SAPIENZA
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Attitude Pointing as a Shareable Resource in Federated Satellite Systems

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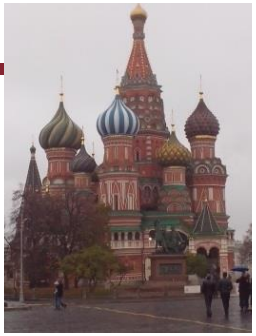
Pointing Resource Sharing: rationale

- almost all missions do have one or more pointing requirements
- pointing can be requested by payload and/or by ground – S/C link

- in advanced - or simply in recent - missions the downlink is accomplished at least in S-band (and therefore is likely to require specific pointing)
- the pointing can be obtained by steering the antenna, or the overall spacecraft bus if a simpler fixed antenna is used. In the latter case, complex – i.e. not orientable payloads – are going to waste some observation time
- of course, capability to share the pointing, by relaying the data to be downlinked to other spacecraft, would increase the data return (in time or in equipment costs)

Background (2014 meeting in SkolTech)



- The case of a payload producing data in space, as an example environmental observation with limited directivity constraints, which should point towards the ground station to downlink the data

- If these pointing capabilities have been lost, data can be transferred to a different platform which will take care of the downlink

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- A more realistic case, where a frequent re-orientation of a spacecraft is required. If the attitude determination and control system of this satellite is not working properly, it can be of interest to divide its tasks:

  some operation, and above all relevant re-orientation (again, the ones relevant to downlink seem the easiest to be shared) left to other federated platforms in order to save the resources of the ill-one and to extend the mission of the onboard payload beyond the failure

- Proposal: consider pointing as a resource to be “offered to /shared with” other S/C

Topics

Indeed, present works aims to elaborate these concepts, nominally by

- Measuring pointing resources
- Identifying some application:

I. Sharing to recovery missions with hardware failures

II. Sharing to increase the return of missions with almost steady pointing requirements

III. Pointing sharing considered since the mission design phase to enhance effectiveness/performance

Measuring pointing resources (1)

- The pointing capability can be measured by exploiting quaternion-based attitude representation. Given the quaternion associated with the current orientation of a spacecraft i (expressed with respect to an absolute inertial reference frame I)

$$\mathrm{Q}_{i,I} = \begin{bmatrix} \vec{q}_{i,I} \\ q_{i,I} \end{bmatrix}$$

vector part

scalar part

and the (targeted) pointing T, being required at the same time

$$\mathrm{Q}_{T,I} = \begin{bmatrix} \vec{q}_{T,I} \\ q_{T,I} \end{bmatrix}$$

the rotation between them can be computed as

$$\mathrm{Q}_{i,T} = \mathrm{Q}^{*}_{T,I} \otimes \mathrm{Q}_{i,I}$$

$$\vec{q}_{i,T} = -q_{i,I}\vec{q}_{T,I} + q_{T,I}\vec{q}_{i,I} - \vec{q}_{T,I} \times \vec{q}_{i,I}$$

$$q_{i,T} = q_{T,I}q_{i,I} + \vec{q}_{T,I} \cdot \vec{q}_{i,I}$$

Measuring pointing resources (2)

- The vector part of the resulting quaternion

$$Q_{T,i} = \begin{bmatrix} \vec{q}_{T,i} \\ q_{T,i} \end{bmatrix}$$

namely (φ is the angle associated with the rotation along the eigenaxis)

$$\vec{q}_{T,i} = \begin{bmatrix} \sin{}^{\varphi}/_{2}\, \hat{e_1} \\ \sin{}^{\varphi}/_{2}\, \hat{e_2} \\ \sin{}^{\varphi}/_{2}\, \hat{e_3} \end{bmatrix}$$

can provide the info we look for. In fact the magnitude of the vector part offers an indication of how large is the requested rotation *(see also Felicetti & Palmerini, IEEE Aerospace Conference 2015)*, assuming all axes are attainable for the S/C attitude control system.

