Collision risk in Earth orbit

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Outline

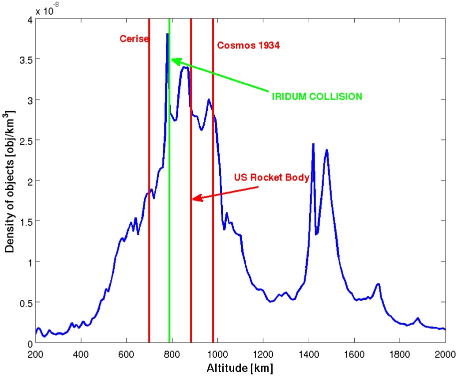
1. Collision Risk
    - Collision Risk in LEO
    - Collision Risk in MEO
2. The Iridium collision
    - Nature sims
    - Long term dynamics of the debris cloud
    - Modelling the Feb. 2009 collision
    - Collision avoidance in the cloud

Spatial density of objects $>$ 10 cm in LEO

The collisions happened in high density regions of LEO.

All the orbits have large inclinations $\Rightarrow$ high density at the crossing at high latitude.

Density of objects > 10 cm



Accidental collision

- Currently hundreds of close approaches (i.e., passes within less than 1 km) between cataloged objects occur on a daily basis.
- In all the documented accidental collisions, before 2009, only 6 catalogued debris were produced.....BUT...

Collision risk evaluation

- The number of collisions between two orbiting particles expected during a time interval Δt can be formally expressed as $P_i \, (R + r)^2 \, \Delta t$, where:
    - r and R are the projectile and target radius, respectively (both bodies are assumed to be spherical),
    - P_i is the so–called *intrinsic collision probability per unit of time*, a quantity depending only on the two sets of orbital elements
- P_i may be interpreted as the collision rate between two bodies for which $(r + R) = 1$ m.
- Of course, $P_i = 0$ if the two orbits cannot intersect each other for geometrical reasons; this occurs when the apocenter distance of the inner orbit is smaller than the pericenter distance of the outer one.

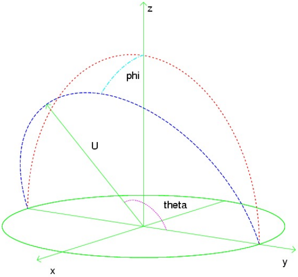
Öpik's formulation

The geometry:

the x direction goes from the center of the Earth (which is on the negative x axis) to the target,

y is in the direction of the target motion

U is the projectile velocity.



Öpik's formulation

The intrinsic collision probability per unit time is

$$P = \frac{U}{2\pi^2 (a/a_0)^{1.5} |U_x| \sin i} , \tag{1}$$

a: semimajor axis of the projectile, a_0: target orbit radius;
i: relative inclination between the orbital planes of the projectile and the target
U: projectile's velocity relative to the target (in units of the target's geocentric velocity)
U_x: component of the projectile velocity along the (radial) axis containing the centre of motion (the centre of mass of the Earth in our case) and the instantaneous position of the target.

Öpik’s formulation

U: projectile’s velocity relative to the target (in units of the target’s geocentric velocity)

$$U = \sqrt{3 - \frac{a_0}{a} - 2\sqrt{\frac{a(1-e^2)}{a_0}}\cos i}\ , \qquad (2)$$

a_0 is the semimajor axis of the target body (assumed to be on circular orbit) and e is the eccentricity of the projectile.

Öpik's formulation

The components of $\vec{U}$ are:

$$U_x = \pm\sqrt{2 - \frac{a_0}{a} - \frac{a(1-e^2)}{a_0}}$$

$$U_y = \sqrt{\frac{a(1-e^2)}{a_0}}\cos I - 1$$

$$U_z = \pm\sqrt{\frac{a(1-e^2)}{a_0}}\sin I.$$

Öpik's formulation

We can introduce two angles, θ and ϕ, such that:

$$U_x = U \sin\theta \sin\phi \qquad U_y = U \cos\theta \qquad U_z = U \sin\theta \cos\phi$$

$$\Longrightarrow \qquad \cos\theta = \frac{U_y}{U} \qquad \tan\phi = \frac{U_x}{U_z}$$

θ, colatitude (angle between the vector U and the y axis), and ϕ, longitude, measured from the U-y plane to the y-z plane.

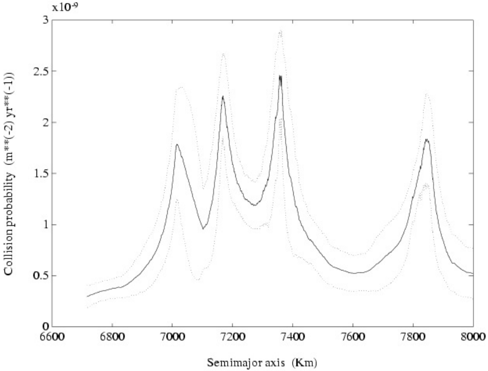
θ and ϕ define the direction of arrival of the projectile, in the frame co-moving with the target.

Intrinsic collision probability in LEO

In a similar way as done for the Asteroid Belt, using Wetherill's algorithm and the *nCUBE 2* multicomputer at CNUCE-CNR, Paolo and I calculated the mutual collision probabilities and impact velocities for a set of 2700 objects with perigee < 1600 km.

The average intrinsic collision probability P_i is of $1.105 \pm 0.812 \times 10^{-9}\ m^{-2}yr^{-1}$; the average impact velocity in LEO V is $9.65 \pm 0.88\ km/s$.

(Rossi & Farinella, *ESA J.*, 1999)



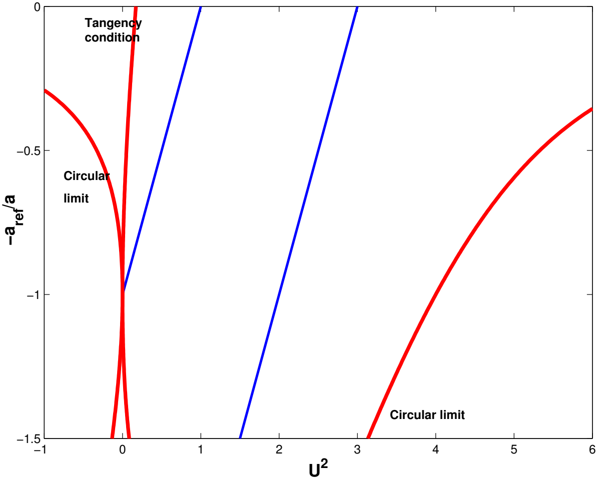
Distribution in the U^2 vs E plane

Distribution of the cataloged (TLE) objects, with respect to a target orbit:

$a_0 = 6828$ km

$e = 0$

$i = 0°$



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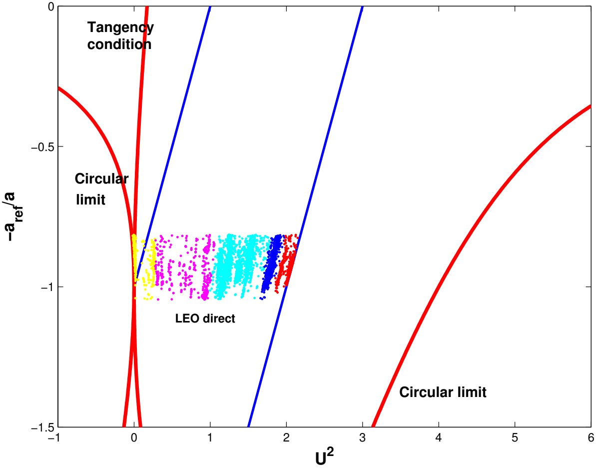

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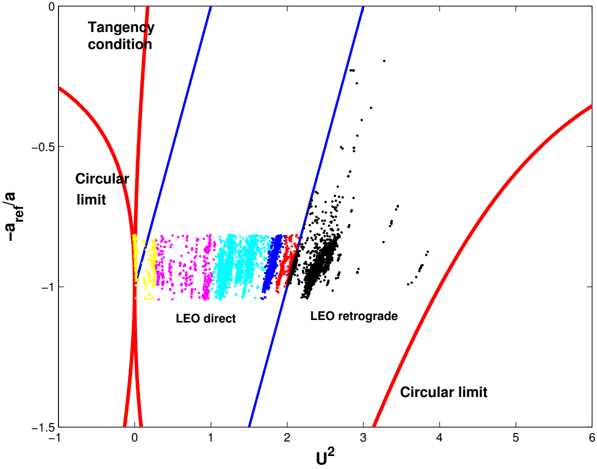

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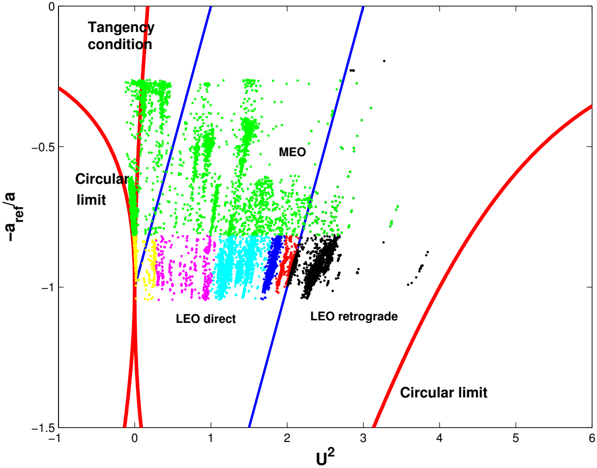

