Satellite INFANTE

Preliminary orbital dynamics analysis
Maritime surveillance capability assessment

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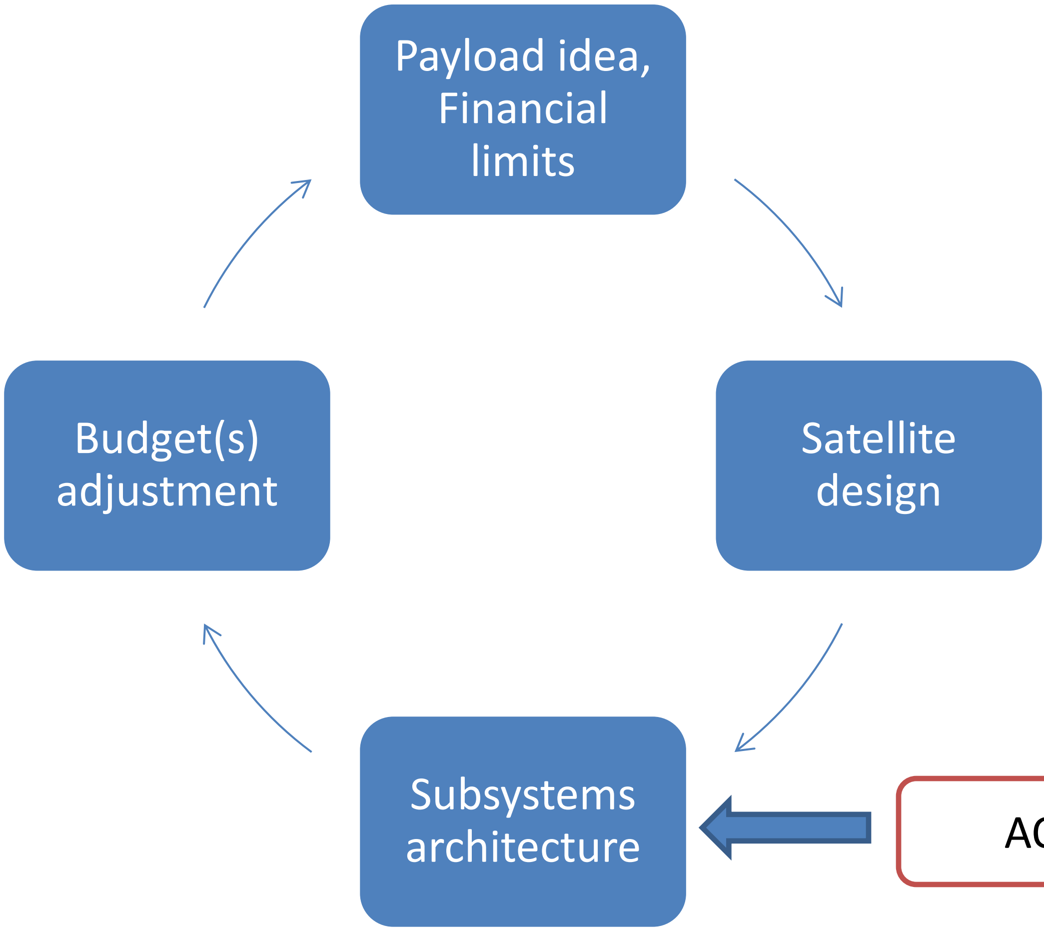
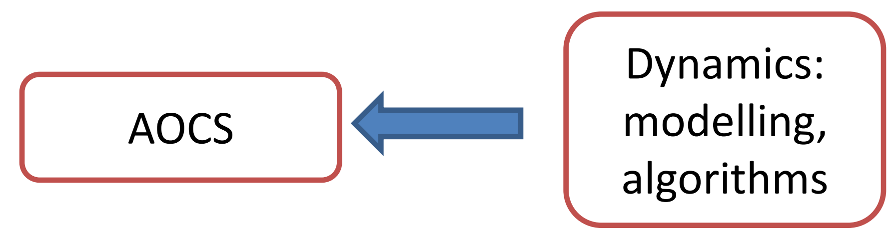
Dynamics place in mission design



Dynamics: mathematical aspects of one of the subsystems.

Do it have profound influence on the whole mission?



Dynamical aspects in a mission

Why bother about AOCS among other subsystems?

- Dynamical problems (both angular and orbital) seem negligible in overall mission structure.
- *Maybe buy popular solutions?*

AOCS easily consume third of space and energy budget available

- *Maybe spend more effort on AOCS?*
- Free some mission resources for improvement of other subsystems and payload.