Measuring pointing resources (3)

- This magnitude of the "difference in pointing" can be added iteratively all along the duration of the required pointing phase (NV steps where the ground station is visible)

$$D = \sum_{i=1}^{NV} \left| sign(q_{T,i}) \overrightarrow{q_{T,i}} \right| \quad (1)$$

to provide a value of the advantage granted by the shared strategy

- Real effort to be performed by either the pointing buyer and the pointing seller spacecraft can be actually less than (1), as each pointing will be incrementally achieved from the previous one. It is possible to consider a second incremental expression, still to be evaluated all the pointing phase

$$D_{incr} = \sum_{i=1}^{NV} \left| sign(r_{T,i}) \overrightarrow{r_{T,i}} \right| \quad (2)$$

where $R = \begin{bmatrix} \vec{r}_{T,I} \\ r_{T,I} \end{bmatrix} = Q_{T,I}{}^{*} \otimes Q^{(i-1)}{}_{T,I}$

Measuring pointing resources (4)

- The very same “distance” among quaternions easily translates in a given amount of torque to be provided by the attitude control system (i.e. requested power and, in the end, consumables to de-saturate the wheels, and maneuvers' commands increasing failures’ risk)

- Correspondence between “distance” and required command can be evaluated on the basis of the classical attitude dynamics relations:

$$ {}^{i}\dot{\vec{\omega}}_{i,I} = {}^{i}\mathbf{J}_{i}^{-1}\left(-{}^{i}\vec{\omega}_{i,I} \times {}^{i}\mathbf{J}_{i} \cdot {}^{i}\vec{\omega}_{i,I} + {}^{i}\vec{M}_{i}\right) $$

(possibly including the effect of environmental torques) where $\mathbf{J}$ is the inertia and ω is the angular rate required to modify the quaternion

$$ \dot{\vec{q}}_{i,I} = \frac{1}{2}\left(q_{i,I}\,{}^{i}\vec{\omega}_{i,I} - {}^{i}\vec{\omega}_{i,I} \times \vec{q}_{i,I}\right) \qquad \dot{q}_{i,I} = -\frac{1}{2}\,{}^{i}\vec{\omega}_{i,I} \cdot \vec{q}_{i,I} $$

Path I

Exploiting pointing resources sharing to fix failures

Failing Attitude Control

- In recent years several missions have been plagued by failures of the Attitude Control System components

- Among components, gyros seem especially prone to fail! (examples include ESA Artemis and NOAA Landsat 5). One or more gyros missing limit the envelope of possible pointing maneuvers, while the combination of remaining ones with other sensors can help up to a certain level

- Before complete failure, it makes sense to re-plan maneuvers.

  To have the chance to neglect downlink pointing adds a lot of chances to a quite successful recovery

Due-to-fail hardware

- The case of capabilities due to end/fail in a short time
- Main example: Thrusters' propellant for desaturation, which consumption can poses a boundary to the operational life of a still working S/C
- To "buy" pointing capabilities from other federated systems makes sense, as it drastically reduces the maneuver's requirements.

- Details strongly depend on the antenna configuration and on the relative orbits of both pointing *buyer* and *seller*, and for such a reason no quantitative data are presented