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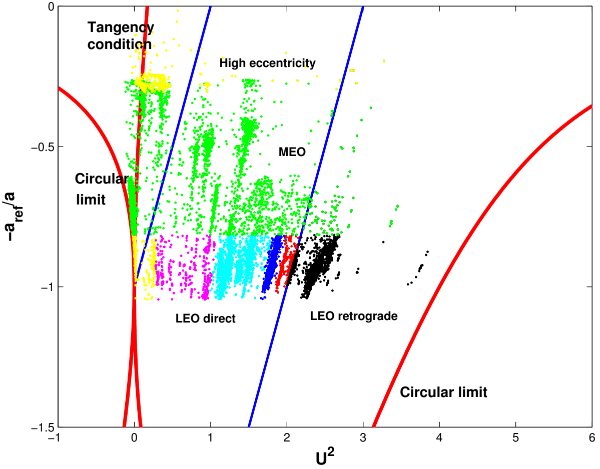

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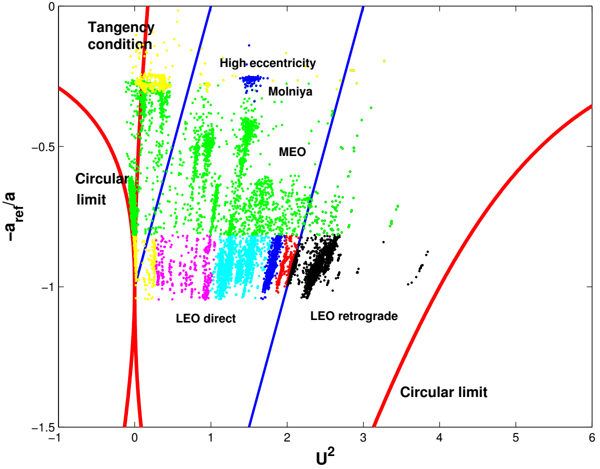


Distribution in the U^2 vs E plane

By calculating the mutual inclination between the target and the projectiles:

$$I = 2\arcsin\sqrt{\left[\sin\frac{i-i_0}{2}\right]^2 + \sin i_0 \sin i \left[\sin\frac{\Omega-\Omega_0}{2}\right]^2}$$

where i_0, i and Ω_0, Ω are the inclinations and longitudes of node of the target and the projectile, respectively, it is possible to work on a target in a generic circular orbit.

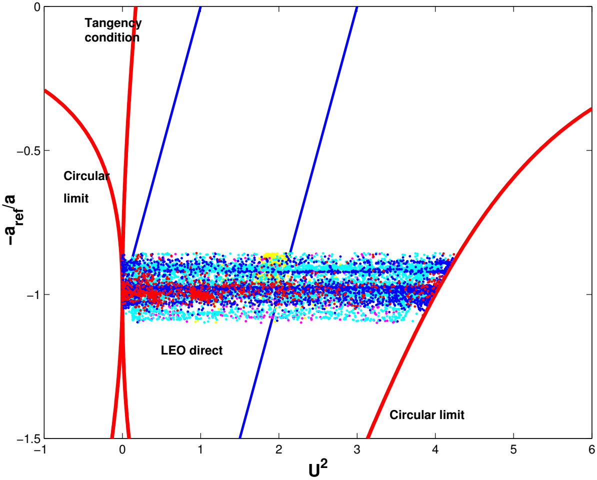
Distribution in the U^2 vs E plane

Distribution of the cataloged (TLE) objects (no fragments included), with respect to a target orbit:

$a_0 = 6828$ km

$e = 0$

$i = 52°$



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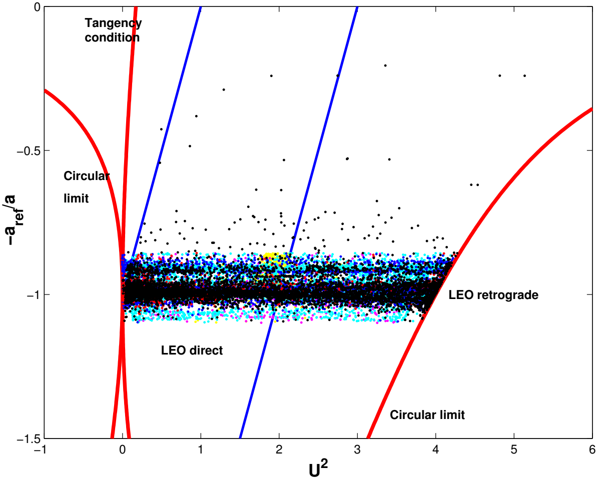

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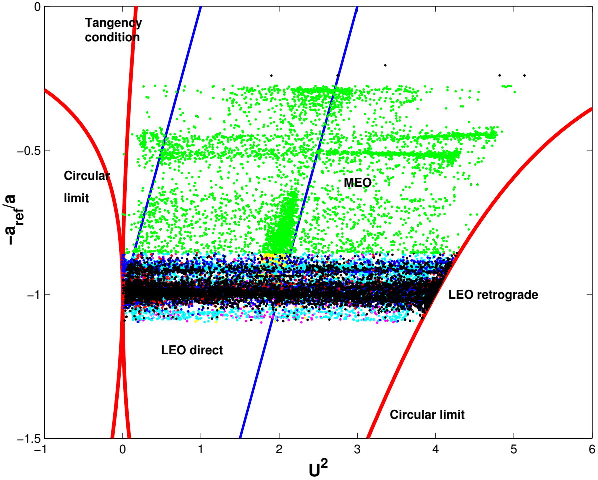

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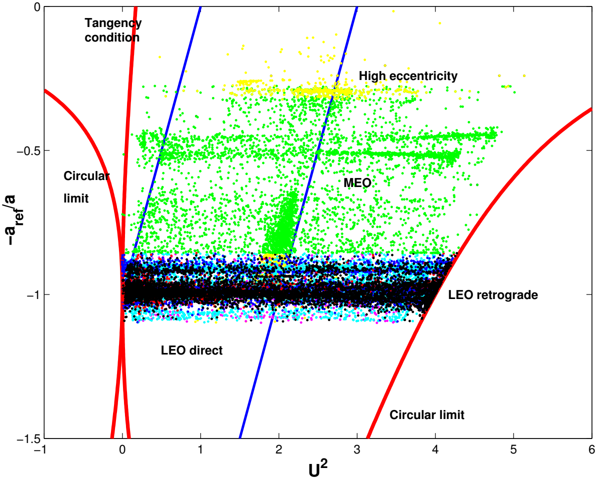

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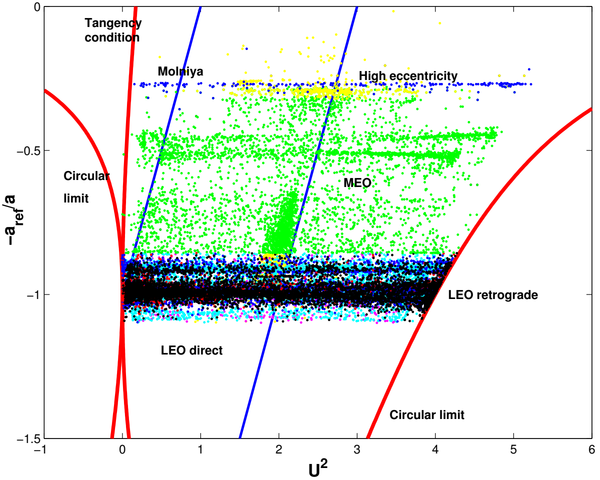

The Öpik method as visualizing tool

- TheÖpik method allows fast visualization of complex dynamical evolutions.
- Evolution of the fragments from a collision happening on the ISS orbit.
- $a = 6890$ km , $e = 0$, $i = 52^\circ$, $\Omega = 10.3^\circ$
- $M_T = 800$ kg, $M_P = 0.8$ kg, $V_{imp} = 10$ km/s
- $\sim 870\,000$ fragments generated
- Orbit of the ISS and of the fragments (sampled) propagated for several years.

The Öpik method as visualizing tool

- The initial inclination i of the ISS and of the fragments are the same, but $I \neq 0$ due to the different $\Omega \Longrightarrow$ large U^2 (high impact velocity)!
- Differential precession of $\Omega \Longrightarrow$ snake like behaviour.
- $0^\circ \leq I \leq 104^\circ$ maximum relative inclination.
- The debris cloud dynamics can be followed for a long time w.r.t. the background.

Collision risk for the ISS

Öpik's analytical expressions are particularly suited to analyse and represent, on a suitable projection, the evolution of the collision risk for the International Space Station (ISS):

$$a_0 = 6\,778 \text{ km}, \; e = 0,$$
$$i_0 = 52^\circ, \; \Omega_0 = 147^\circ.$$

The ISS is shielded against debris smaller than 1 cm only.