Swift comparison

Buy AOCS	Develop architecture, build/buy components
• Fast • Reliable • Expensive	• Slow • Initially prone to faults • Initially expensive (education) • *Optimized for a mission* • Long-term investment in skilled personnel and overall group expertise • Interesting!

Analytical vs. numerical

- Numerical analysis
  - \+ Comprehensive satellite and environment models
  - \+ Exceptional accuracy
  - ± Time consuming, rewarded with a long lasting tool
  - – Unique result
- Analytical solution
  - \+ General result, satellite behavior prediction
  - ± Time consuming, rewarded with a tool and publications
  - – Simplified and restricted satellite and environmental models
  - – Bad accuracy
  - – Higher qualification necessary

Example 1. Mission design speedup

Analytical analysis benefits

Example of dynamics analysis that can speed up AOCS hardware fitting

- Detumbling angular velocity with magnetorquers
- Restriction on detumbling time is imposed (Sun acquisition, antenna pointing)
- Magnetorquers parameters are derived to satisfy this restriction
- Two approaches:
  - Numerical analysis
  - Analytical solution

Dynamics simplification steps

- Convenient equations of motion
- *Osculating variables*

- Simple, but authentic environment models
- *Averaged geomagnetic field*

- Assumptions and analysis method
- *Multiple time scales for detumbling*

- Solution in explicit form
- *Different parameters influence on satellite behavior*

Convenient equations of motion

- Common Euler equations:

$$A\frac{d\omega_1}{dt}+(C-B)\omega_2\omega_3=M_{1x},\ B\frac{d\omega_2}{dt}+(A-C)\omega_1\omega_3=M_{2x},\ C\frac{d\omega_3}{dt}+(B-A)\omega_1\omega_2=M_{3x},$$

$$\frac{d\alpha}{dt}=\frac{1}{\cos\beta}(\omega_2\cos\gamma-\omega_3\sin\gamma),\ \frac{d\beta}{dt}=\omega_2\sin\gamma+\omega_3\cos\gamma,\ \frac{d\gamma}{dt}=\omega_1-\operatorname{tg}\beta(\omega_2\cos\gamma-\omega_3\sin\gamma)$$

- Osculating variables:

$$\frac{dL}{dt}=M_{3L},\ \frac{d\rho}{dt}=\frac{1}{L}M_{1L},\ \frac{d\sigma}{dt}=\frac{1}{L\sin\rho}M_{2L},$$

$$\frac{d\theta}{dt}=\frac{1}{L}\left(M_{2L}\cos\psi-M_{1L}\sin\psi\right),$$

$$\frac{d\varphi}{dt}=L\cos\theta\left(\frac{1}{C}-\frac{1}{A}\right)+\frac{1}{L\sin\theta}\left(M_{1L}\cos\psi+M_{2L}\sin\psi\right),$$

$$\frac{d\psi}{dt}=\frac{L}{A}-\frac{1}{L}M_{1L}\cos\psi\operatorname{ctg}\theta-\frac{1}{L}M_{2L}\left(\operatorname{ctg}\rho+\sin\psi\operatorname{ctg}\theta\right)$$

