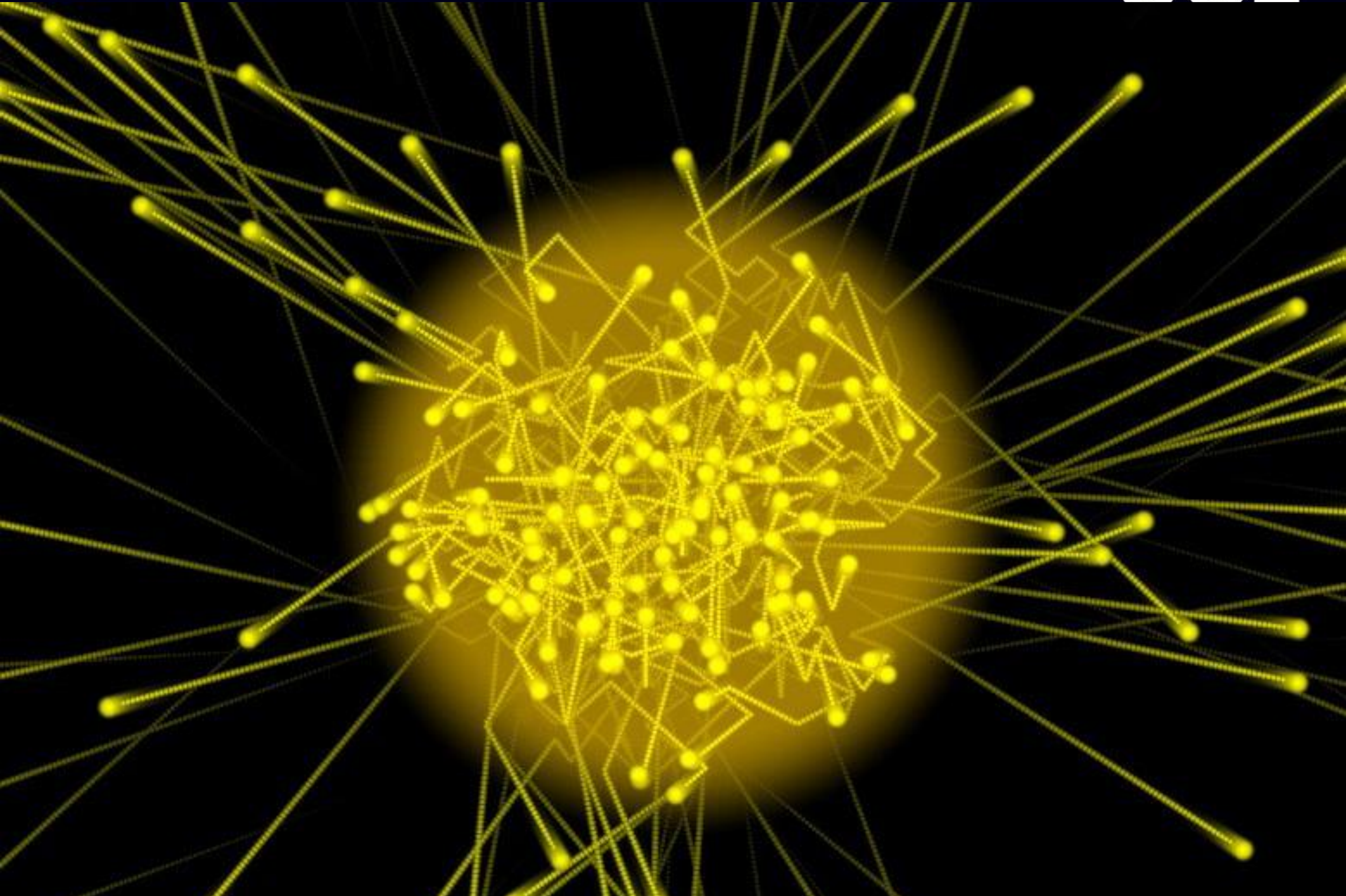
17th PNT Advisory Board Meeting, Washington DC May 19, 2016

Orbits and clocks: defining the reference frame

Forces acting on a GPS spacecraft



Photons and Radiation Pressure



The Maths……….

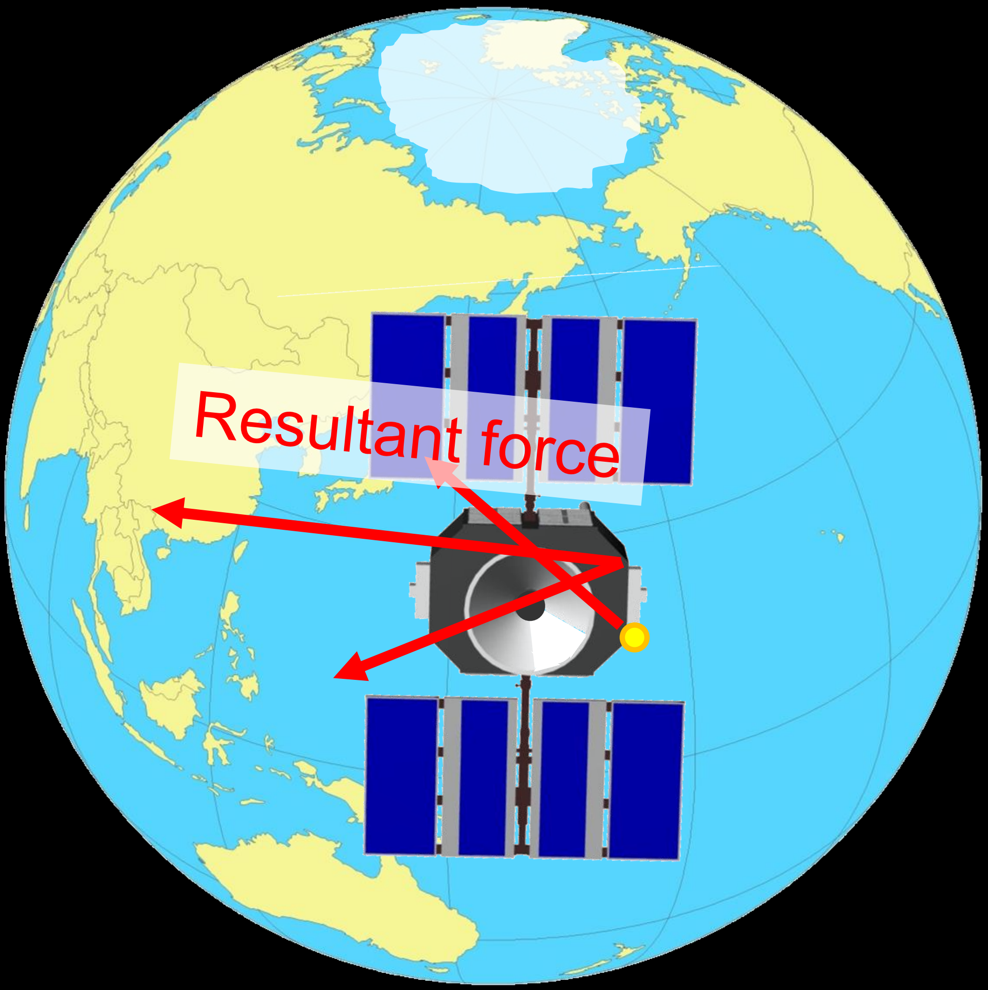
$$E = mc^2$$

For Photons:

$$\rho = E/c$$

Momentum = Energy/speed of light

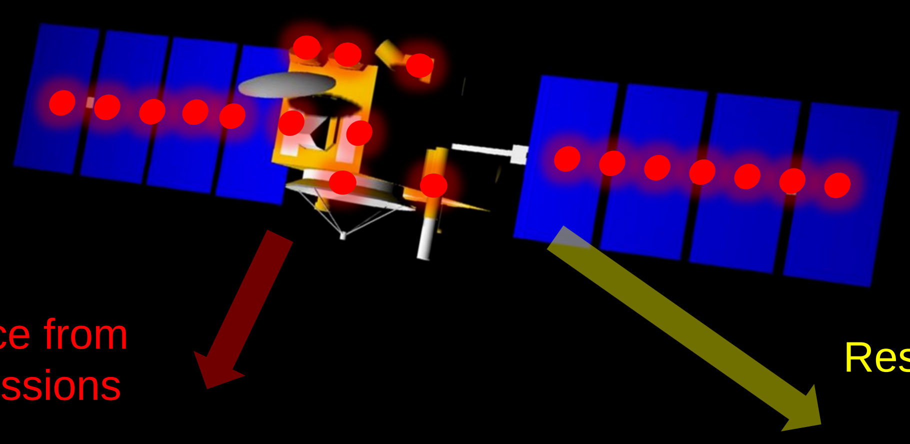
Radiation Pressure

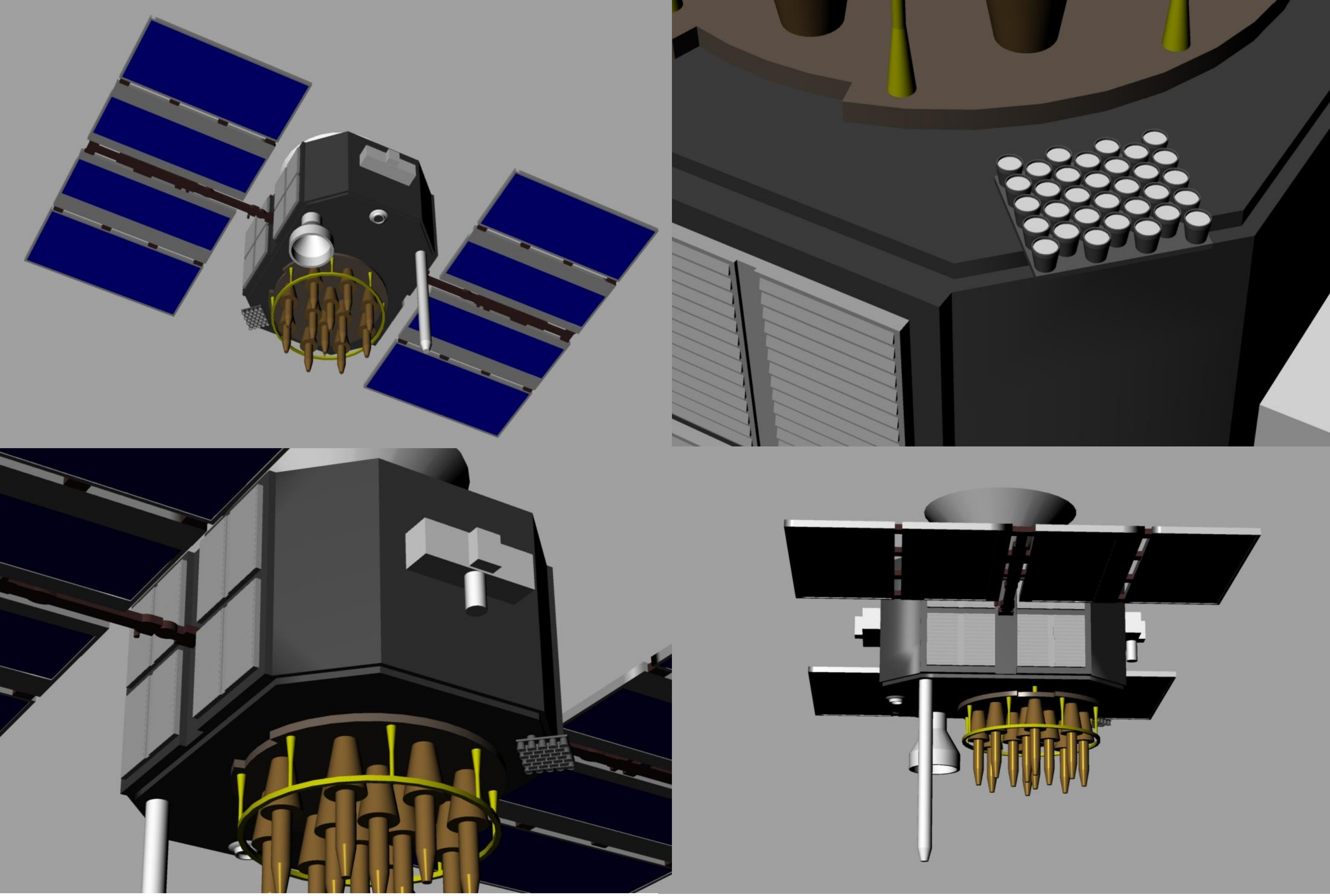


Solar radiation pressure

Thermal Re-radiation forces

How big are these forces?
What effect do they have?