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Collision risk for the ISS

- To visualize the impact risk on the ISS an Hammer-Aitoff (equal-area) projection of the celestial sphere is used.
- The map is centered on the instantaneous direction of motion of the ISS, and rotating around the Earth.
- On such a projection, it is possible to draw contours of equal impact probability, $P = P(\theta, \phi)$. Projectiles lying on these lines have the given probability P of impacting against the target.

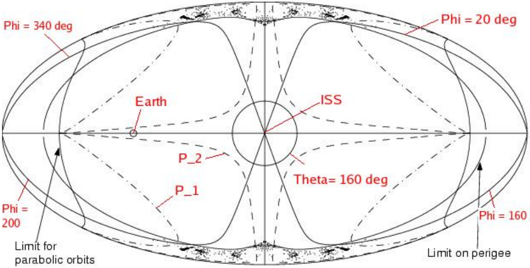
Collision risk for the ISS – H-A 4 - 5 km/s

- Projectiles come from close to the border, i.e. from the back of the ISS.
- Impacting directions not far from the local horizontal plane (defined by $\sin\phi = 0$), within less than 30° of that plane.
- All the crossing objects have impact probabilities $> P_1$. Only those closer to the ISS orbital plane have impact probabilities $> P_2$.

Impact velocities between 4 and 5 km/s.

$P_2 = 10^{-9}\ \mathrm{m}^{-2}\ \mathrm{y}^{-1}$

$P_1 = 10^{-10}\ \mathrm{m}^{-2}\ \mathrm{y}^{-1}$



Collision risk for the ISS – H-A 4 - 5 km/s

- Most of the projectiles are in moderately to high e orbits.
- About half of them have $a \sim 13\,000$ (up to about $20\,000$ km) and their perigee close to the ISS orbital altitude.
- i ranges from about $20°$ to about $38°$.
- More than 95 % of these particles are Solid Rocket Motors related debris.

Impact velocities between 4 and 5 km/s.

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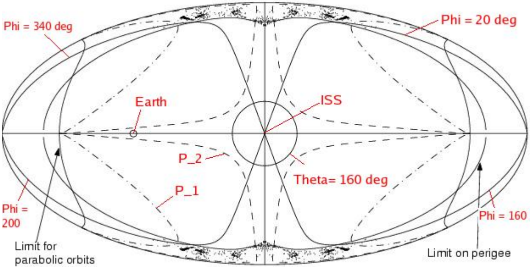
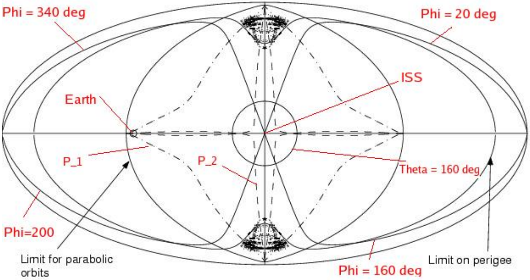


Collision risk for the ISS – H-A 8 - 9 km/s

- The projectiles directions move away from the back, θ is approaching (but not reaching) $180°$, i.e. head-on collisions;
- the projectile directions are concentrated closer to the $\sin\phi = 0$ plane.
- the equal probability curves shrink toward the axis of the plane (in particular toward the $\sin\phi = 0$ plane).

Impact velocities between 8 and 9 km/s.

$$P_2 = 10^{-9}\ \mathrm{m}^{-2}\ \mathrm{y}^{-1}$$
$$P_1 = 10^{-10}\ \mathrm{m}^{-2}\ \mathrm{y}^{-1}$$



Collision risk for the ISS – H-A 8 - 9 km/s

- More than half of the objects have $a \sim 18\,000$ km and $e \sim 0.65$. i is larger than in the previous case and clustered in a few different bands, between about 52° and 72°;
- The region comprised between the parabolic and the atmospheric reentry limit (i.e., the allowed region) has shrunk to a small portion of the $\theta - \phi$ plane. $\Longrightarrow$

Impact velocities between 8 and 9 km/s.

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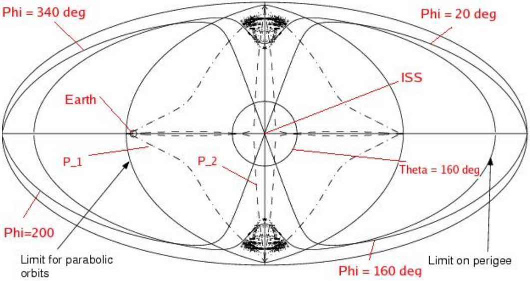

Collision risk for the ISS – H-A 8 - 9 km/s

$\Longrightarrow$ for a given target in a circular orbit and for a given impact velocity (especially if the latter is high), the range of allowed impact direction is strongly constrained and easily characterized by the present method.

Impact velocities between 8 and 9 km/s.

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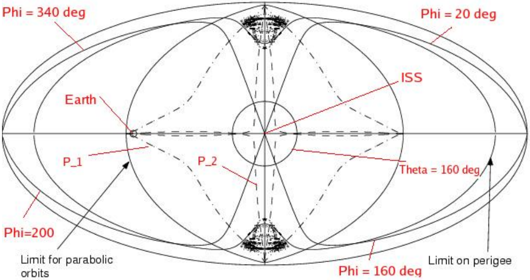

Collision risk for the ISS – H-A 13 - 15 km/s

- A small number of potential impactors is left.
- Nearly head-on collisions, with a high impact probability too.
- They are objects in retrograde, nearly circular, Low Earth Orbits, with semiaxis close to the ISS one.
- Almost all fragments or cataloged objects, not related to SRM firings.

Impact velocities between 13 and 15 km/s.

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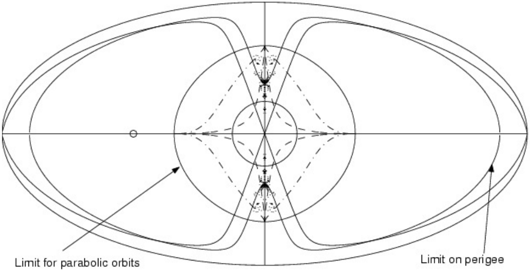

Collision risk for the ISS – H-A Summary

Summary

- The potential impactors tend to come from directions close to the $\sin\phi = 0$ plane, the deviation from this plane being a decreasing function of the impact velocity U.
- Most of objects crossing the ISS orbit have impact velocities between about 9 and 12 km/s, with impact probability in excess of $P_1 = 10^{-10}$ m^{-2} y^{-1}.
- The SRM-related particles dominate the potential impactors for nearly all the velocity range; only at very high velocities, above 13 km/s, the impactor population is dominated by fragments.

MEO Collision Risk Estimation

- A basic assumption of Öpik's theory is that the argument of perigee ω of the projectile orbit, evaluated using as reference plane the orbital plane of the target, is randomly distributed between 0 and 2π.
- This means, for instance, that the theory is not applicable to situations in which a resonance is constraining the distribution of ω (e.g., for the Molniya orbits).
- In LEO, the randomization induced by the drift of ω_{eq} due to the Earth's quadrupole J_2 is so effective that Öpik's theory can be easily applied without significant loss of accuracy.
- In MEO $\dot{\omega}_{eq}$ is about two orders of magnitude smaller than in LEO (e.g., at the GPS altitude $\dot{\omega}_{eq} \simeq -0.02$ deg/day).

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MEO Collision Risk Estimation

Necessary conditions for a collision on a target in a circular orbit of radius a_0 to occur are:

- that the perigee and apogee of the projectile orbit are such that $q = a(1-e) < a_0 < Q = a(1+e)$;
- that the geocentric distance of the projectile, at its crossings of the orbital plane of the target, within the region $[a_0 - R_c, a_0 + R_c]$, where R_c is the collision radius.

MEO Collision Risk Estimation

- The crossings take place at the ascending and the descending nodes of the projectile orbit on the target orbital plane, where we have $\omega + f = 0$ (at the ascending node, f being the true anomaly of the projectile), and $\omega + f = 180^\circ$ (at the descending node); the geocentric distances of the nodal points are given by

$$\begin{aligned} r_a &= \frac{a(1-e^2)}{1+e\cos(-\omega)} = \frac{a(1-e^2)}{1+e\cos\omega} && (3) \\ r_d &= \frac{a(1-e^2)}{1+e\cos(180^\circ-\omega)} = \frac{a(1-e^2)}{1-e\cos\omega} \,. && (4) \end{aligned}$$

MEO Collision Risk Estimation

- When both r_a and r_d are sufficiently different from a_0, collisions are impossible.
  When, for a particular value ω_c of ω,

$$a_0 = \frac{a(1-e^2)}{1+e\cos\omega_c} \; .$$

  a collision is possible.
- Note that collision is also possible for $\omega_{c2} = \omega_c + 180^\circ$ (i.e. at the other node) and for $\omega_{c3} = 360 - \omega_c$ and $\omega_{c4} = 180 - \omega_c$ (since $\cos\alpha = \cos(360^\circ - \alpha)$).
  These four values of ω are all in different quadrants.