Environment models

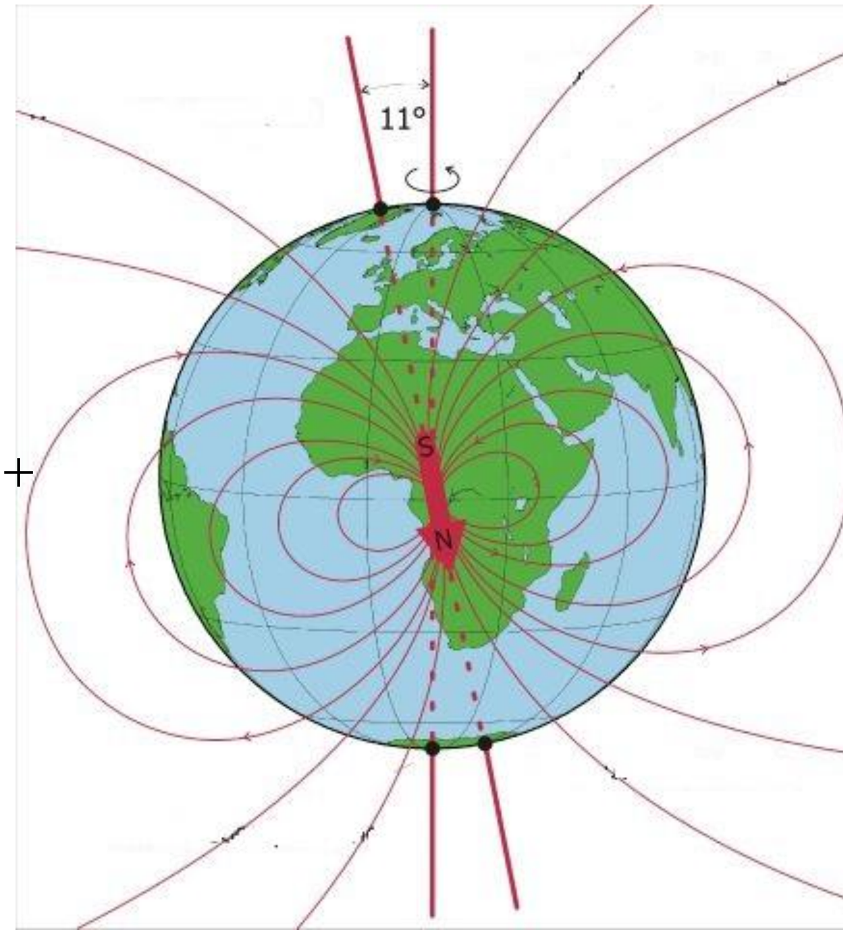
- Empirical IGRF
- Inclined dipole

$$\mathbf{B} = \frac{\mu_e}{r^3}\begin{pmatrix} \sin\lambda\sin\delta - 3\xi\cos u \\ -\cos\lambda\sin\delta + 3\xi\cos i\sin u \\ \cos\delta - 3\xi\sin i\sin u \end{pmatrix},$$

$$\xi = \cos u\sin\delta\sin\lambda - \sin u\cos i\sin\delta\cos\lambda + \\ +\sin u\cos\delta\sin i,\ \lambda = \omega_E t + \lambda_0$$

- Averaged

$$\mathbf{B} = B_0\begin{pmatrix} -\sin\Theta\sin 2u \\ \sin\Theta\cos 2u \\ \cos\Theta \end{pmatrix}$$



Assumptions and analysis method

- Fast initial rotation
  - Multiple time scales method
  - Angular momentum changes slowly
  - Satellite attitude changes rapidly
- Evolution of angular momentum obtained by averaging the equations of motion

Solution in explicit form: spherical satellite damping

torque value

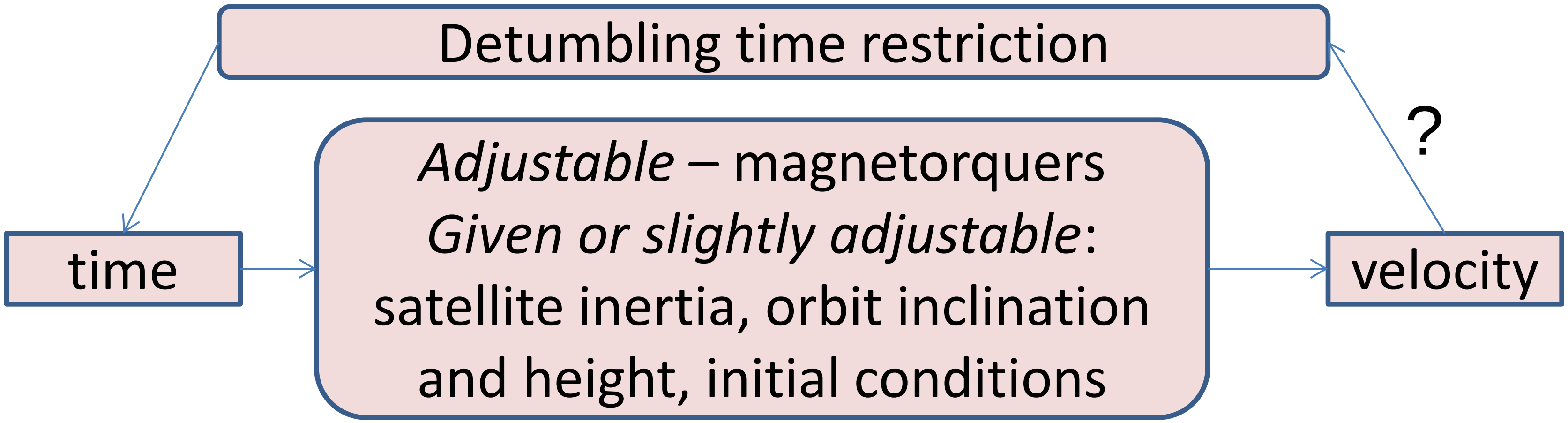
geomagnetic model parameter

$$l = \exp\left[-2\varepsilon pu + \frac{1}{2}\ln\left(\frac{1+\exp\left(2\varepsilon\left(3p-1\right)u + c_0\right)}{1+\exp c_0}\right)\right]$$