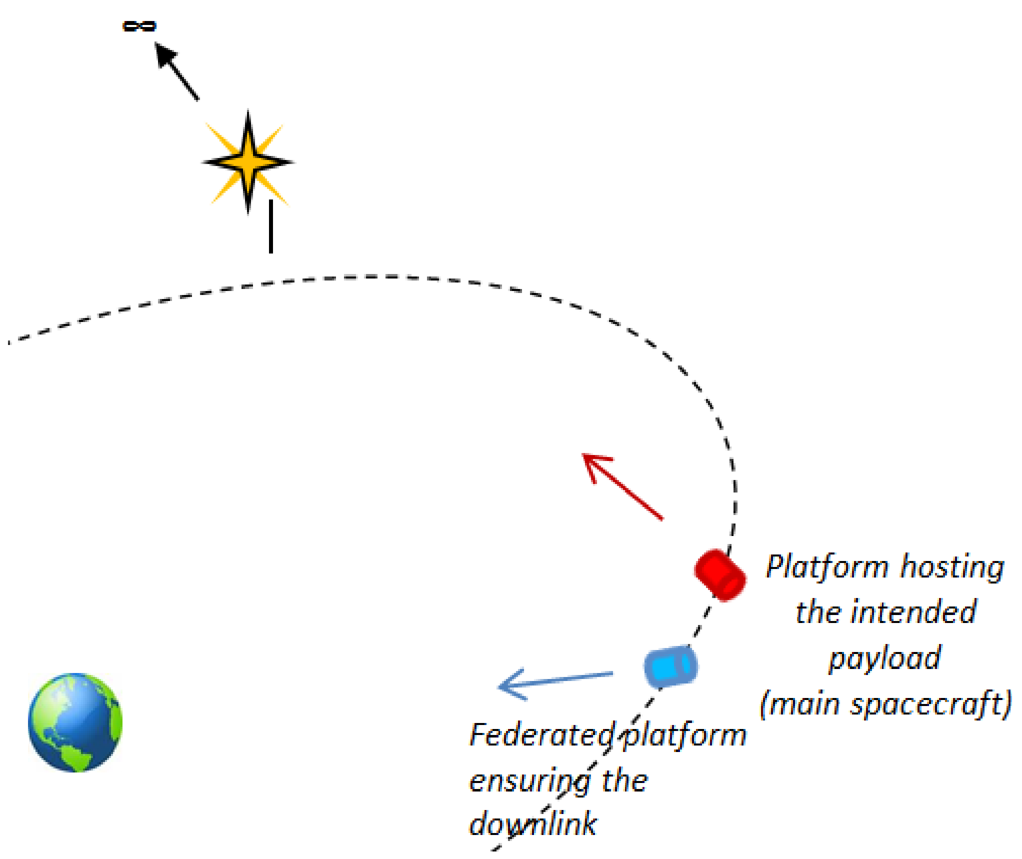
Path II

Missions requiring a given, almost continuous pointing*

* i.e. not limited to a fixed, “constant” in time one

Steady pointing (1)

- Steady (Fixed) pointing can be reserved to the main platform, limiting the need to manoeuvre and rotate the spacecraft

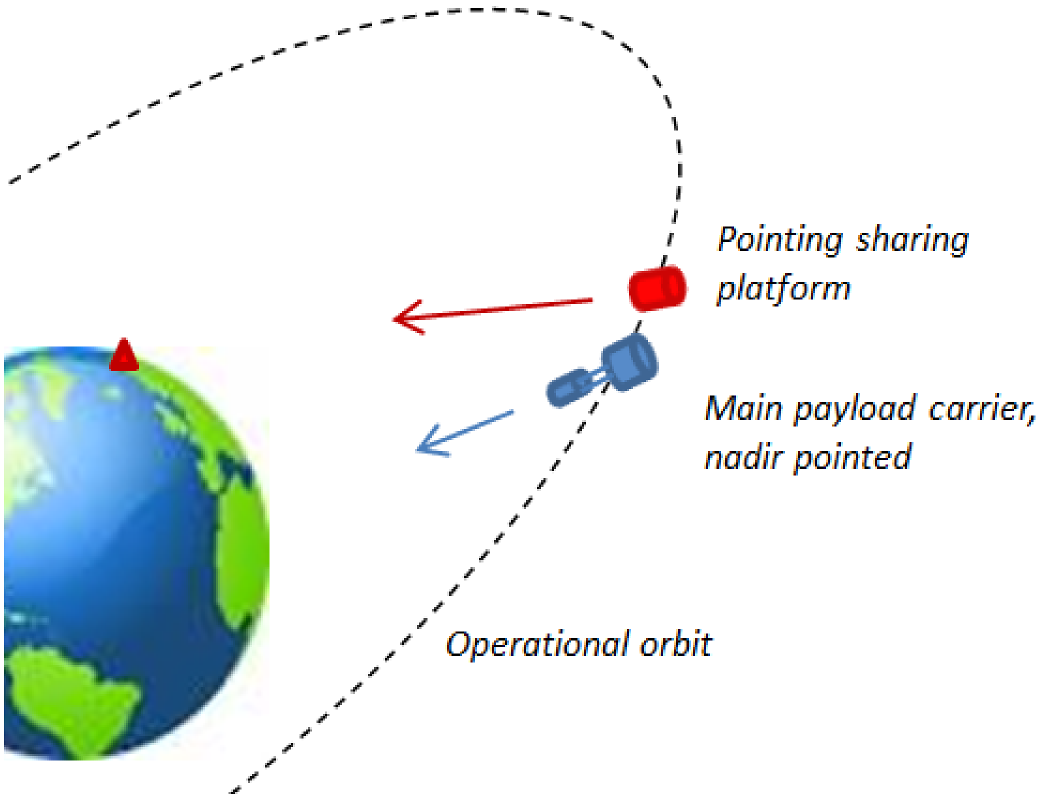


Sharing of pointing resources: the inertially pointing S/C conveniently maintains its attitude, while downlink (and continuous "tracking" of the ground station by the platform itself or a steerable antenna) is left to the federated platform.