MEO Collision Risk Estimation

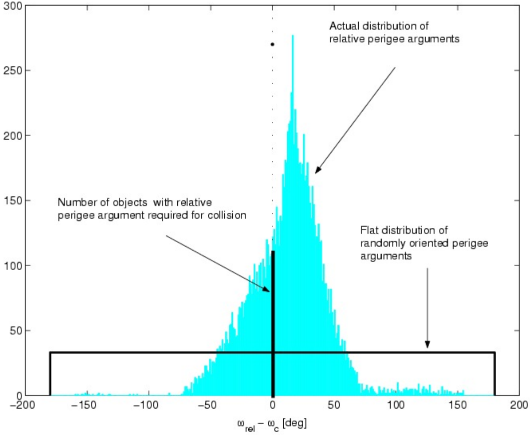
- The difference between the current value of ω and the nearest collision solution is expressed by:

$$\omega^{\star} = \min(\omega - \omega_{c1}, \omega - \omega_{c2}, \omega - \omega_{c3}, \omega - \omega_{c4});$$

- The ω-randomness assumption of Öpik's theory can be considered equivalent to the assumption that the distribution of $\omega^{\star}$ is flat between -180° and 180°

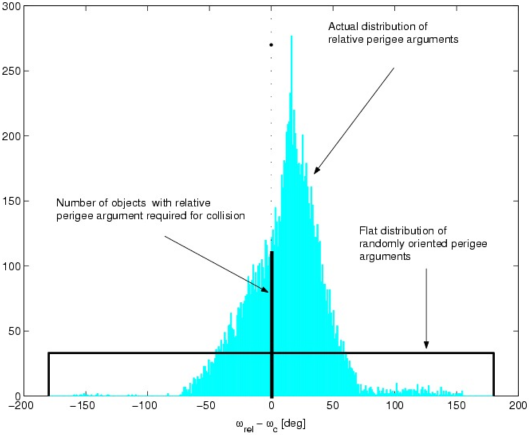
MEO Collision Risk Estimation

- The true distribution of $\omega^\star$ (y_t) for the projectiles (coming from the numerical integration) is compared at $\omega^\star = 0^\circ$, at any time, with the value of the flat distribution, y_f.
- y_t/y_f gives the correction factor by which the probability of collision calculated assuming the flat distribution of perigee arguments, has to be multiplied.



MEO Collision Risk Estimation

- In this way, for each projectile, the true collision probability, taking into account the slow diffusion of the orbital elements in MEO, is obtained.



MEO Collision Risk Estimation

Orbital elements of the debris w.r.t. target orbit

To apply this method, ω, the argument of perigee of the projectile has to be computed with respect to the orbital plane of the target.
This can be done by exploiting the orbital angular momentum:

$$h = \sqrt{G m_{\oplus} a(1 - e^2)}\,.$$

and eccentricity vectors:

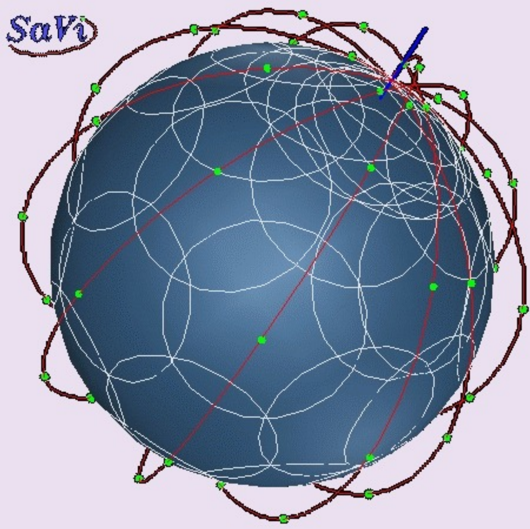
$$\vec{\varepsilon} = GM\vec{e}$$

....and a lot of algebra (see Rossi, Valsecchi & Perozzi, *JAS*, 2005).

Outline

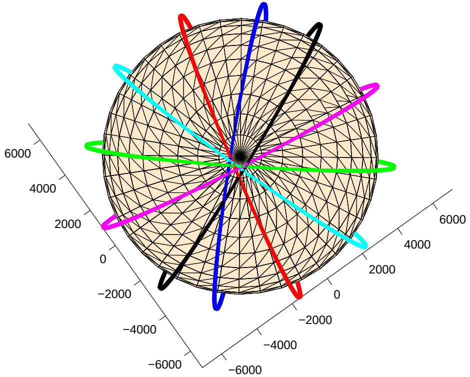
LEO Satellite constellations

- The Iridium constellation has 66 operational satellites (+ 6 spares) located on 6 orbital planes, separated by 30°.
- $a = 7158$ km; $e \simeq 0$; $i = 86.4$



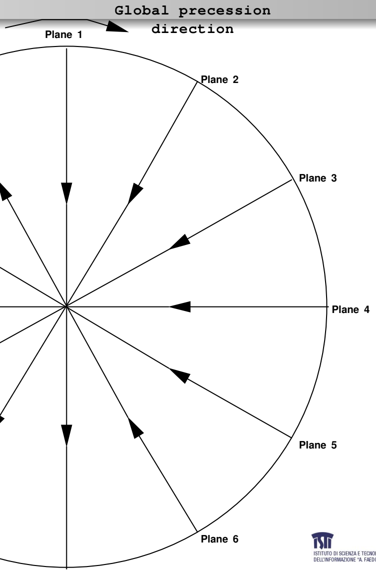
IRIDIUM - Dynamics

- North celestial pole view of Iridium.



IRIDIUM - Dynamics

- In near-polar multi-plane constellations there are necessarily two neighboring planes that contain satellites moving in opposite directions.
- Plane 1 and 6, in the IRIDIUM case, are only 30° from each other when crossing the equator either northward or southward.



Nature paper simulation setup

- We simulated the impact between a 1 kg projectile and a 650 kg Iridium satellite at $V_{rel} = 10$ km/s.
- It could be shown that there was an ≈ 10 % hazard per decade of such a collision......
- Collision was simulated with CNUCE Model (power law with energy dependent exponent)
- About 10^6 fragments with mass $m > 1$ mg and ≈ 8000 fragments with $m > 1$ g were produced.
- The orbit of all the larger fragments was propagated for 20 years.
- The flux on the different constellation planes was evaluated with the Öpik method.

IRIDIUM - Dynamics

- The ejection velocities of the fragments send them into different orbits, where differential perturbations (J_2 - oblateness of the Earth - and drag) spread the initial concentration in orbital element space.
- Higher altitudes fragments have longer lifetime and slower nodal precession rates w.r.t. the constellation satellites.
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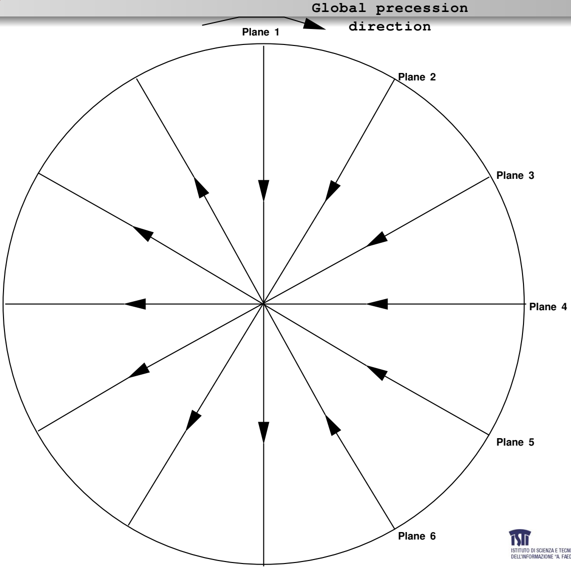
Long term dynamics

- If a satellite orbiting, for example, in the preceding one of these two planes is broken up, its fragments will be reached by the satellites in the following plane, and then they may cause very energetic head-on collisions, with higher than average collision speeds and impact probabilities.