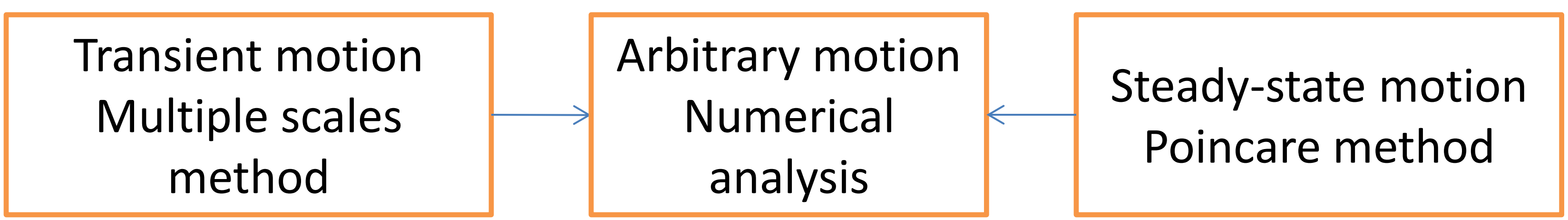
angular momentum

argument of latitude (time)

Simple parameters adjustment



Numerical simulation – verification, more accurate result after parameters are roughly adjusted



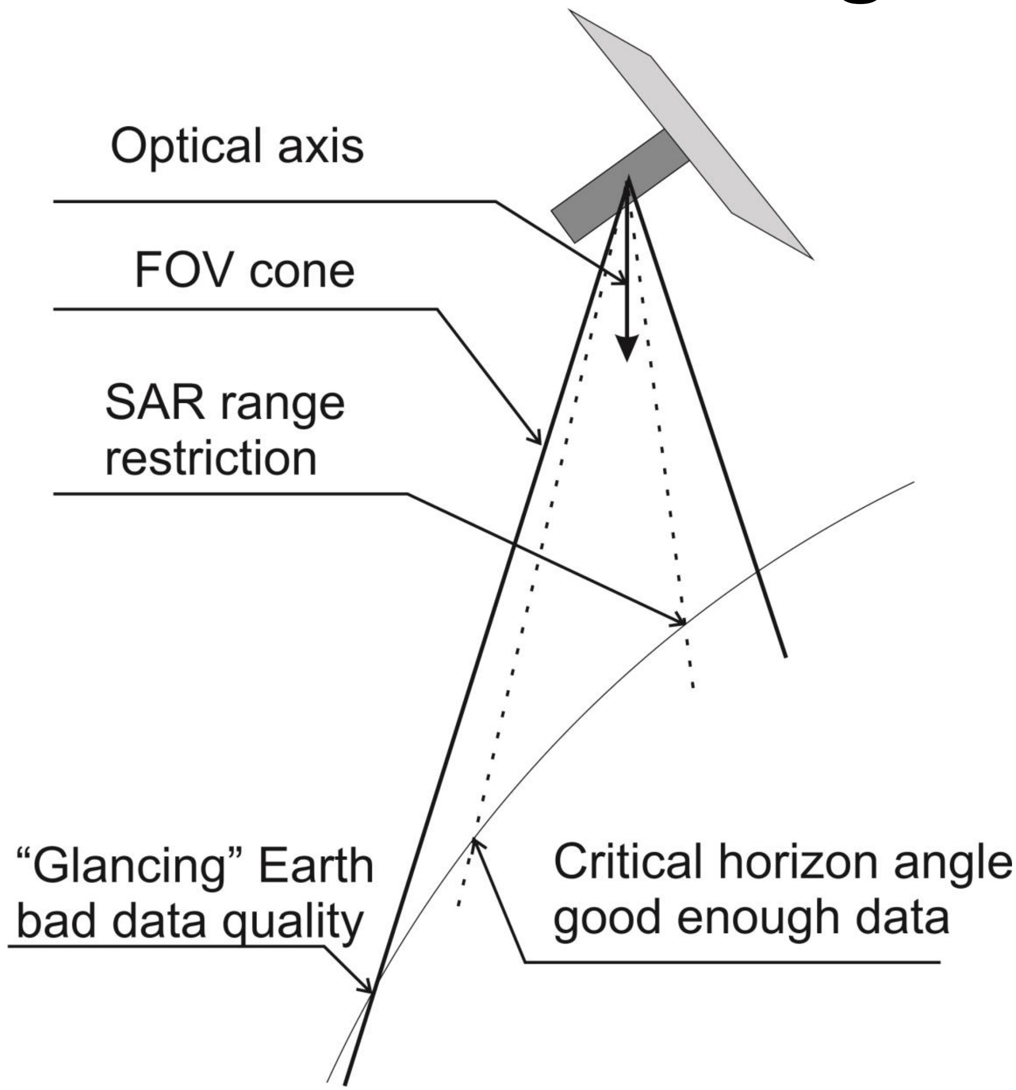
Example 2. Earth monitoring analysis Numerical analysis benefits