Note that federated platform is not required to be located on the same orbit of the main one.

Steady pointing (2)

- Pointing of interest does not need to be fixed ("constant") in time, but can slowly vary *[Frequent changes (agile maneuvering) limit the possible benefit]*

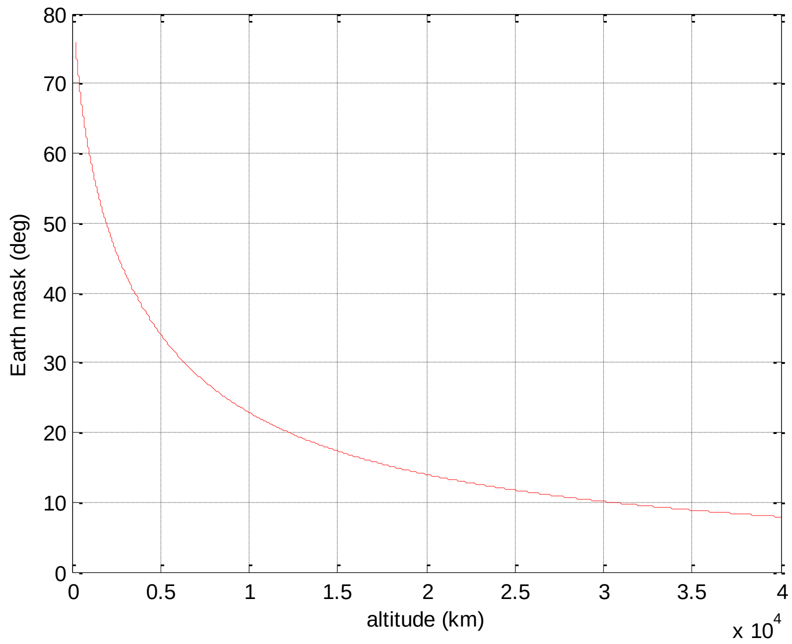


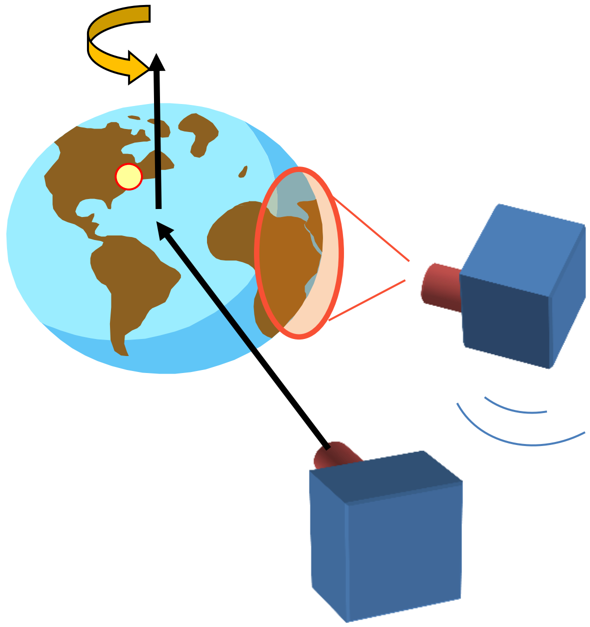
Sharing of pointing resource:
a simple, nadir-looking platform without steerable antenna continues observation without the need to stop it for pointing the ground station for downlink. Data are simply relayed to a federated platform, with far easier link budget due to the shorter distance without attenuation.

Note that federated platform is not required to be located on the same orbit of the main one.

Earth (Nadir) Pointing

Nadir pointing isn't exactly equal to point a specific target on Earth. Earth mask, given by $\sigma = \pi - acos\frac{R_{Earth}}{R_{Earth}+h}$ is far larger than antenna beamwidth at S-band