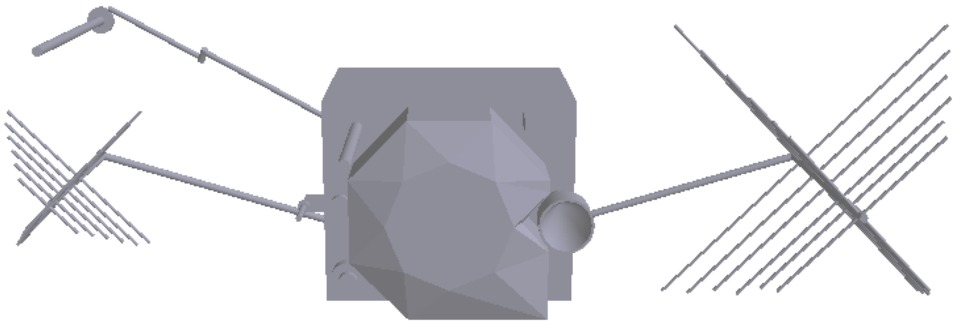


We develop a detailed structural computer model of the spacecraft

Ray Tracing - 1

Geometry

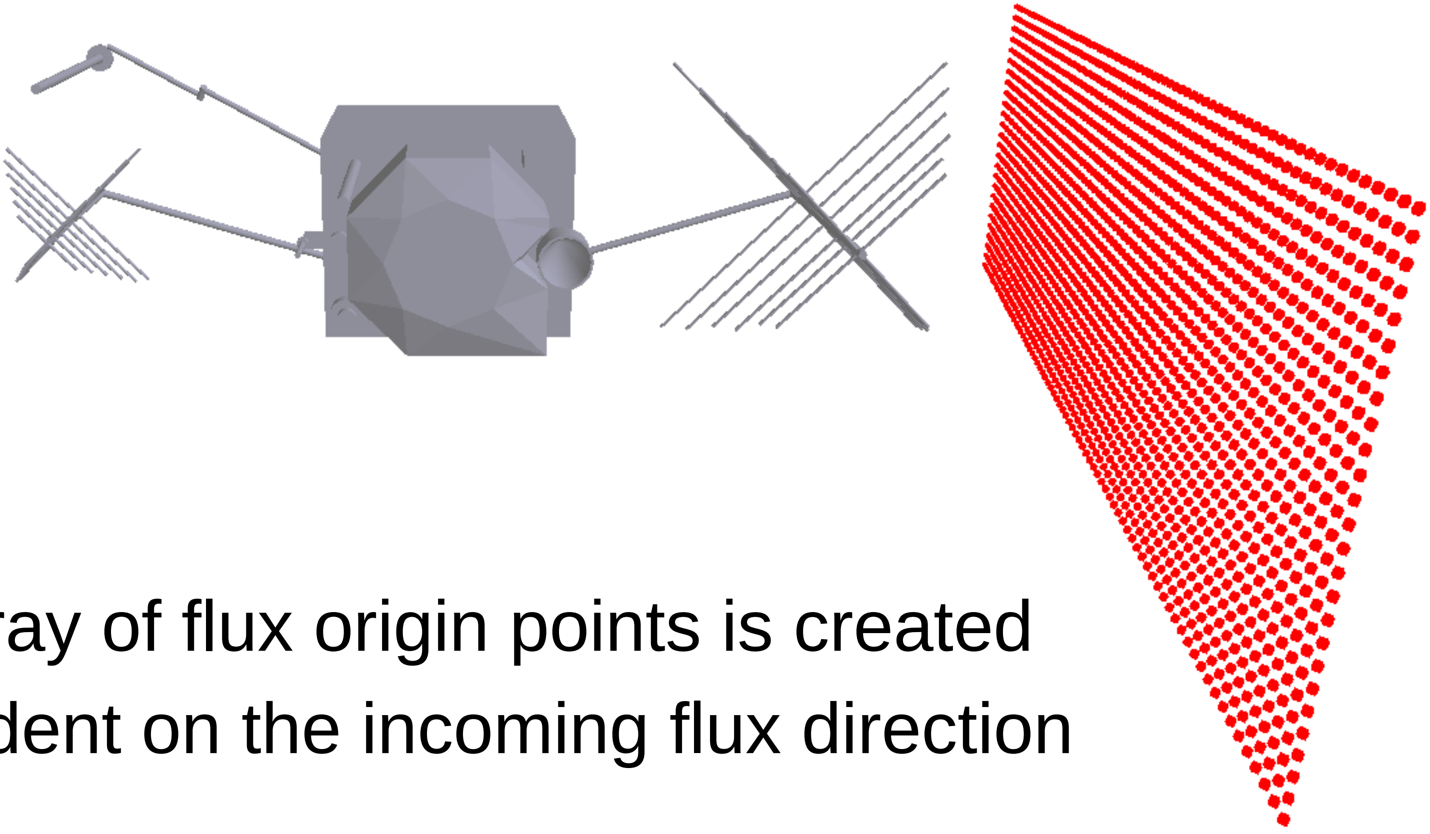
Material types



Optical and thermal properties

Spacecraft model represented in the SV body frame

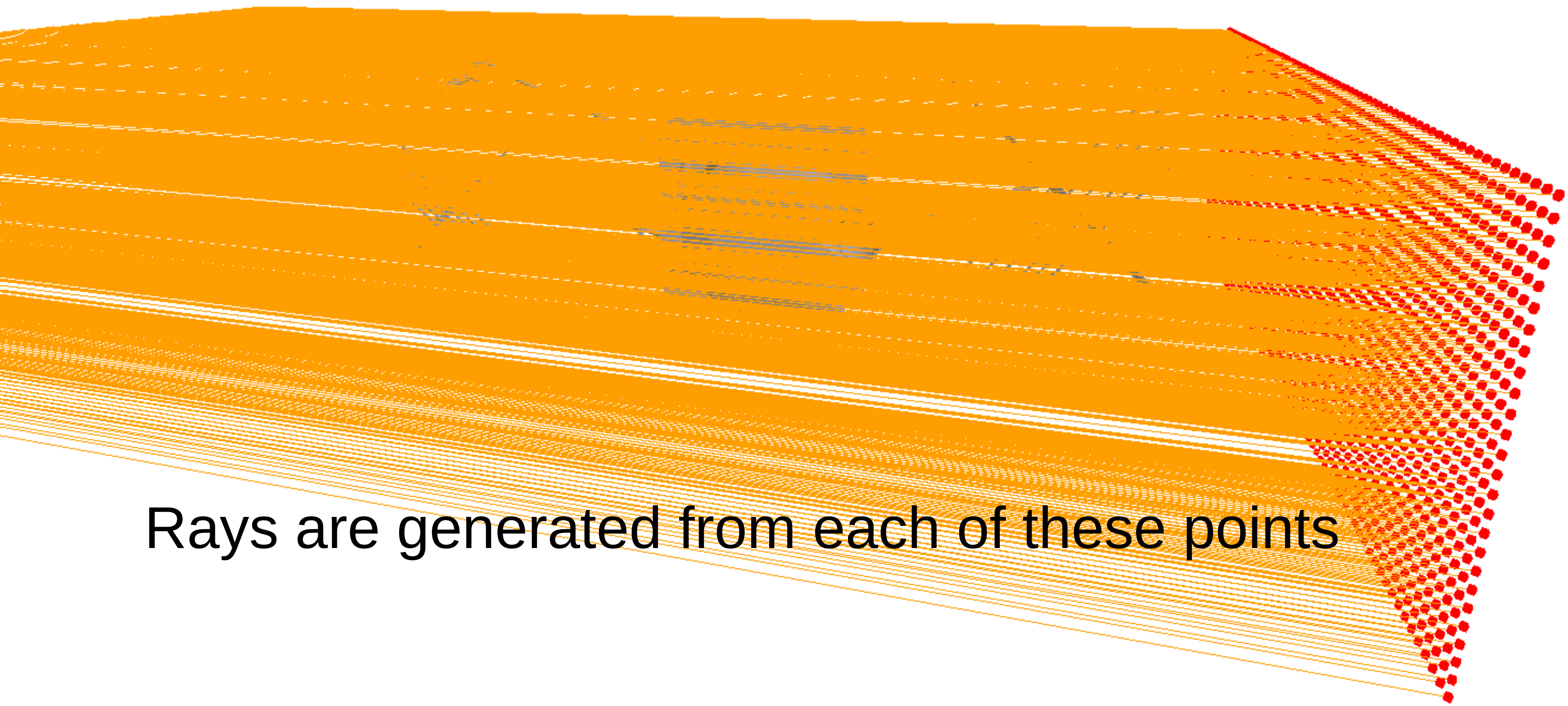
Ray Tracing - 2



An array of flux origin points is created

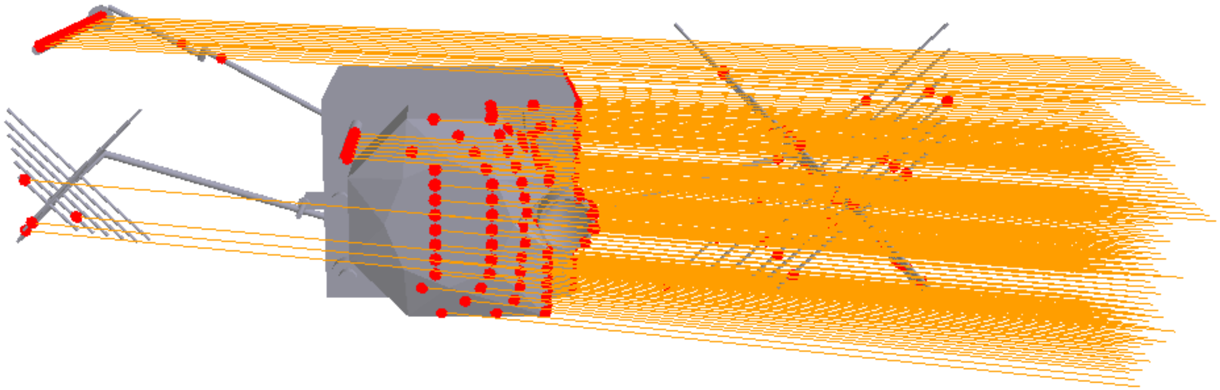
Dependent on the incoming flux direction

Ray Tracing - 3



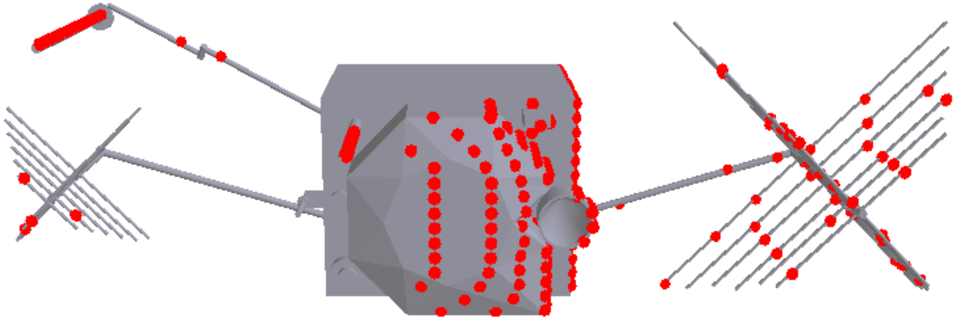
Rays are generated from each of these points