- 100 kg, 0.7 m cube, 4.6 m solar panel + SAR (JAXA SDS-4 satellite redesigned for a SAR at 620 km SSO)
- 550 km circular orbit, 60° inclination
- SAR/camera is always facing down
- Satellite with GPS, reaction wheels (Lyapunov control), precise attitude determination
- FOV half angle 30°/ 20° corresponds to SAR working up to 650/590 km (covered area differs by 2.6 times)

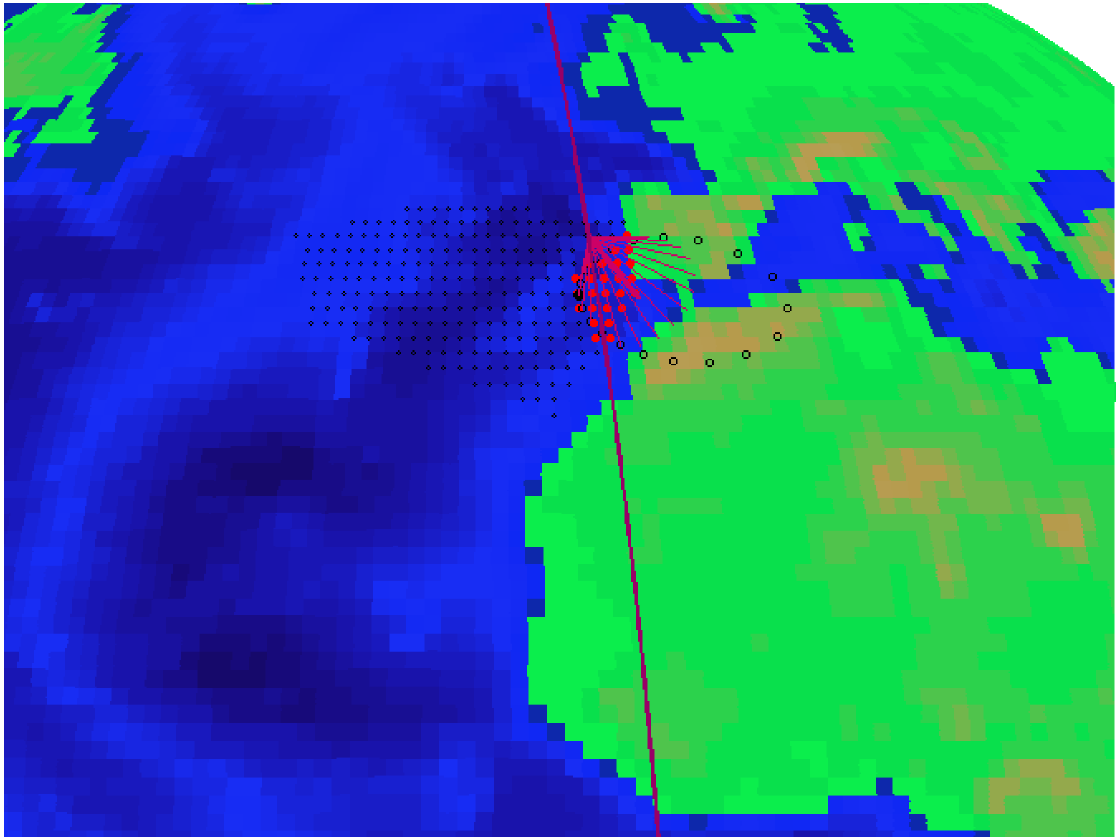
Earth monitoring software

- Satellite dynamics is processed after the simulation
- Payload has a conical field of view
- Earth is divided into a grid by a *one degree* step, WGS84 ellipsoid
- Area of interest is a *convex envelope* of a set of points (mainland coast, Azores, Madeira)
- Each point inside the envelope has *the same* “importance” weight
- Critical horizon angle for a “good” data is defined as 10 degrees (or SAR/camera maximum range may be used)