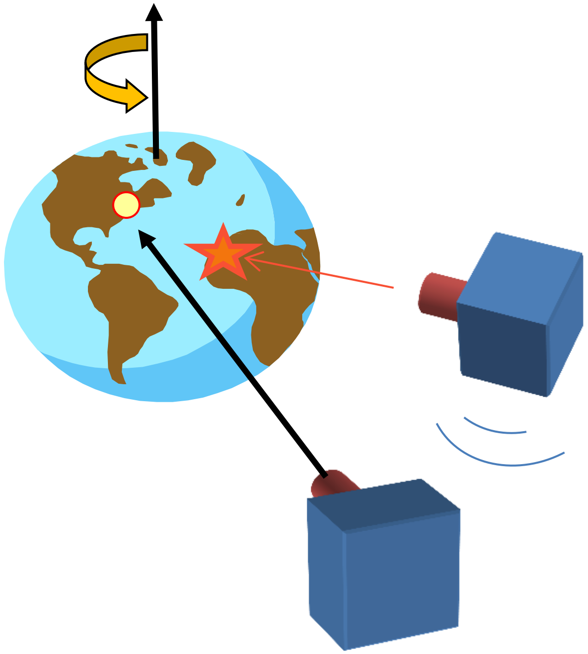


It could be useful for certain instruments (climate/weather payloads) to maintain a global coverage (climate/weather) while a friend S/C carry out the downlink

Earth (Nadir) Pointing (2)

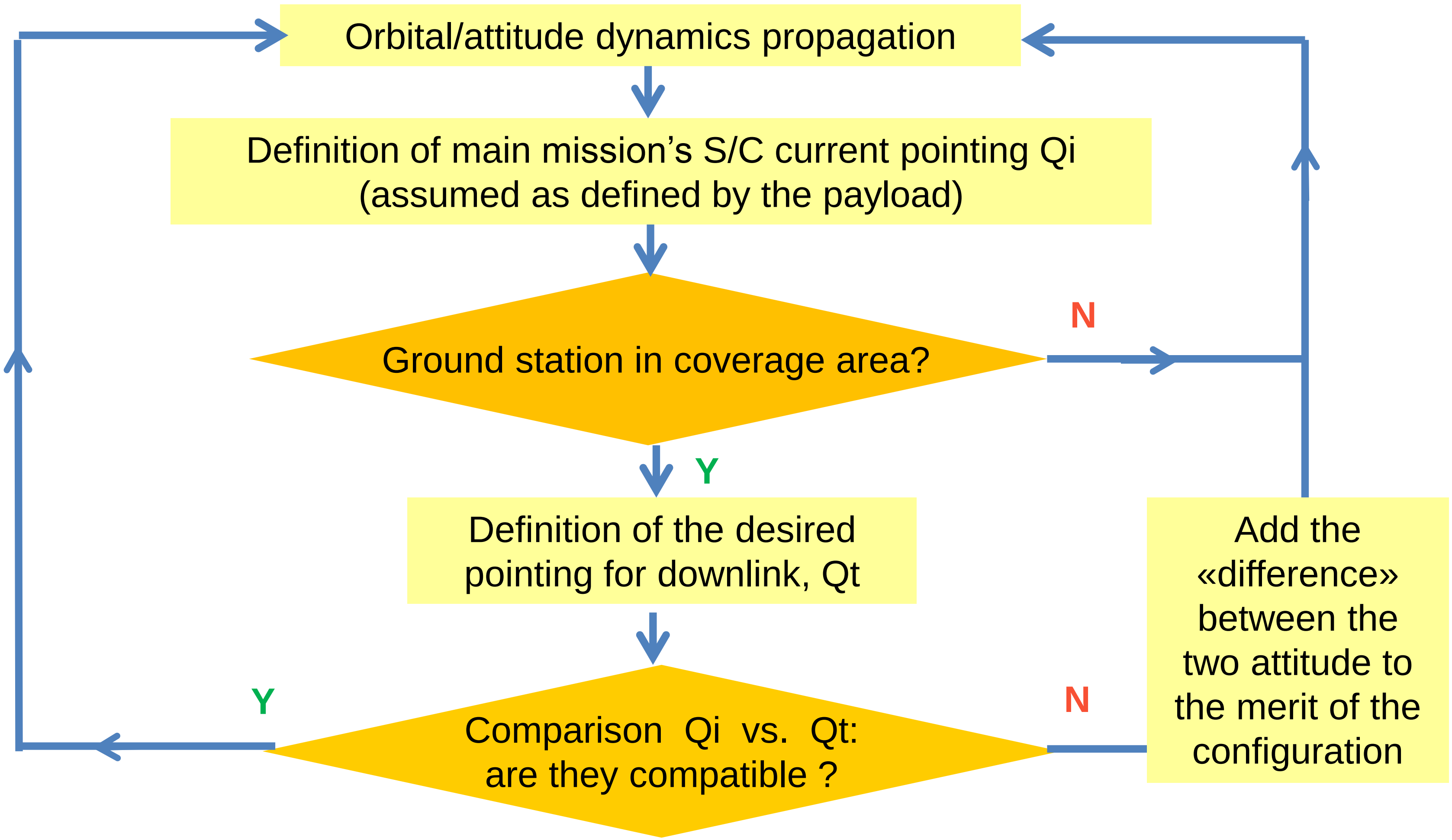
The very same applies to really strict field of view payload that are allowed to continuous, dedicated sensing operation with a very stable platform (no steerable antenna onboard, no vibes)