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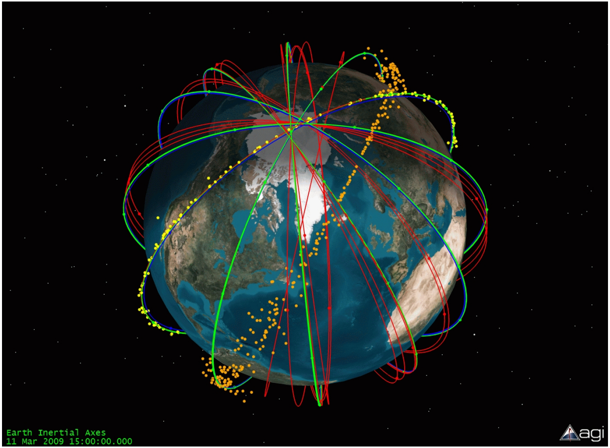

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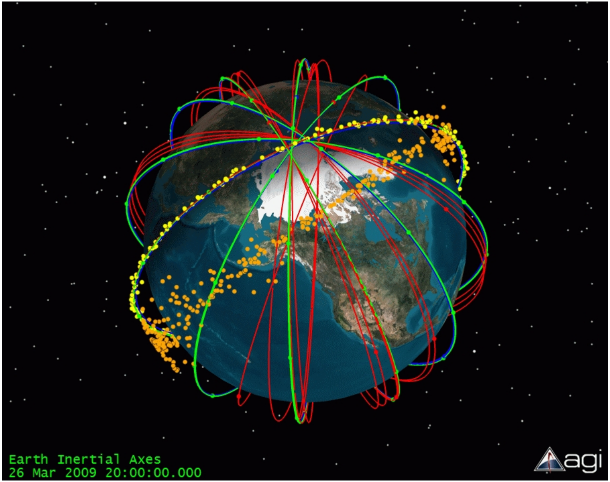

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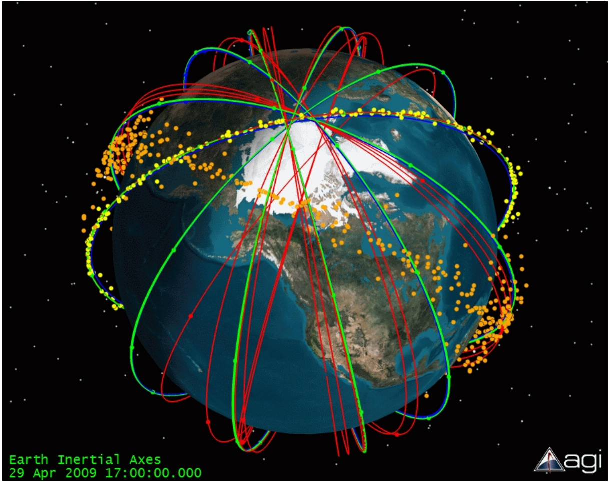

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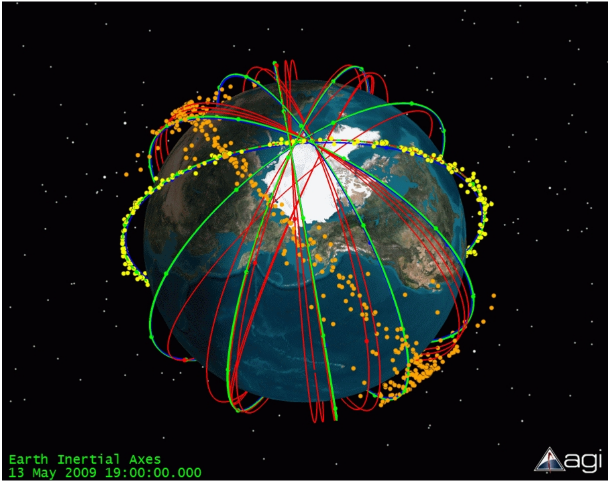

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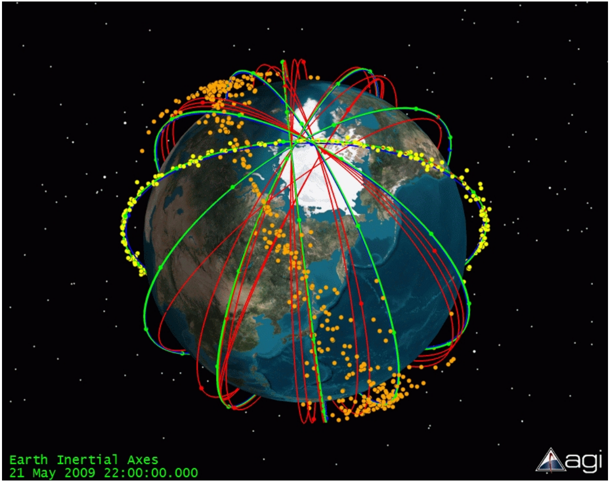

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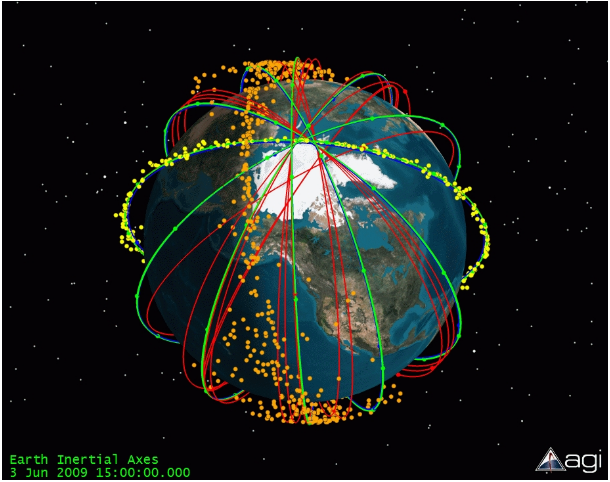

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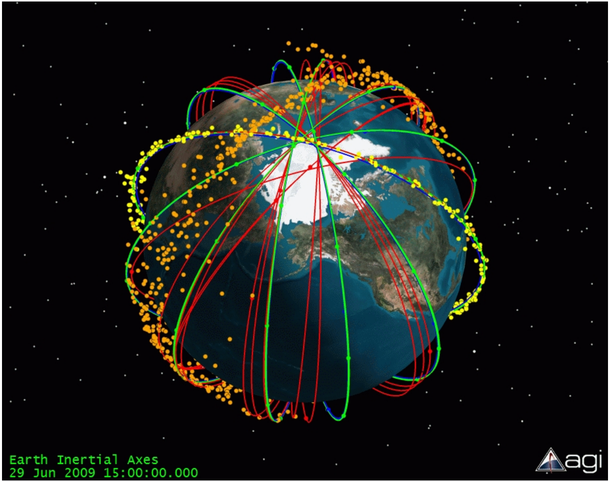

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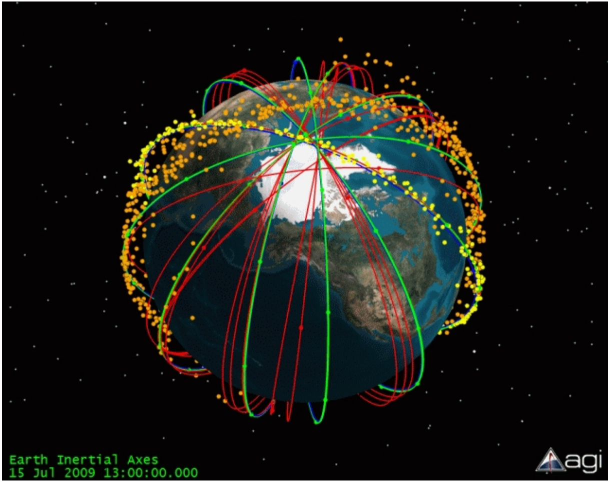
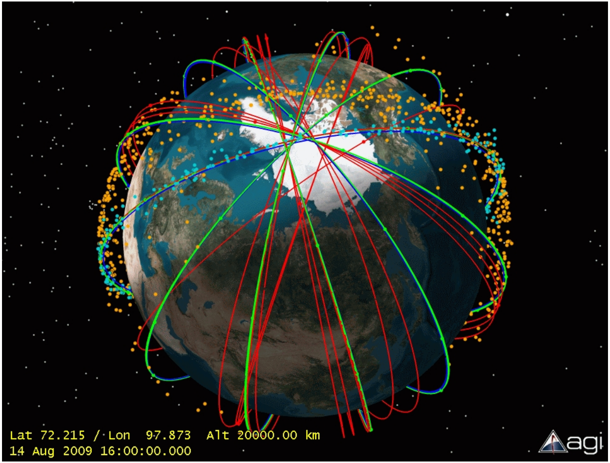
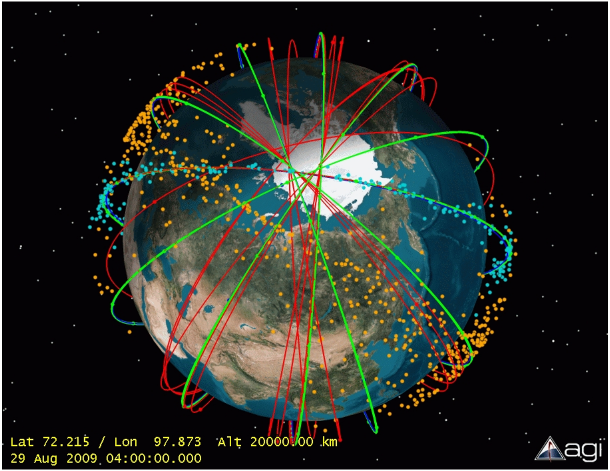