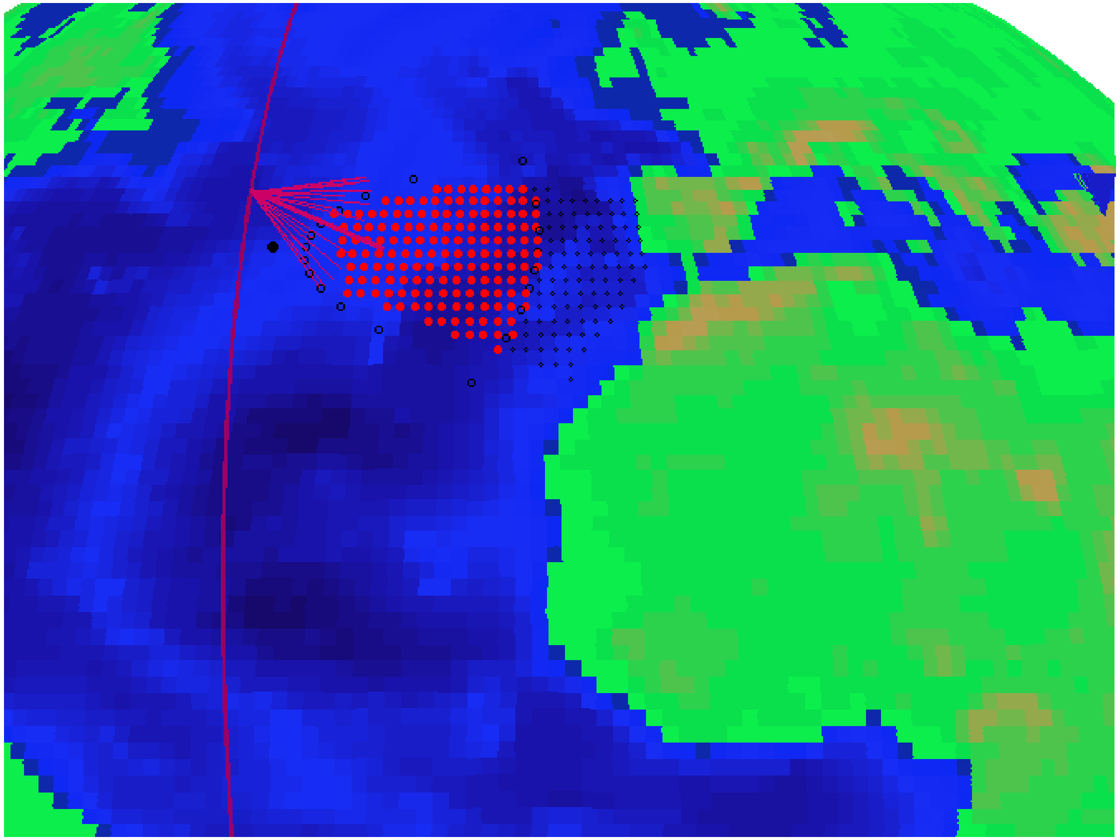
Critical horizon angle



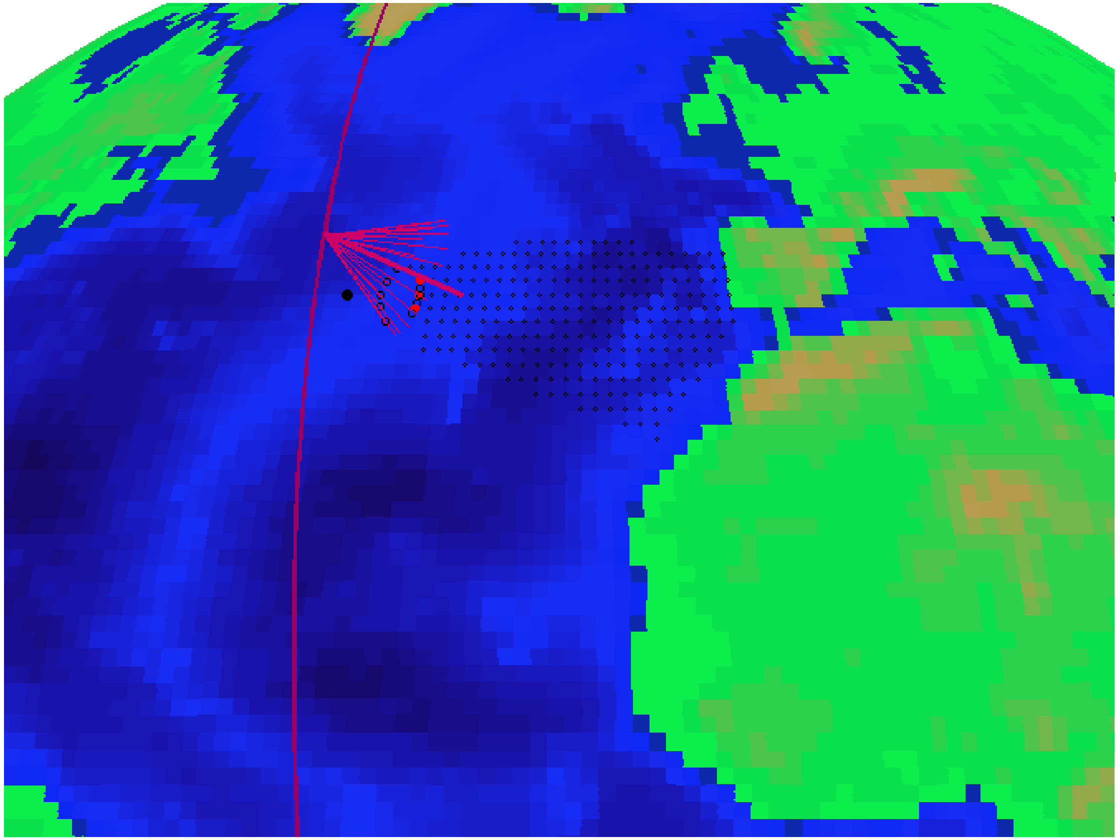