Meanwhile, an omnidirectional antenna transfer gathered data to (one out of many) federated S/C that assume the downlink task



Benefits

- A simple Matlab script has been prepared using previous relations



Path III

pointing resources taken into account since mission design phase

Rationale

- To simplify the design and limit the costs by differentiating the tasks among specialized spacecraft
- Part of the assets (i.e. payload) will be with the main spacecraft
- Part of the assets (the ones related with pointing capabilities) will be provided by federated satellites, not strictly belonging to the same mission and able to provide their services to different missions (as NASA TDRS)
- To simplify modes and limit re-pointing can be an interesting option, leading to a lighter and simpler subsystem
- ADCS is quoted slightly less than 20% of the platform cost
- *It is possible to proceed with parametric cost analysis and the cost estimate requirements (CERs). Different models apply …..*

Cost models

- Mass. Take into account (Larson & Wertz) that ADCS costs are strongly dependent on the required/expected lifetime. In case of the famous FireSat example, the subsystem mass is 7 kg for 1 year, 9 kg for 5 years and 22 kg for 7 years (redundancy affect the size of the components). The resulting relation to cost can read as

$$Y = 1.358 + 8.56\, X^{2} \qquad [Y=\$,\ X=\text{mass(Kg)}]$$

- Pointing. Again from Larson & Wertz

$$Y = 341 + 2651\, X^{-0.5} \qquad [Y=\$,\ X=\text{accuracy(deg)}]$$

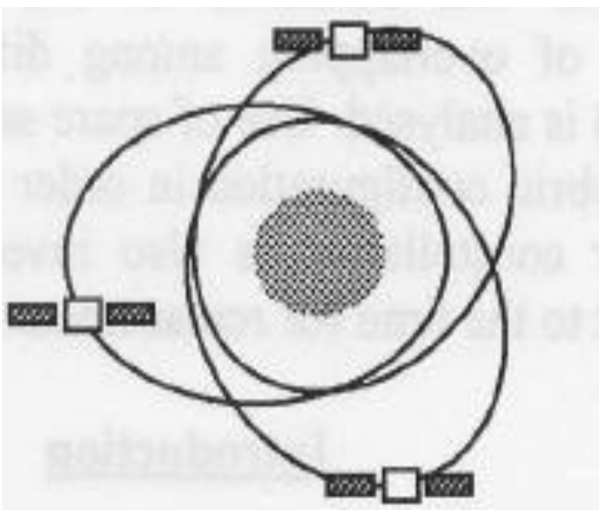
- Complexity. From Aerospace Corp. cost model for small satellites, factors affecting ADCS include among others the type of stabilization and the number and type of sensors, with a resulting CER like

$$Y = F(X)\, 1.99^{X1} \qquad [Y=\$,\ X=\text{power related parameter(s)},$$

$$X1=1 \text{ for 3-axes technique, } =0 \text{ for others (GG, spin)}]$$

Optimality problem for federated systems

- Interestingly, there is a requirement for agile spacecraft
- Existing systems (Orbcomm, etc)
- Some insight into convenient design: “system approach” (G.Palermo, A.Golkar and P.Gaudenzi, *Acta Astronatuica 2015*)
- Unusual configurations: different inclinations, non circular orbits, choice of parameters to have “matching” effects of the perturbations …………



Old orbital dynamics studies:

→ *Hybrid configurations for Satellite Constellations (1997)*

→ *J2-driven free span of the service volume to monitor space environment (1995)*

Final remarks: findings & further work

- A measure for pointing sharing assessment has been identified
- Simple codes allows to evaluate possible advantages
- Economical benefit (the real driver to federated systems) is more difficult to evaluate. However, it's actually the same business as the evaluation of a traditional mission cost

Next steps:

- Cost related issues. Moving from attitude evaluation to data relay cost should better "price" the service offered, while attitude dynamics and control maintains its role in the evaluation of the advantages for the considered mission program.
- To investigate orbital design for federated satellite systems able to serve as much as possible users *(Heuristic approach would definitely help)*