Ray Tracing - 4



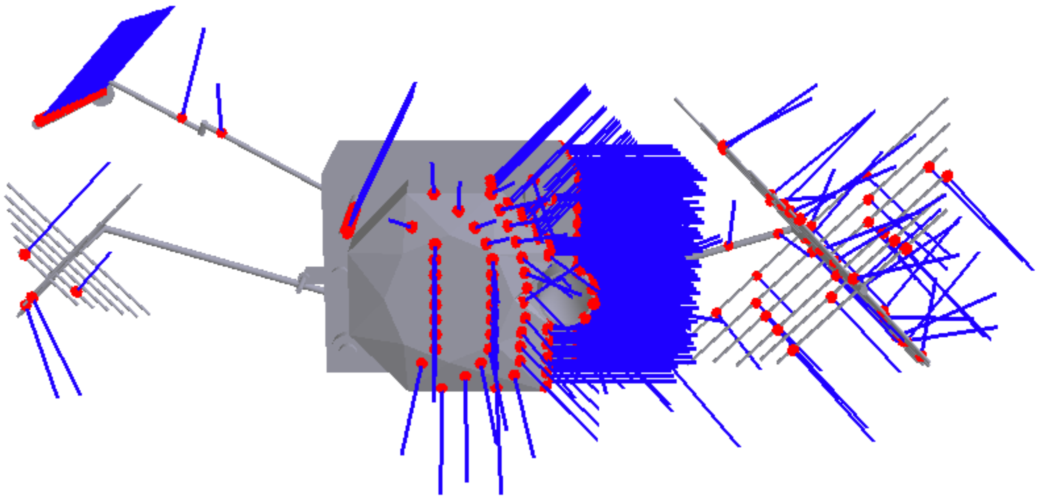
The intersection between each ray and the spacecraft is computed

Ray Tracing - 5



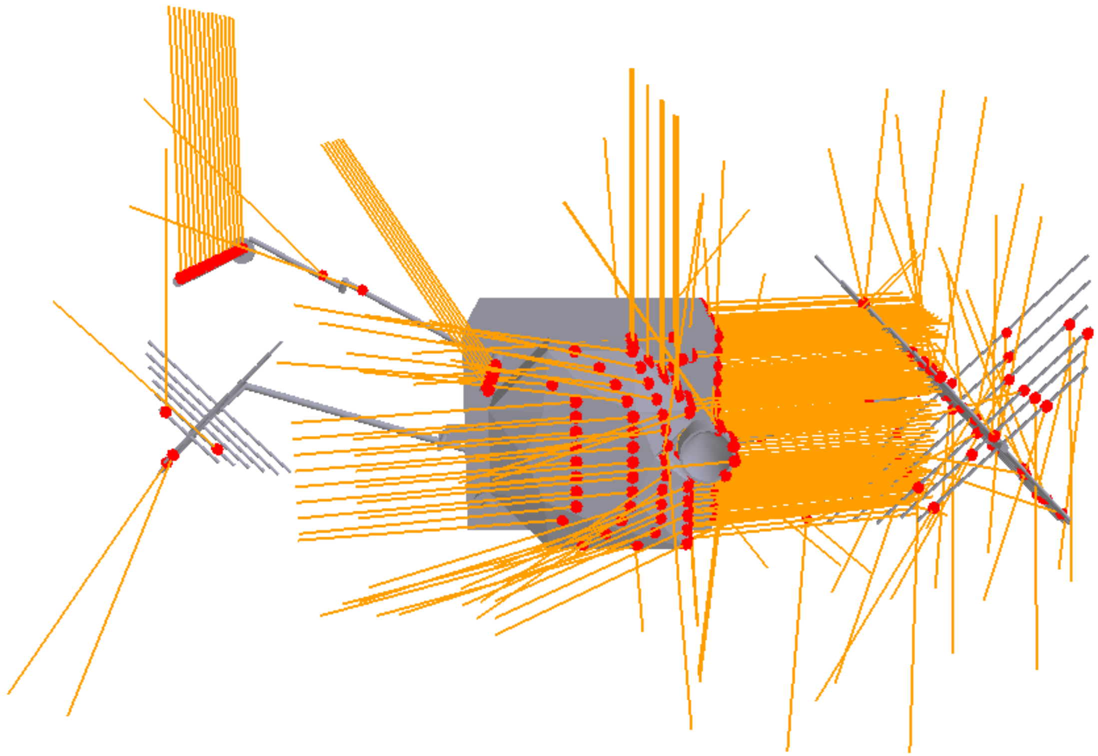
The material properties of the surface are known at each of these points

Ray Tracing - 6



The surface normal is calculated at each of these points for planar or **curved** surfaces

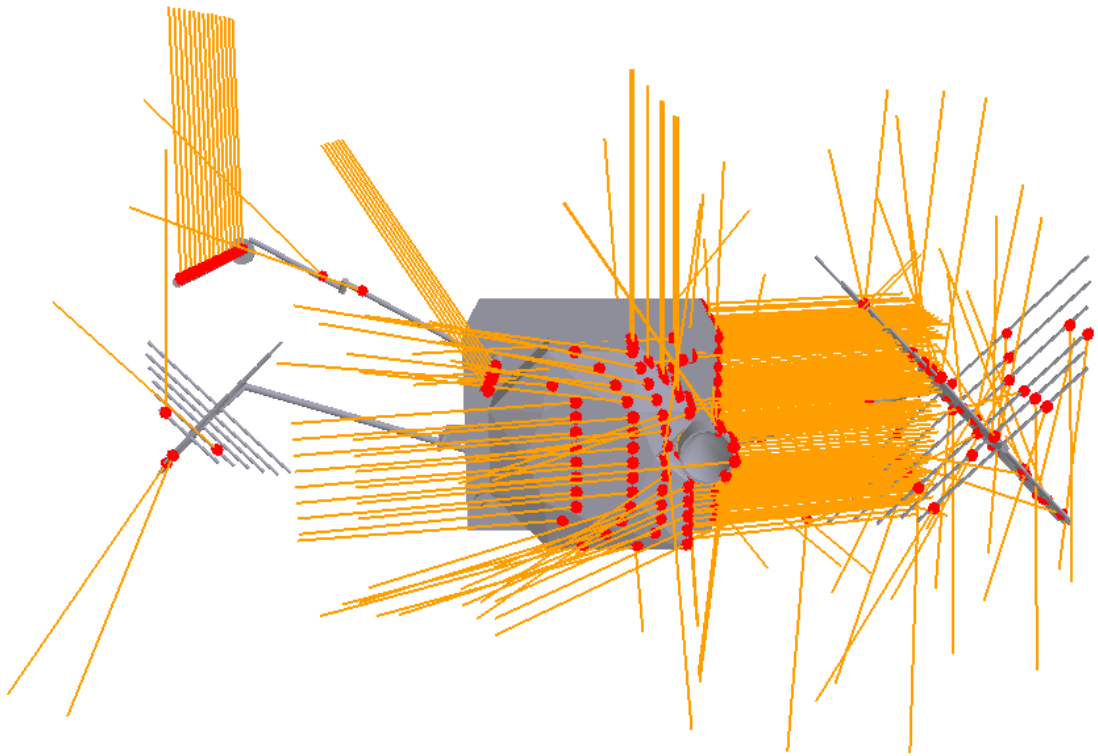
Ray Tracing - 7



New rays are generated for each reflection and the intersection and reflection step repeated:

Secondary intersections

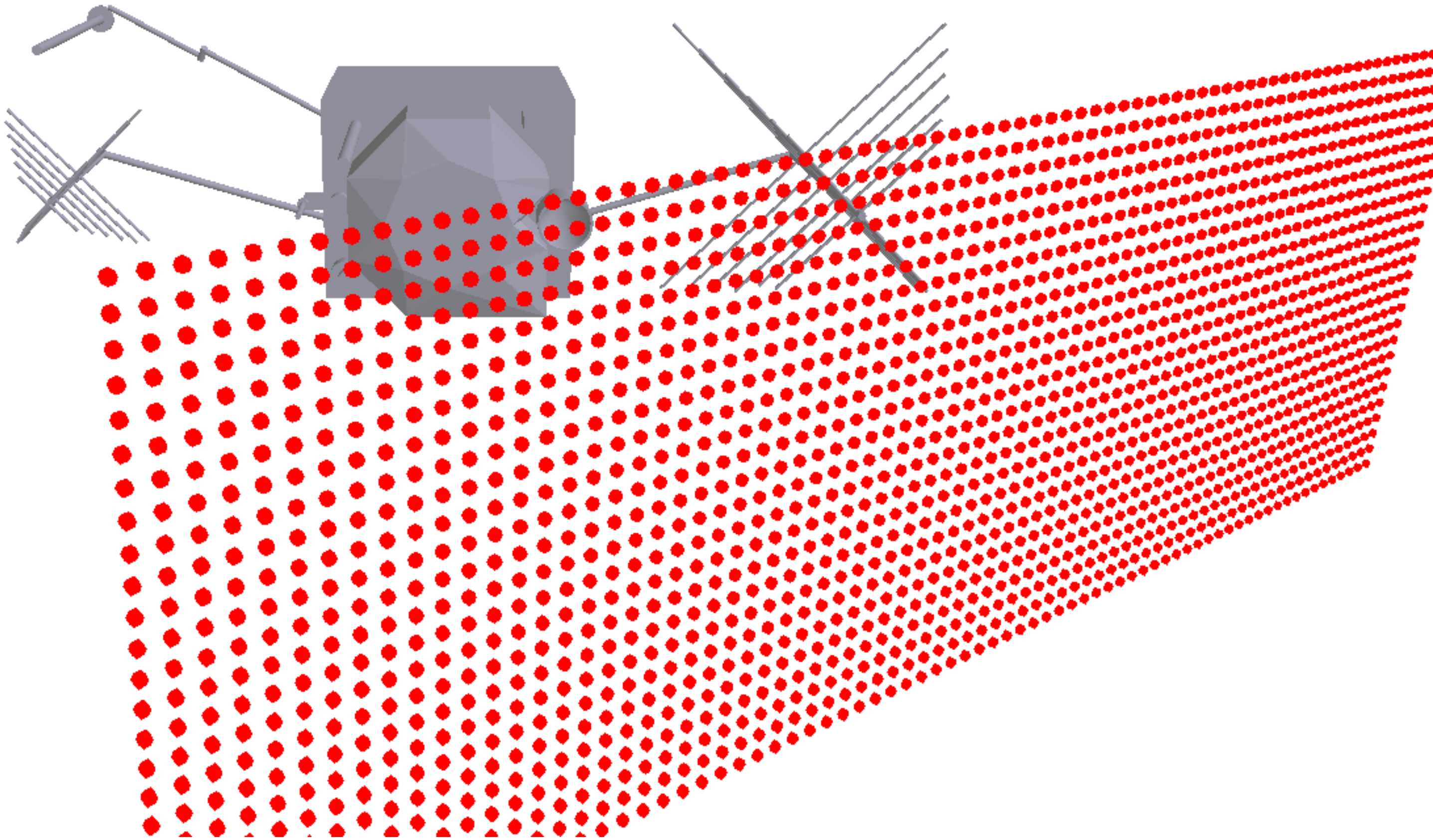
Ray Tracing - 8

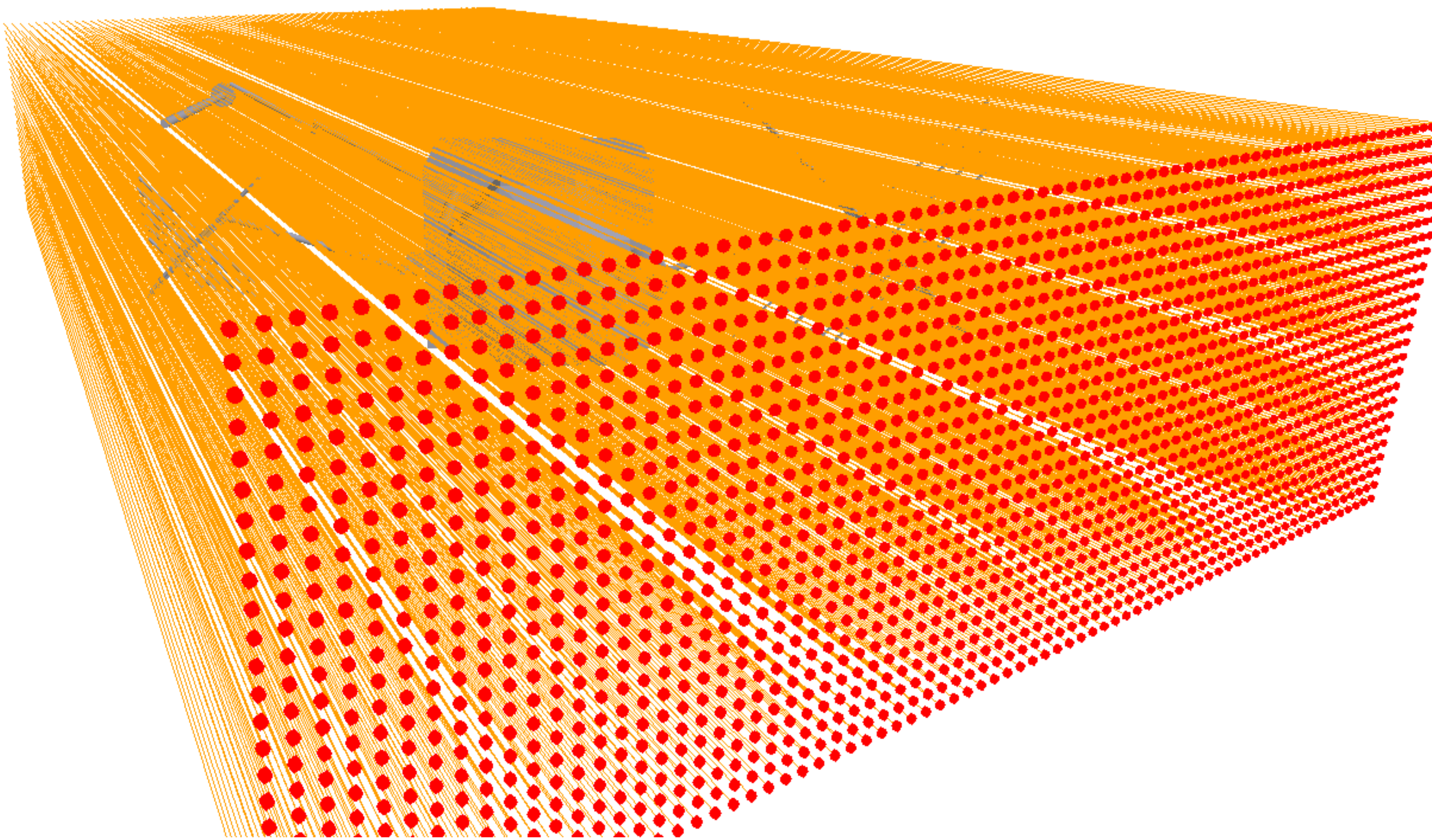


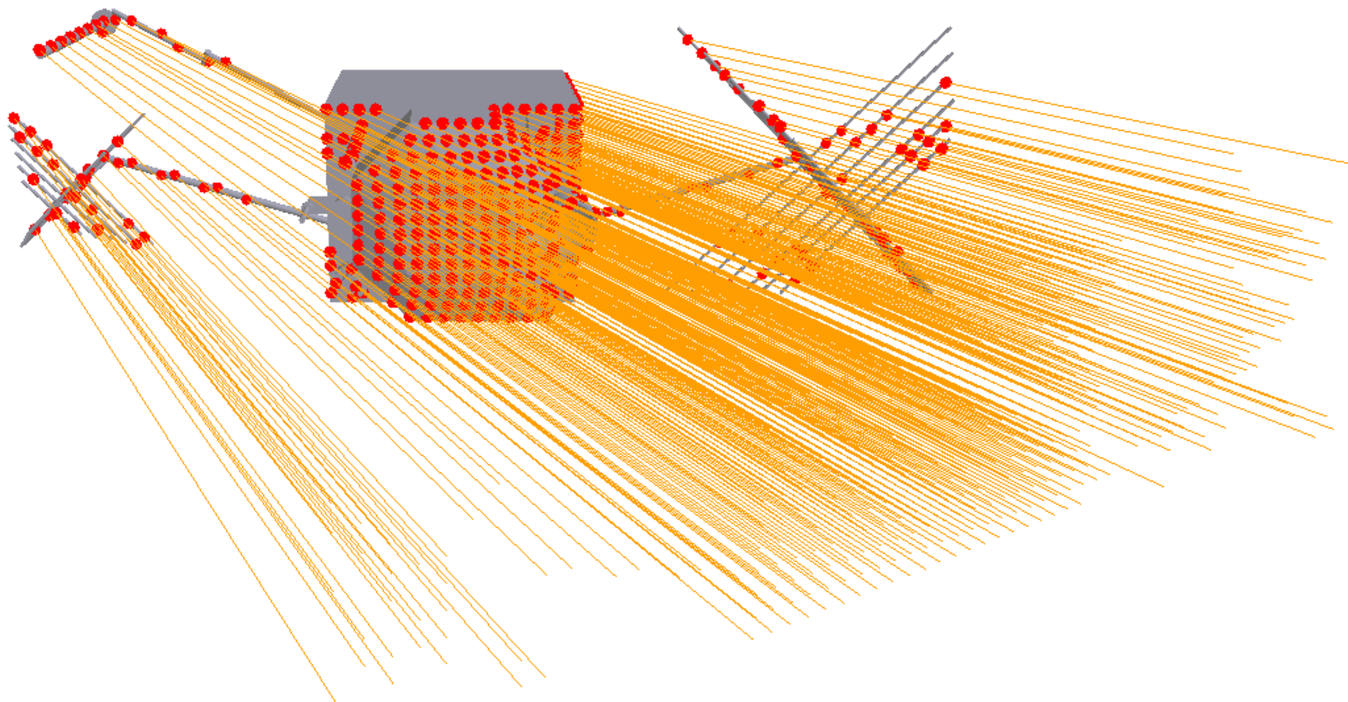
The acceleration data for all rays (primary and secondary) is collected:

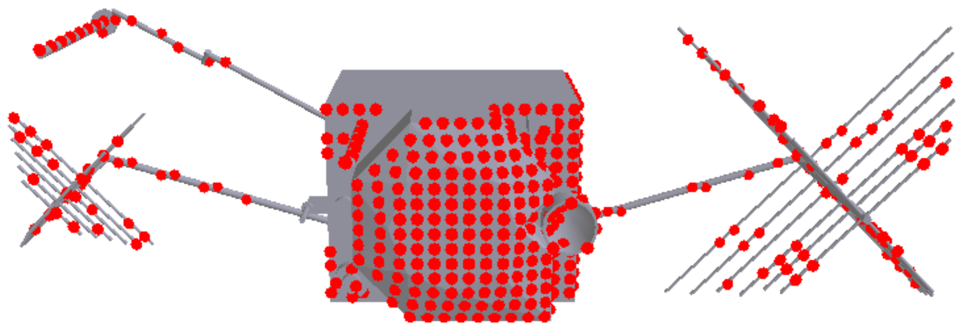
Resultant acceleration computed for that radiation source direction

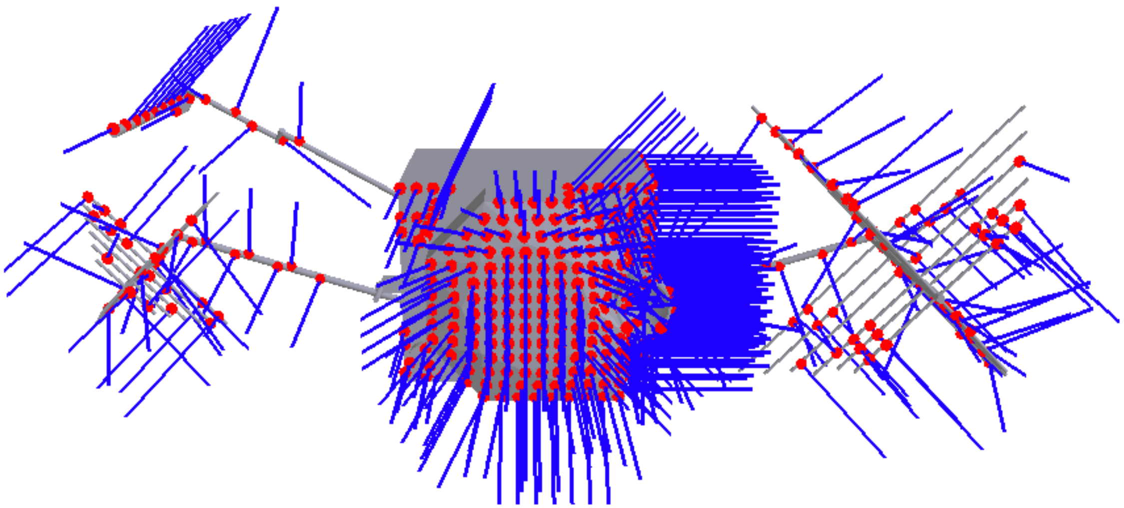
Process is repeated for other incoming flux directions