Portuguese waters coverage example



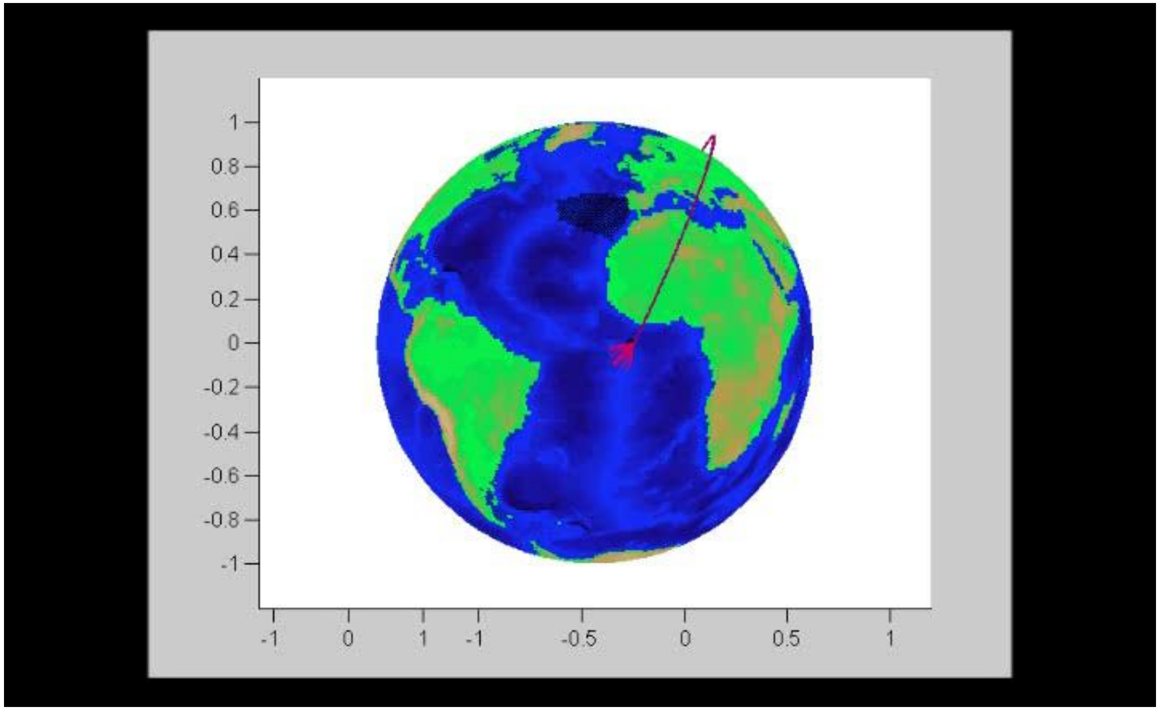
Payload closer to the glancing situation