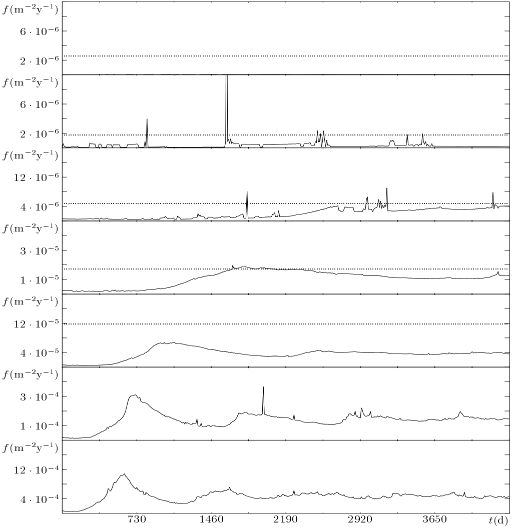
14-8-2009



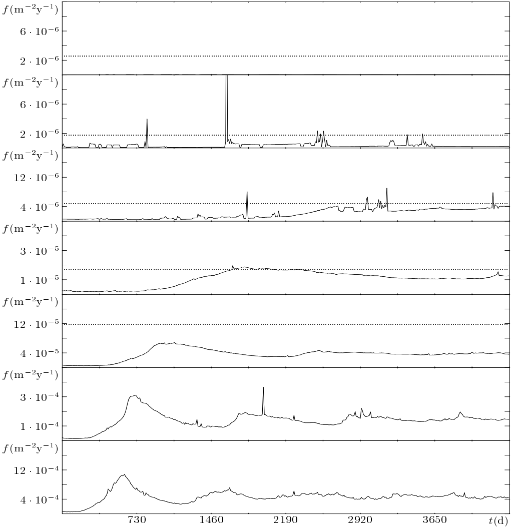
29-8-2009



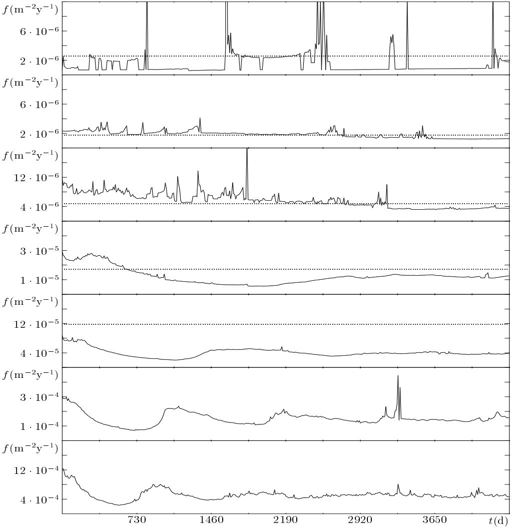
- $10^9 < 2E \implies$
- $10^9 < 2E < 10^8 \implies$
- $10^7 < 2E < 10^8 \implies$
  $\sim$ (fragm. threshold)
- $10^6 < 2E < 10^7 \implies$
- $10^5 < 2E < 10^6 \implies$
- $10^4 < 2E < 10^5 \implies$
- $10^3 < 2E < 10^4 \implies$

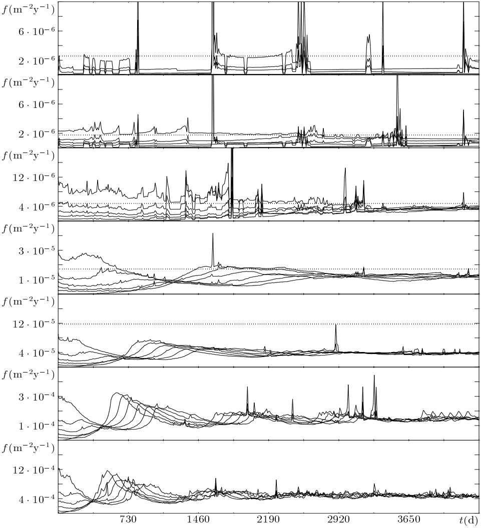


- Flux of fragments vs time.
- Target located in a neighboring plane, same sense of rotation of the parent body of the fragments.



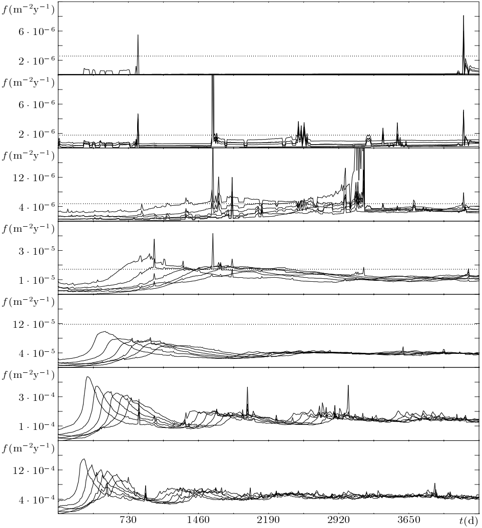
- Target located in a plane revolving in the opposite sense, w.r.t. the parent body of the fragments.





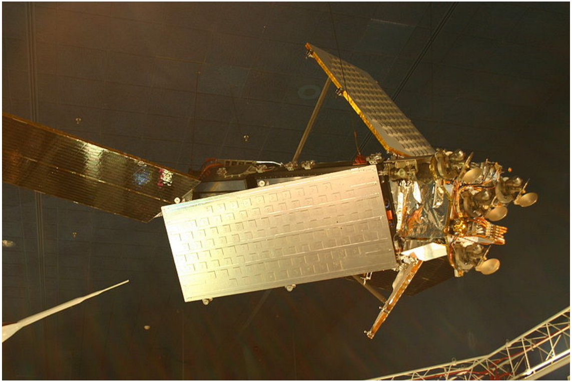
- Flux on all the constellation planes.
- Break-up simulated on plane 6

- Flux on all the constellation planes.
- Break-up simulated on plane 3
- "....a fragmentation occurring in planes nos. 3 and 4 is the least prone to damage the whole constellation."



IRIDIUM 33 vs COSMOS 2251

- On Feb. 10, 2009, 16:56 UTC the satellite Iridium 33 (located on the third constellation plane) collided against an old, non-operational Strela-2M, Russian communication satellite (COSMOS 2251) launched on 16/9/1993.
- The collision took place at an altitude of 789 km above the Taymyr Peninsula in Siberia.



IRIDIUM 33 vs COSMOS 2251

- From the TLE orbits COSMOS should have passed ~ 400 m far from Iridium.
- TLE are NOT good enough for collision avoidance.
-

IRIDIUM 33 vs COSMOS 2251

- From the TLE orbits COSMOS should have passed ~ 400 m far from Iridium.
- TLE are NOT good enough for collision avoidance.
- “*La collision avoidance con i Two Line Elements è una fregatura certa!*”

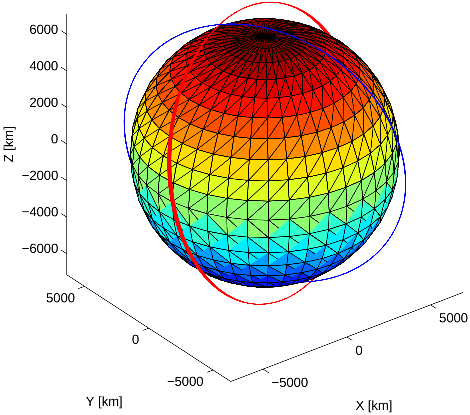
  Andrea Milani

IRIDIUM 33 vs COSMOS 2251

- From the TLE orbits COSMOS should have passed ~ 400 m far from Iridium.
- TLE are NOT good enough for collision avoidance.
- NO collision avoidance procedures were implemented for Iridium (too expensive...?)
- *“Iridium was receiving an average of 400 reports per week of objects coming within 5 km of one of their satellites. ”*

IRIDIUM 33 vs COSMOS 2251

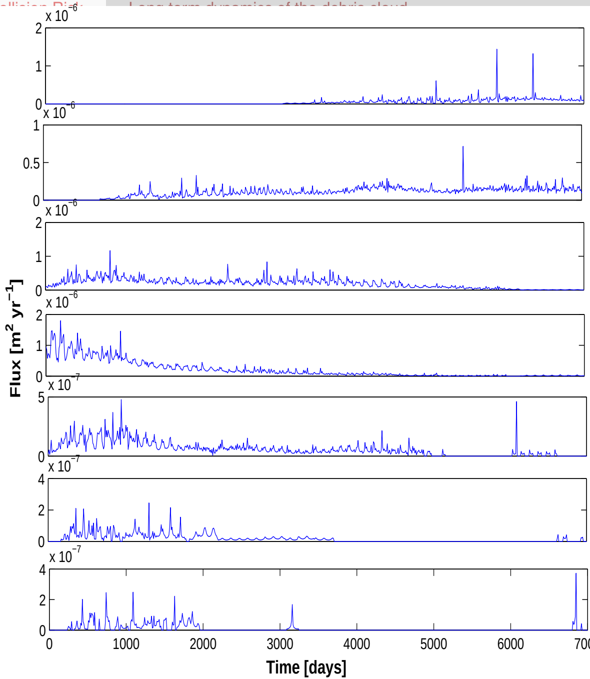
- Orbital elements pre-impact:
  - Iridium:
    $a = 7174.6984$
    $e = 0.0002288$
    $i = 86.399^\circ$
    $\Omega = 121.703$
  - Cosmos:
    $a = 7169.649$
    $e = 0.0016027$
    $i = 74.0355^\circ$
    $\Omega = 19.4646^\circ$
- $\Rightarrow \quad I \simeq= 100.73^\circ$
  Hyper-velocity impact
  $\Rightarrow \quad V_{imp} \simeq 11.48$ km/s
  $\Rightarrow \quad E \sim 10^{10}$ J