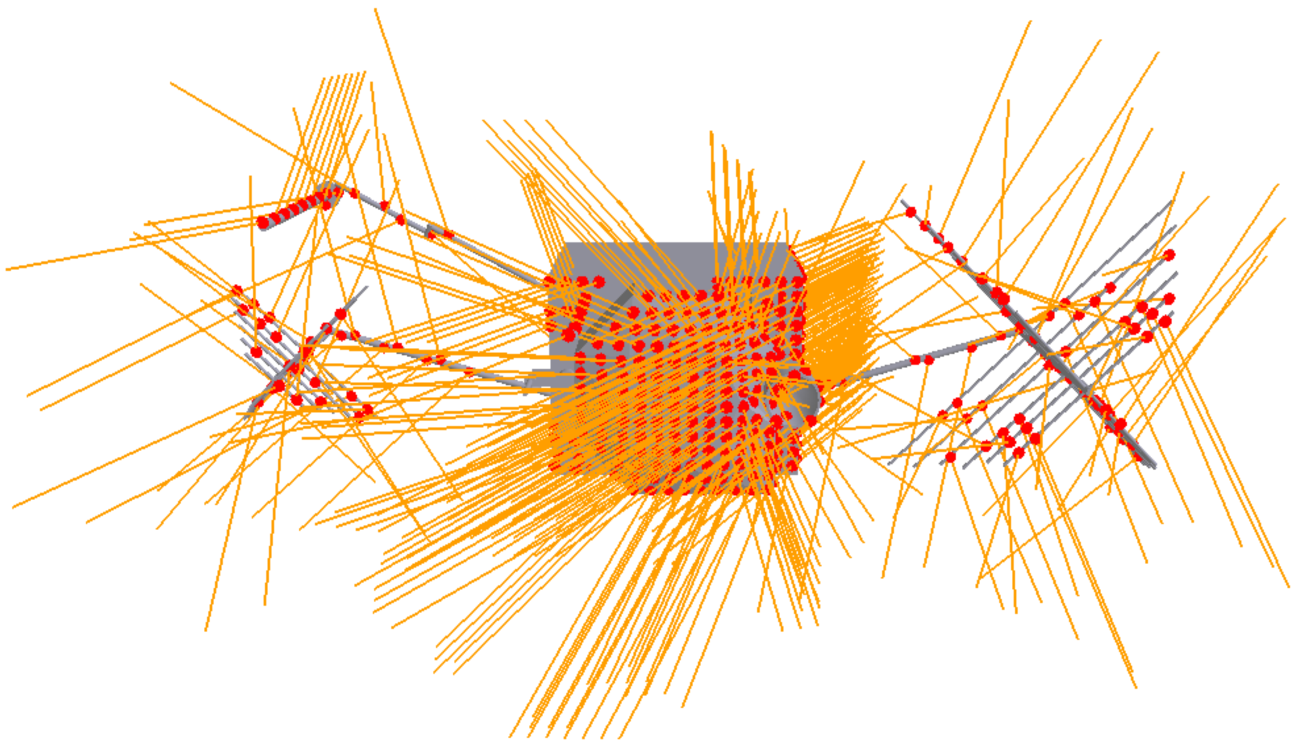






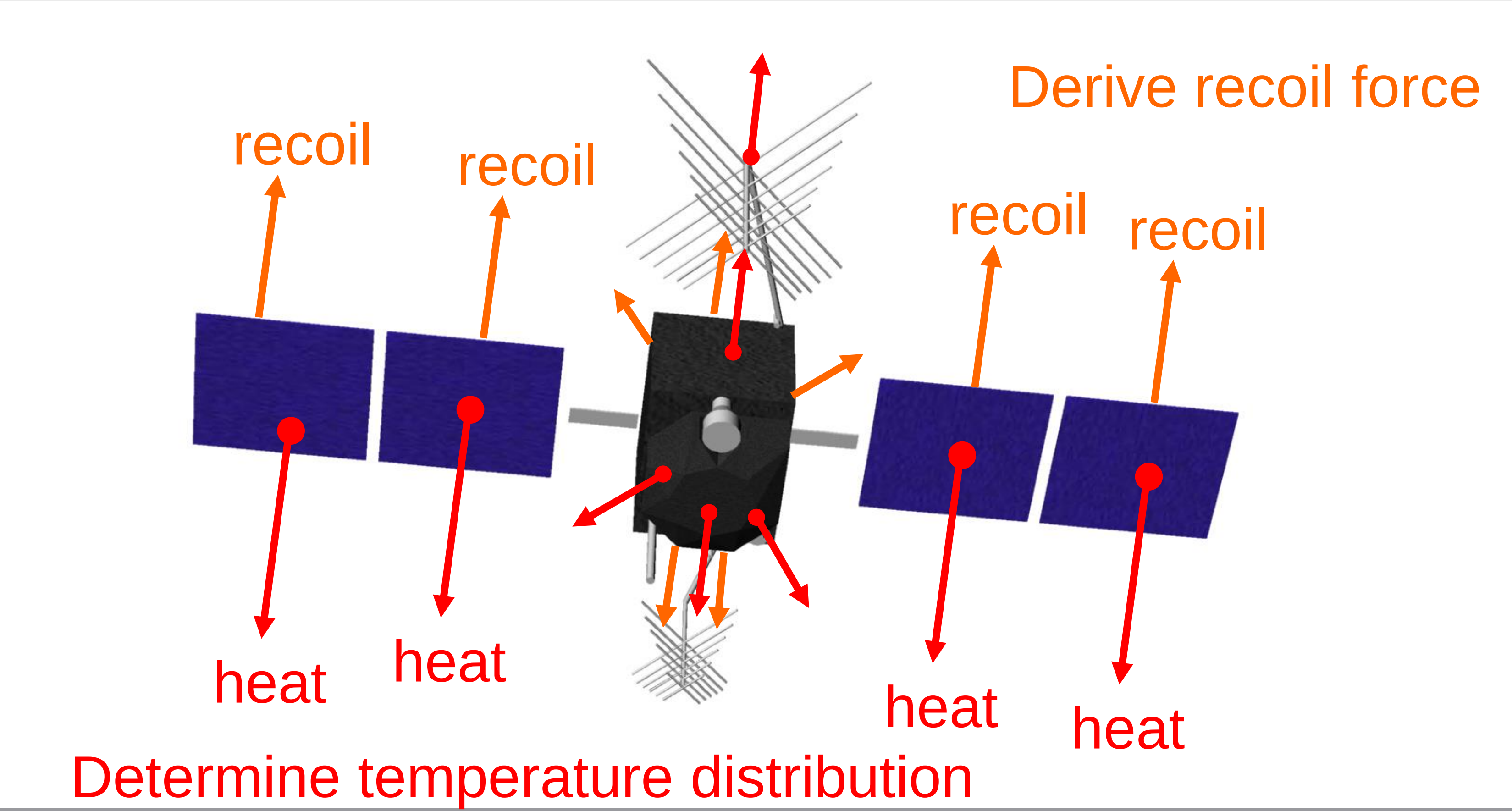






Thermal modelling:

Anisotropic thermal emission from spacecraft results in a net acceleration



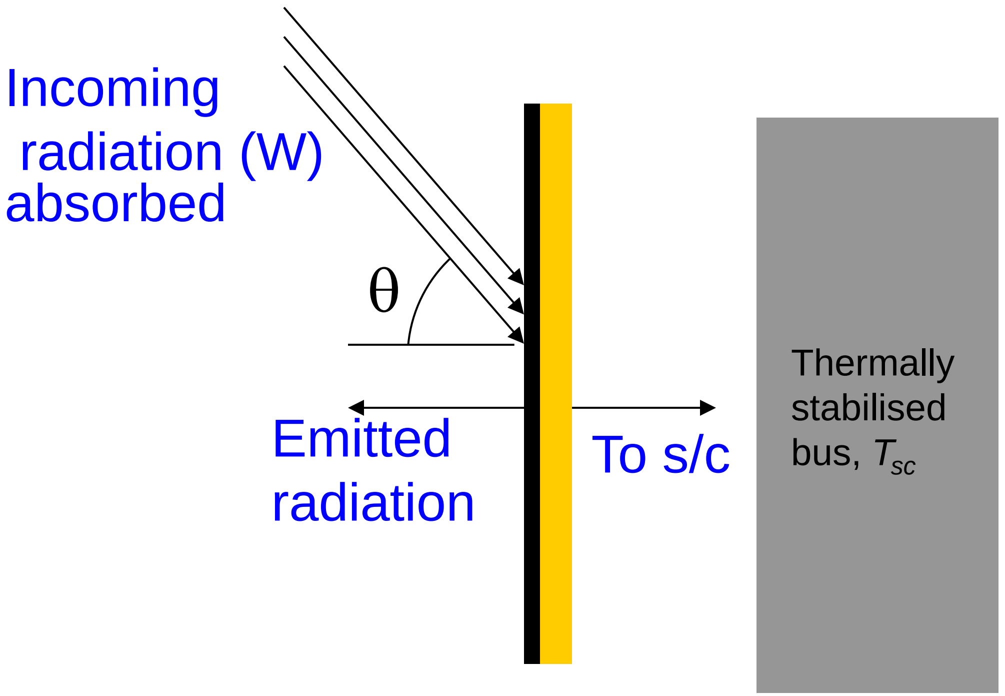
Multilayer Insulation (MLI)

- Pixel array algorithm determines insolation of MLI

- 'Effective emissivity' (ε_{eff}) parameter governs heat transfer to bus

- MLI blackened, α=0.94 $\Rightarrow$ large thermal force

Energy balance:



$$T_{MLI}^4 = \frac{\alpha W \cos\theta + \varepsilon_{eff}\,\sigma T_{sc}^4}{\sigma(\varepsilon_{MLI} + \varepsilon_{eff})}$$

Solar Panel Thermal Analysis

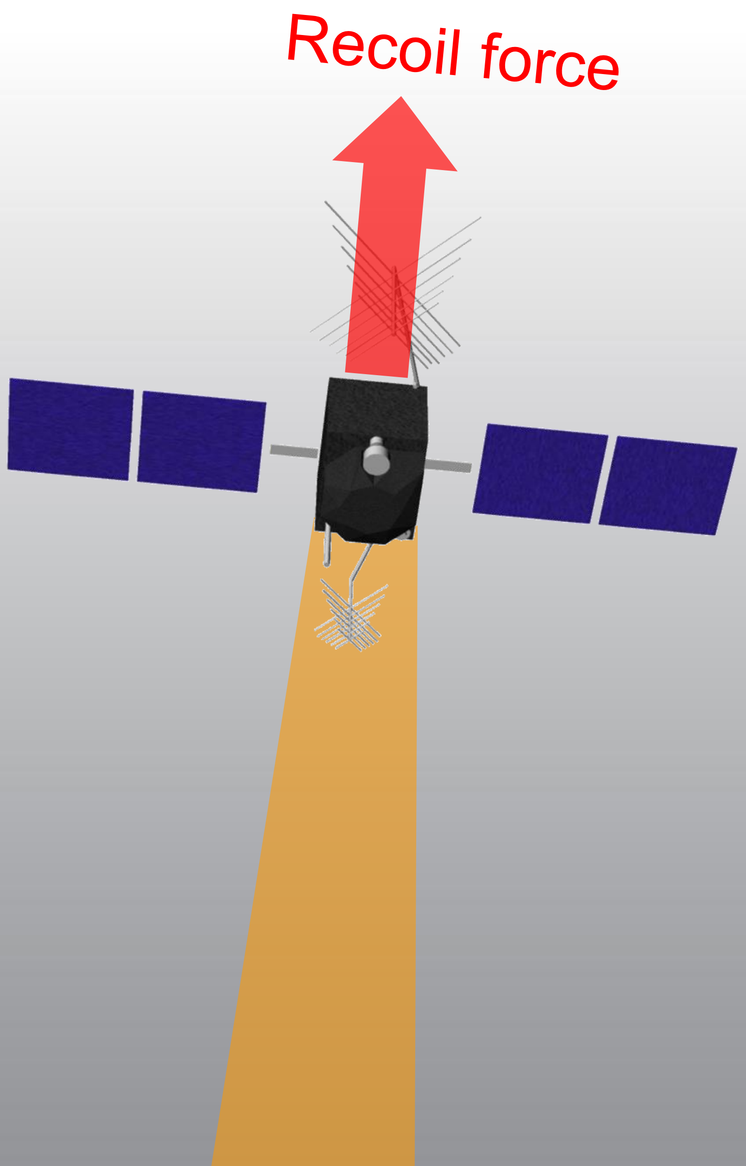
- Steady state and transient models (during eclipse) developed to yield temperatures and forces

- Input data : thicknesses and conductivities of panel composite layers, surface emissivities and absorptivities, power draw

- Model verification by comparison with telemetered surface temperatures

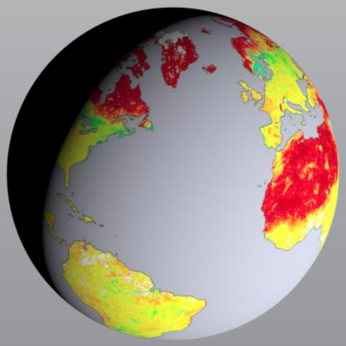
Antenna Thrust

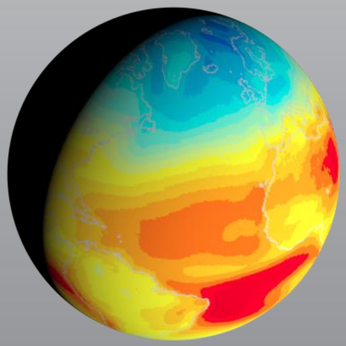
- Recoil force on satellite due to transmitted signals
- Systematic and observable effect
- Requires knowledge of power transmission of satellites

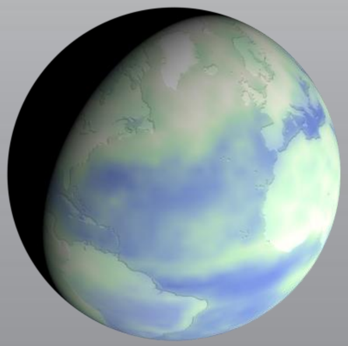


Planetary Radiation Pressure (PRP) models using space based observations of emission and reflectance.