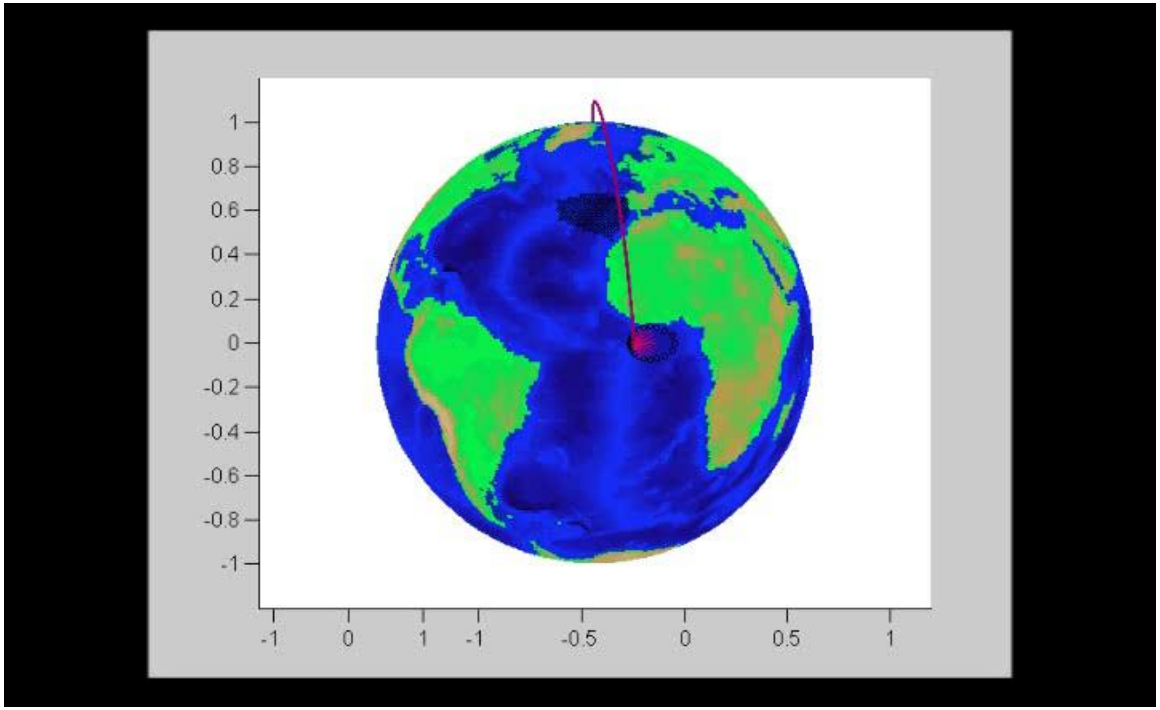
SAR closer to the glancing situation
SAR range is limited



Attitude convergence example



Portuguese waters coverage example. Payload facing almost down



Portuguese waters coverage results

- 30° FOV, J2 perturbation, facing down, 6 months
  - Minimum coverage per point 2089, maximum coverage 2756, average 2411, revisit time 4.6 hours
- 22.5° FOV, J2 perturbation, facing down, 6 months
  - Minimum coverage per point 971, maximum coverage 1257, average 1105, coverage is about 2.2 times less, revisit time 5.3 hours
- 30° FOV, J2 and GOST atmosphere (no maintenance)
  - Minimum coverage per point 1942, maximum coverage 2675, average 2360, revisit time 4.54 hours, orbit decay 41 km

Orbital decay

- Approximate value of the atmospheric drag provides the necessary continuous thrust to prevent orbital decay
- Thrust is approximately 21 (best situation), 75 (average), 130 (worst case – panels always facing the flow) millinewtons
  - A bit large, classic is 10-30 mN for 100 kg LEO
  - Russian SPD-100 83 mN, 1.35 kW, up to 9k hours
- This is *ver*y approximate due to different solar activity and attitude strategy
- Decay is rather slow, may be discarded

Inclination change

- Why not use the same engine for the inclination change?
- Constant thrust normal to the orbital plane changes inclination by 28° in half a year
- Coverage characteristics are a lot worse for the polar orbit (30° FOV, 90° inclination):
  - Minimum coverage per point 1693, maximum coverage 2060, average 1879, revisit time 6.95 hours
- Sun synchronous orbit provides better power balance

Important questions

- Satellite launch orbit and its alterations
  - Nominal insertion orbit is essential
  - Freedom in inclinations and altitudes provides some room for optimization
  - Upper stage booster availability and capabilities are necessary
- Flight program
  - Camera facing down above the region of interest
  - Panels facing Sun for a *given period* during each orbit
  - Minimizing drag at all other times
  - Maneuvering for better Earth monitoring and/or engine test
  - Any other specific payload requirements?
- SAR field of view and/or range, attitude

Conclusion

- AOCS subsystem can reap huge benefits for the whole mission
- Dynamical analysis can (and must) be performed fast and in advance, with only basic mission layout
- Have good specialists at hand

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