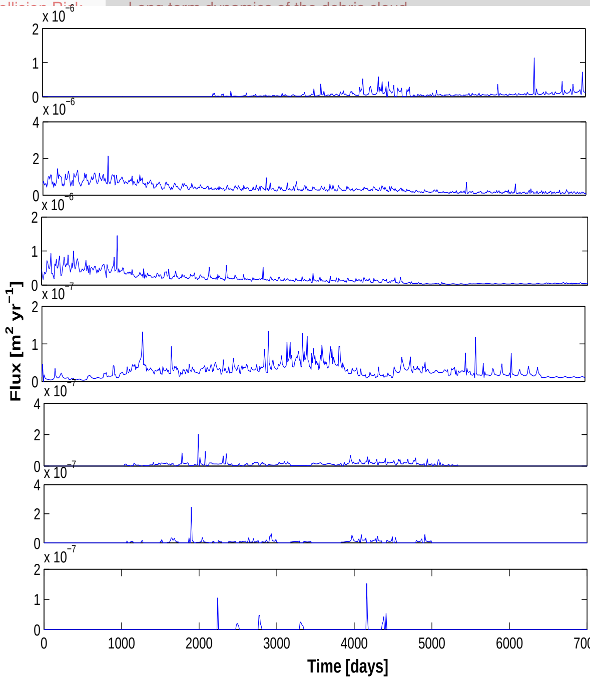
Long term simulation of the Feb. 2009 collision

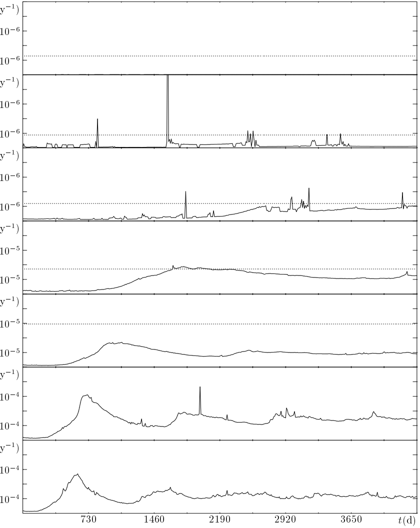
- The initial orbit of the real fragments was taken directly from the TLE and propagated for 20 years.
- 215 Iridium fragments - 454 Cosmos fragments
- The mass and area distribution of the fragments was taken from the NASA breakup model distributions.
- The masses were assigned to real fragments following the ΔV distribution taken from the Gabbard diagrams (i.e., larger masses assigned to lower ΔV fragments).

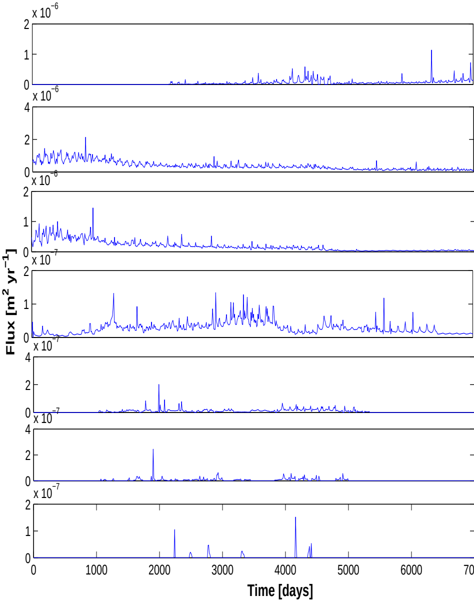
- The Feb. 2009 collision flux.
- IRIDIUM CLOUD
- Flux on plane 3.

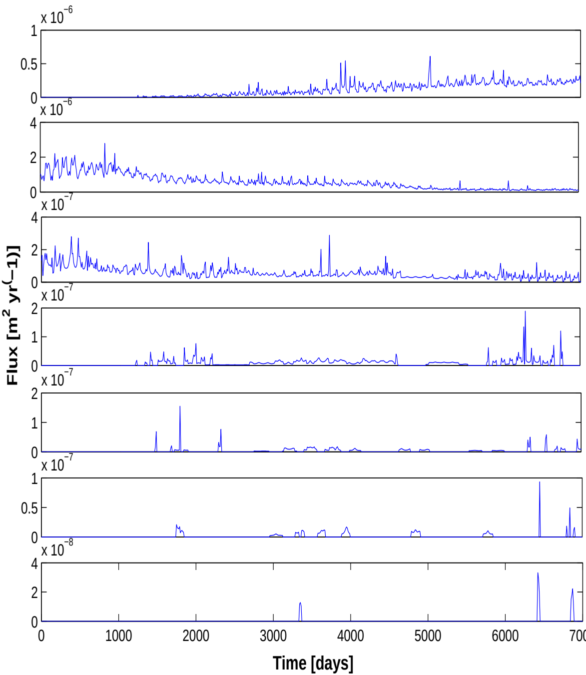


- The Feb. 2009 collision flux.
- IRIDIUM CLOUD
- Flux on plane 4.

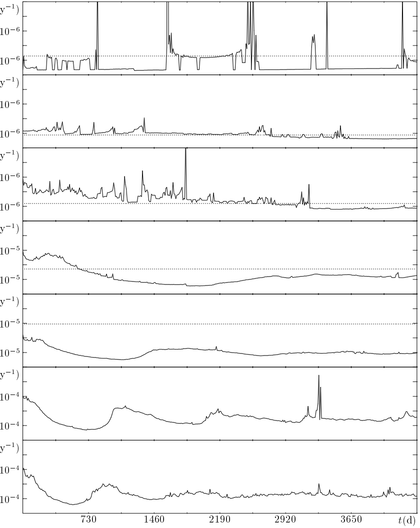



y⁻¹)
10⁻⁶
10⁻⁶
10⁻⁵
10⁻⁵
10⁻⁴
10⁻⁴
730
1460
2190
2920
3650
t(d)


x 10⁻⁶
x 10⁻⁷
0
1
2
4
Flux [m² yr⁻¹]
0
1000
2000
3000
4000
5000
6000
70
Time [days]



- The Feb. 2009 collision flux.
- IRIDIUM CLOUD
- Flux on plane 2.


y^{-1})
10^{-6}
10^{-6}
y^{-1})
10^{-6}
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y^{-1})
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y^{-1})
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10^{-4}
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y^{-1})
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10^{-4}
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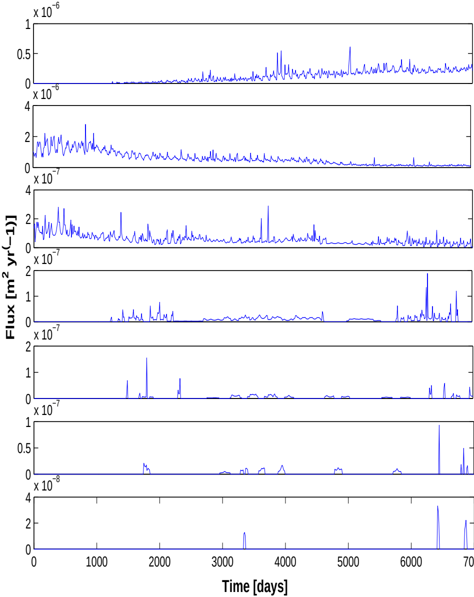
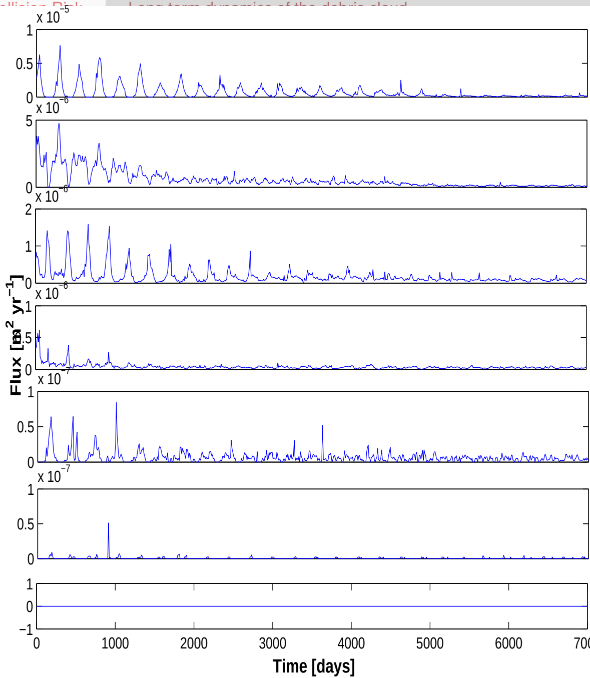
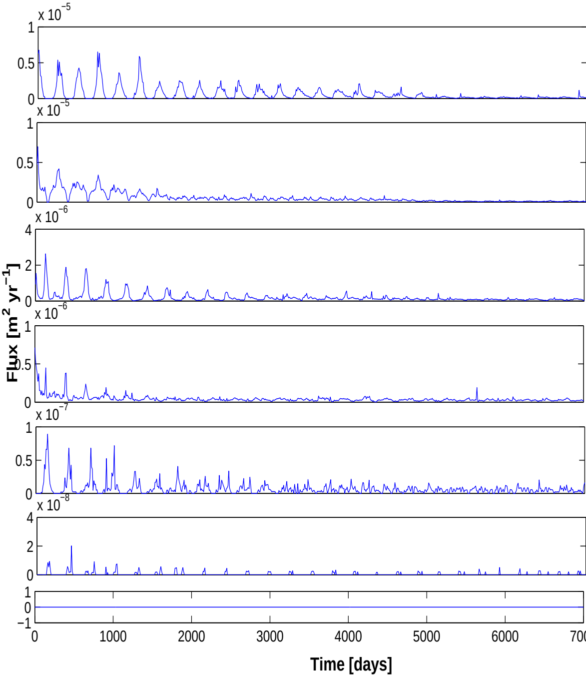
1460
2190
2920
3650
t(d)


x 10^{-6}
1
0.5
0
x 10^{-6}
4
2
0
x 10^{-7}
4
2
0
x 10^{-7}
2
1
0
x 10^{-7}
2
1
0
x 10^{-7}
1
0.5
0
x 10^{-8}
4
2
0
Flux [m^2 yr$^{(-1)}$]
0
1000
2000
3000
4000
5000
6000
70
Time [days]