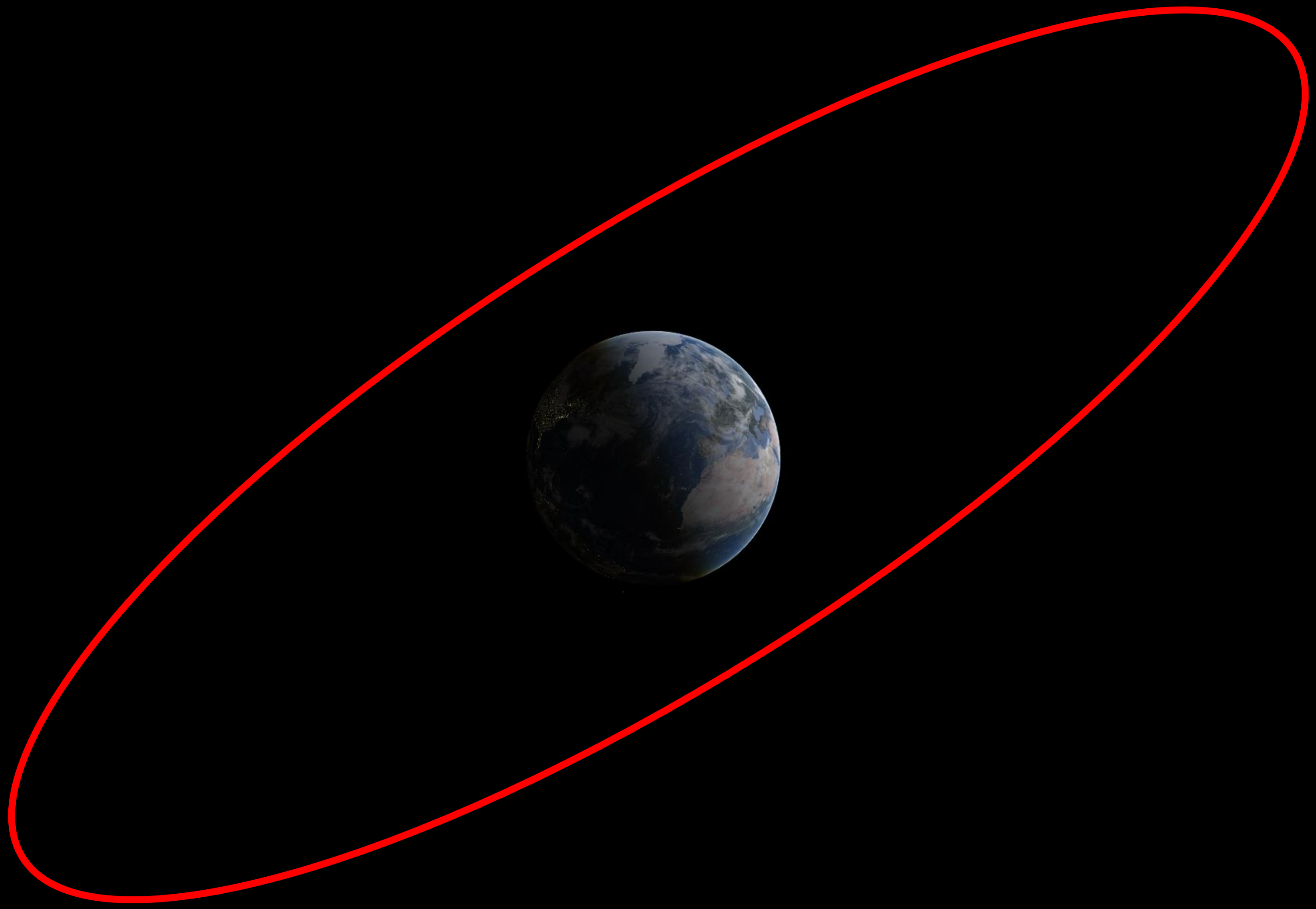
*Earth textures courtesy of NASA Blue Marble: Next Generation. Earth radiation data courtesy of CERES and MODIS.



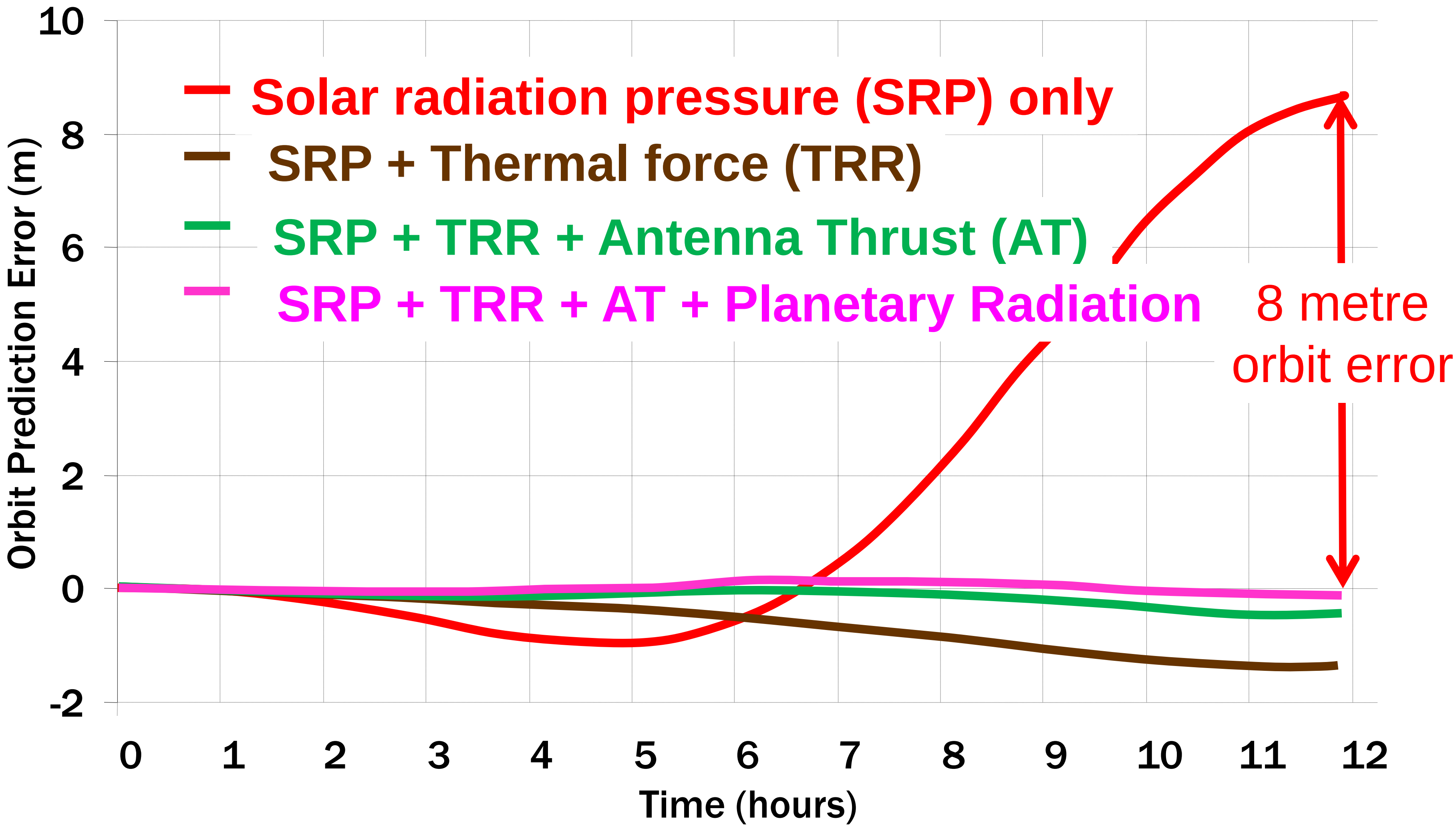




How well do these ideas work? Do they make any difference?:
Predicting a GPS satellite orbit over a 173,000 km trajectory



Along-track orbit prediction errors over 12 hours for one GPS IIR satellite with different photon-based force models



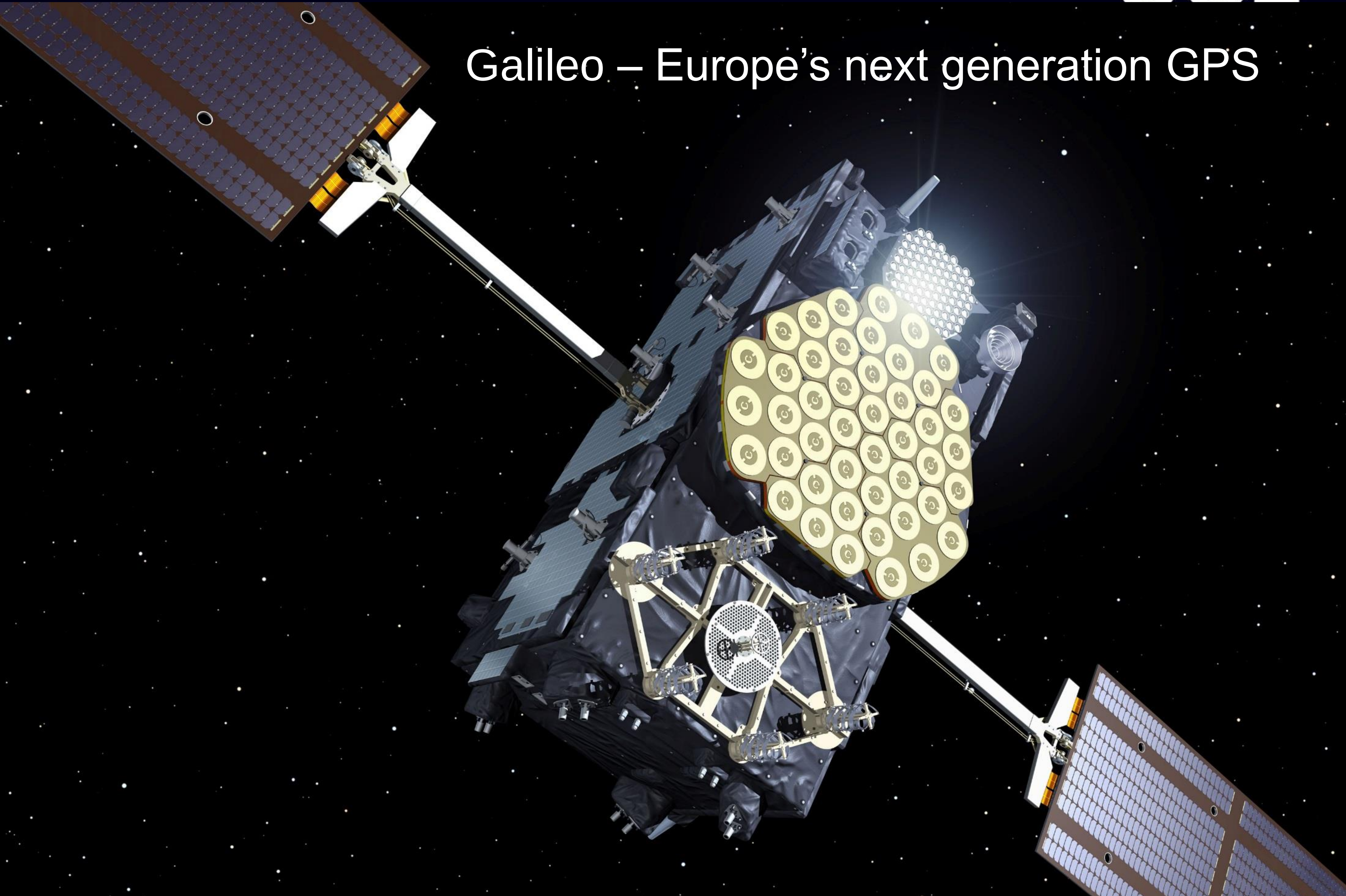
IGS experiments, analysis, standards

- This research leads to IGS standards – applied by all analysis groups within the organization. Ideas are tested by large-scale data processing experiments spanning many years and huge networks of data. The recent REPRO2 exercise re-computed orbit, clock, station positions and earth orientation parameters using over twenty years of daily data from the entire network. Such operations give insight into system and planet scale behaviors.
- Earth radiation forcing and antenna thrust methods changed IGS orbit accuracy from 5 cm to 2.5 cm (radial)

What do we need to do this, and to push the envelope of what is possible:

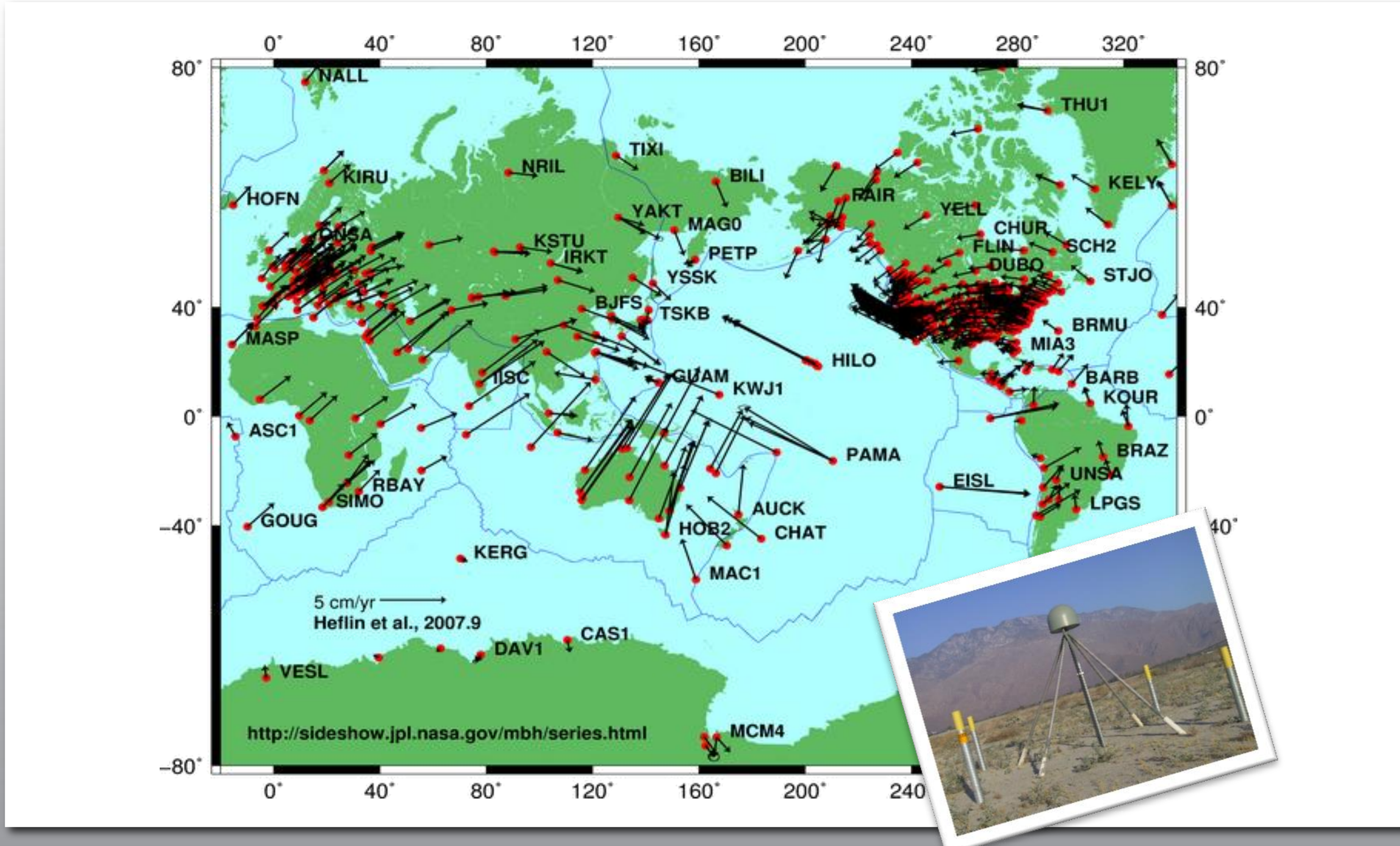
- SV mass and mass history
- Structural details (primarily surface geometry)
- Material types (absorptivity, reflectivity, specularity)
- Specific thermal information (MLI characteristics, power draw, thermal emissions, solar panel construction)
- Satellite attitude (both eclipsing and non-eclipsing, non-nominal attitude, yaw flips, noon day and midnight turns)
- Satellite phase centre (phase centre offset, phase centre variations)
- Laser retro-reflector array position, corner cube phase centre

Galileo – Europe's next generation GPS



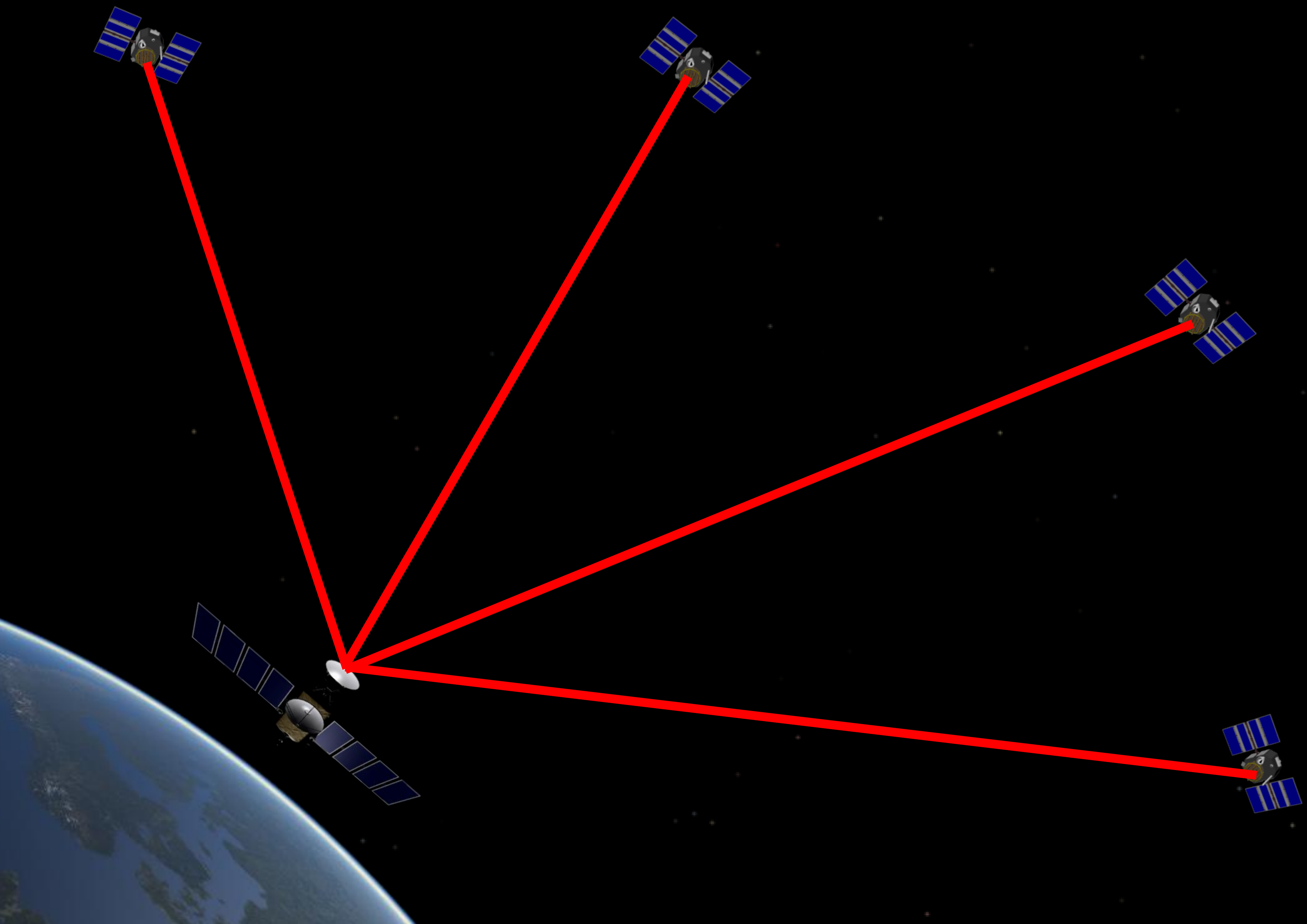
Galileo Atomic Frequency standard:
Passive Hydrogen Maser

Why strive for cm accuracy orbits and clocks?

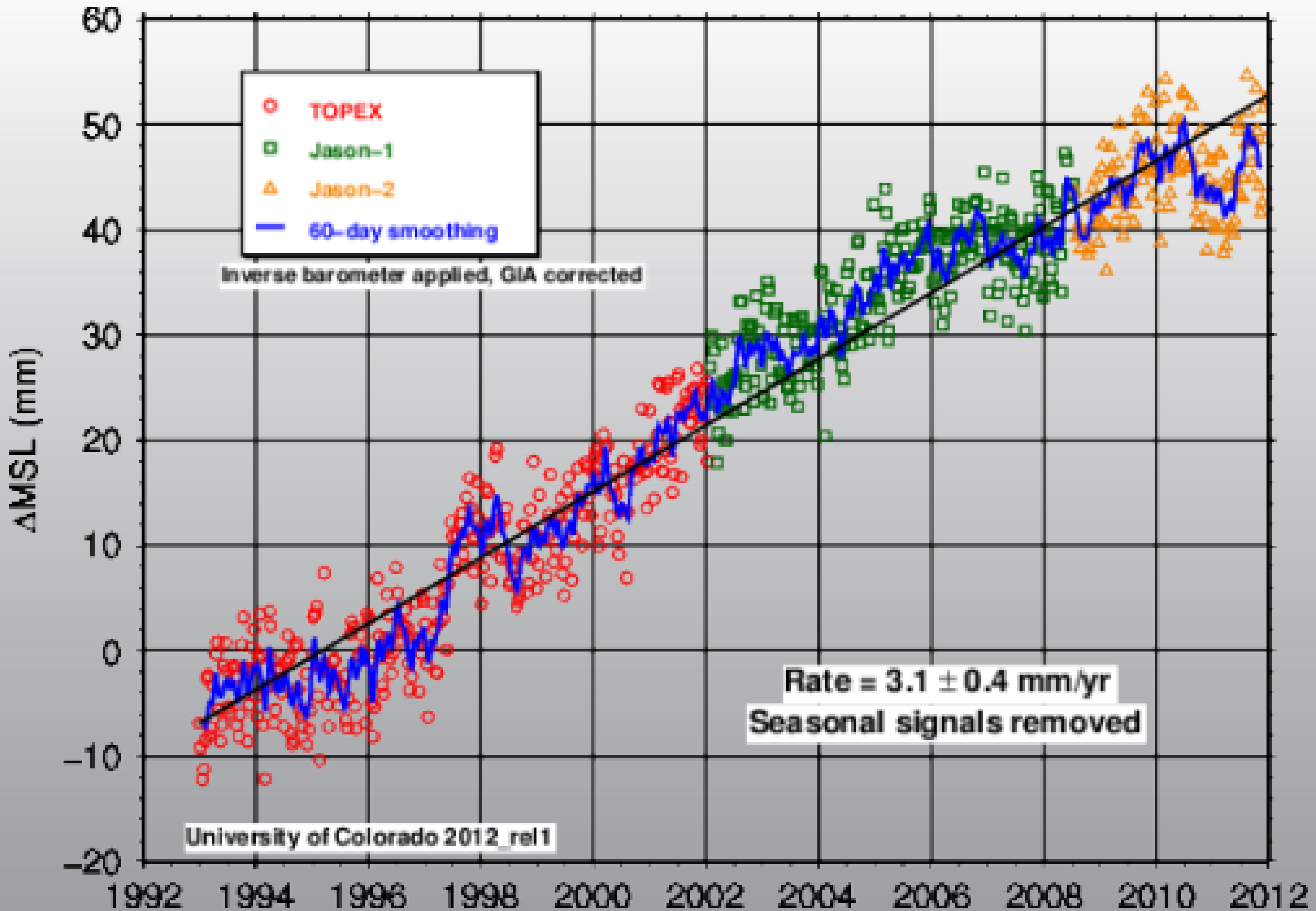


Velocity map courtesy of Mike Helflin, NASA JPL

Satellite Altimetry: determining the satellite position by GPS



Global sea level rise measured by satellite altimetry



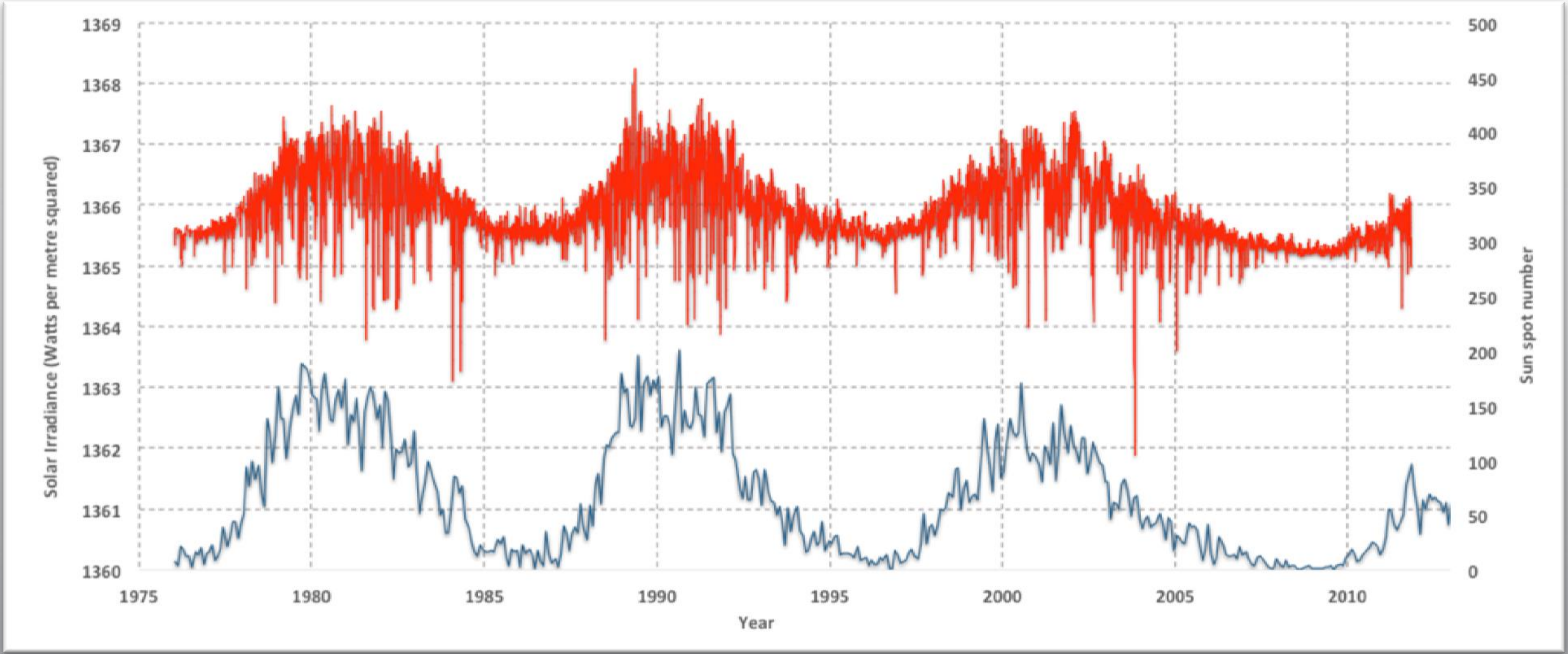
Brief philosophical musings…....

- GPS has been a world-changing technological advance for humanity
- It will feature in history – fire, language, the wheel, farming, electricity, the steam engine, radio, the Internet, ~~e-mail~~, space technology, satellite navigation…..
- Much as Faraday could not have foreseen the Internet, it is difficult to predict what will be feasible in the future
- What is clear is that the work of scientists, engineers, policy makers and commerical companies drives forward what is possible – it is a privilege for all of us to be involved in this great endeavour

Conclusions

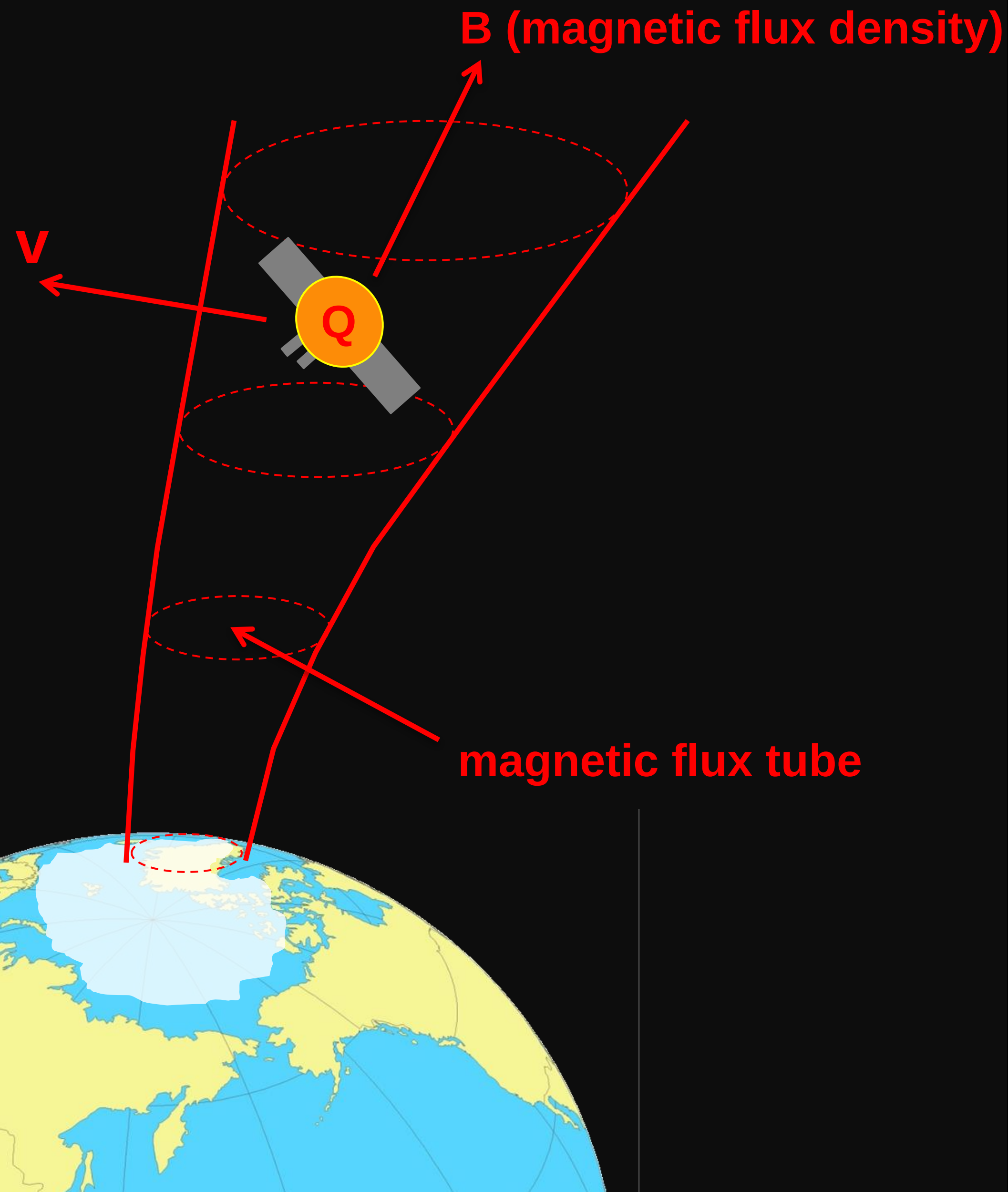
- IGS research in modelling satellite orbit dynamics is *pushing the frontiers of what is possible*
- A central problem is dealing with *radiation pressure*
- We have powerful, proven tools ready to apply to GPS
- Europe's Galileo is flying Passive Hydrogen Maser clocks – early results show a step change in capability: *a 1cm level predicted clock*
- ESA is trying to develop orbit prediction techniques to produce *predicted cm level orbits over many days*
- The IGS seeks the support of the PNT board *to gain access to SV structural data for GPS*
- *To paraphrase Richard Feynmann – there is room at the top – and the IGS is poised to help make it happen*

Total solar irradiance and sunspot number

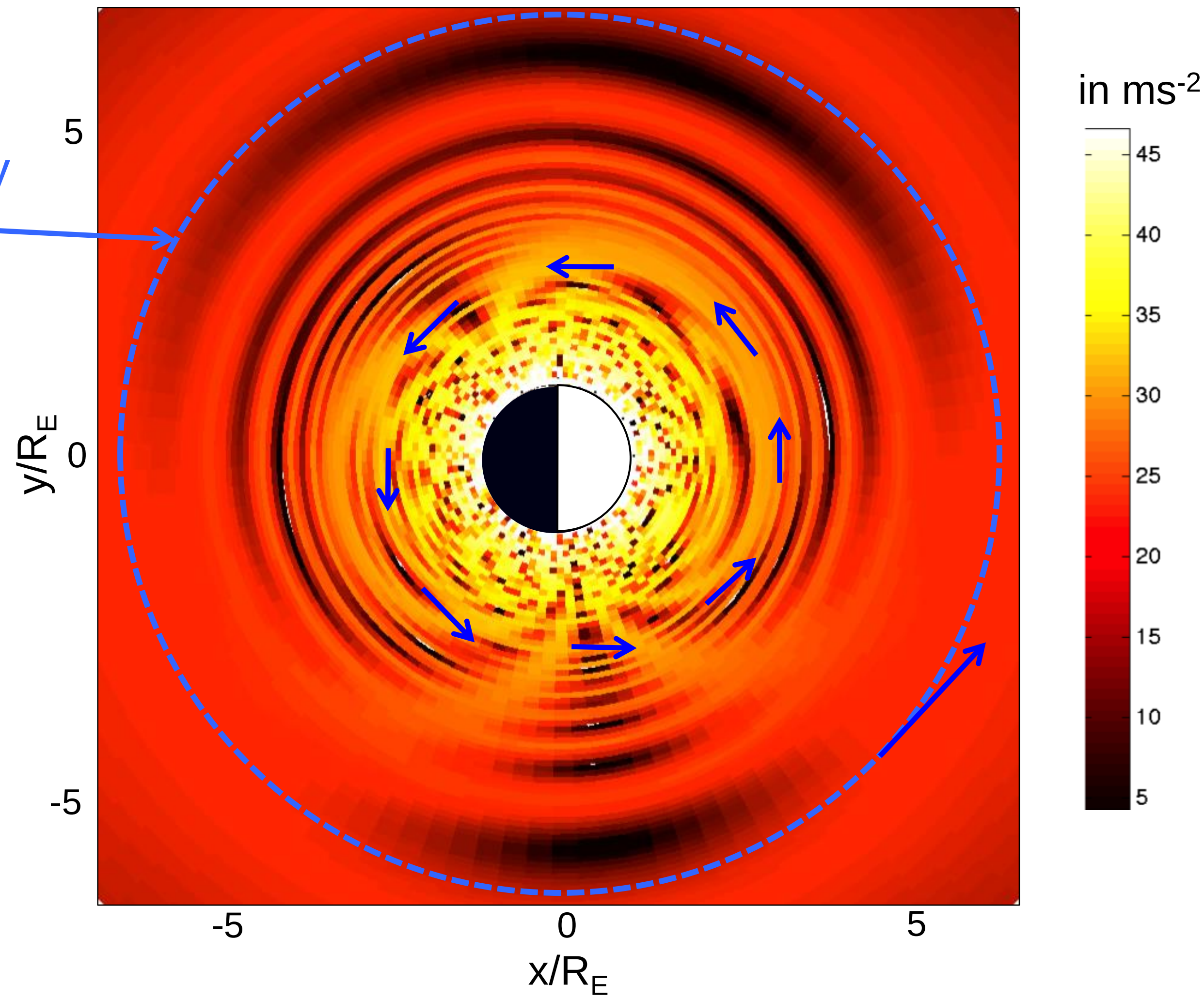


Lorentz Force Effects

If an object in orbit carries a net electrostatic charge (Q), then its motion will be influenced by the interaction of this charge with the local electromagnetic field, due to the **Lorentz force**.

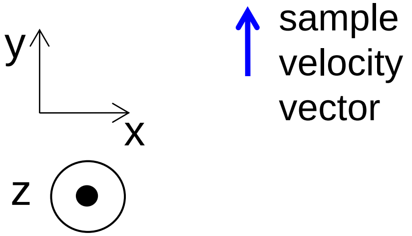


Magnitudes of the standard case GLA (equatorial plane: z = 0), 17 July 2013



The standard case:

- m = 1 kg
- q = 1 Coulomb
- Thus, q/m = 1 C/kg
- Circular orbit
- Inclination = 0
- 2000 km – ~36,000 km



R_E is the mean Earth radius