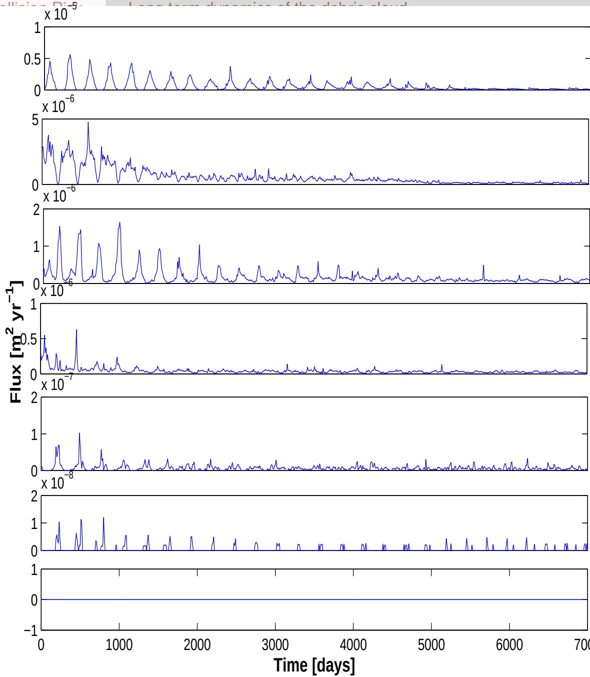
- The Feb. 2009 collision flux.
- COSMOS CLOUD
- Flux on plane 3.



- The Feb. 2009 collision flux.
- COSMOS CLOUD
- Flux on plane 4.



- The Feb. 2009 collision flux.
- COSMOS CLOUD
- Flux on plane 2.



Synodic motion of the debris clouds

- The spikes are spaced by about 260 days.
- The differential period of precession of the RAAN of the Iridium planes and of the Cosmos fragments, $\Delta\dot{\Omega} = \dot{\Omega}_{iridium} - \dot{\Omega}_{Cosmos} \simeq -1.41$ deg/day
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Collision avoidance within a debris cloud

- Time is ripe for an active collision avoidance on a large scale
- The collision avoidance within a debris cloud is a complex and computationally intensive task
- Understanding the overall dynamics of the system is mandatory
- Analytical screening methods will help in filtering the dangerous objects.

Complication - Frozen orbit

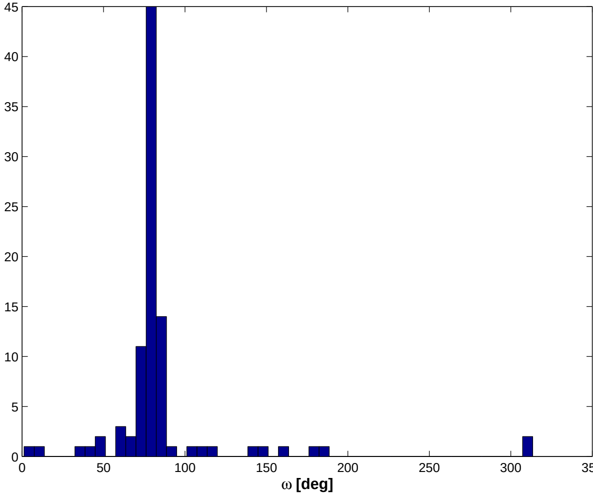
- The Iridium active satellites are placed near a frozen orbit of Type II $\Longrightarrow de/dt = 0$ and $d\omega/dt = 0$ for $\omega = 90^\circ$ and

$$e_{frozen} = (J_3/(2J_2)) * (r_e/a) * \sin i$$

- For the Iridium orbit $e_{frozen} \simeq 8.7976 \times 10^{-4}$.
- The average eccentricity of the Iridium satellites is $3.0841 \times 10^{-4} \pm 2.45 \times 10^{-4}$.

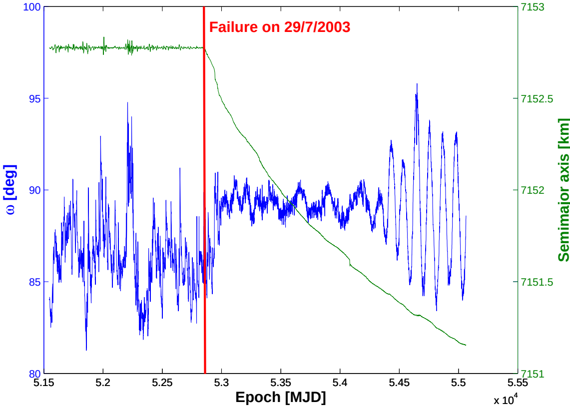
Complication - Frozen orbit

- *As a matter of fact the argument of perigee of the Iridium satellites* $\omega_{irid} \simeq 80^\circ$*, i.e., it is not kept at* 90° *as in the usual frozen orbits.*
- Active and stranded satellites



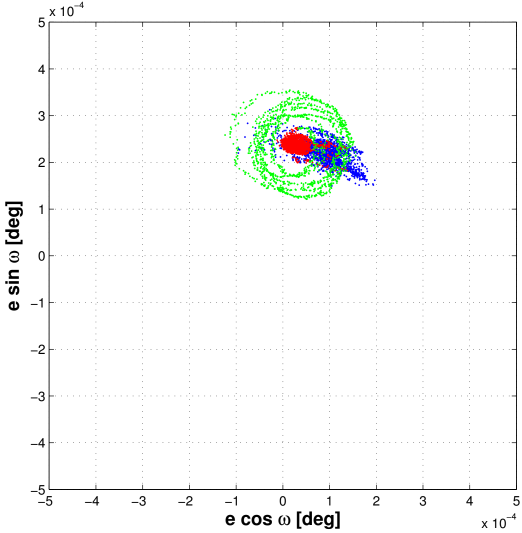
Complication - Frozen orbit

- The satellite Iridium 38 failed on July 2003.
- Leaves the controlled ω and falls into the frozen orbit.
- As the eccentricity grows leaves the frozen orbit.



Frozen orbit – Iridium 38

- Blue: operational orbit
- Red: non-operational frozen orbit after failure
- Green: leaves frozen orbit.



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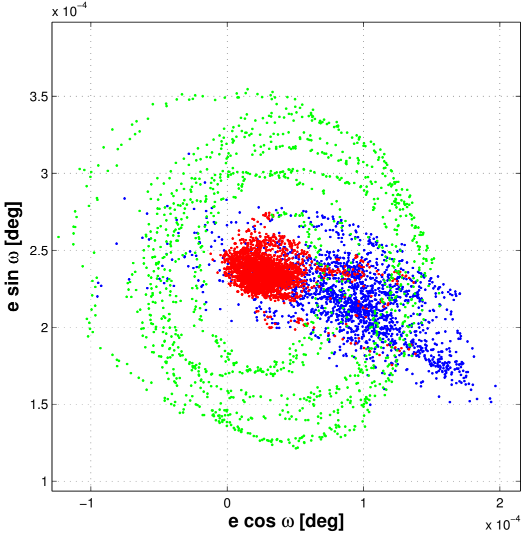
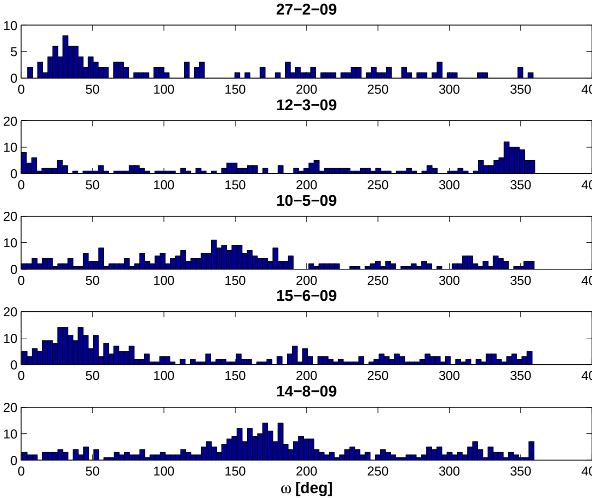


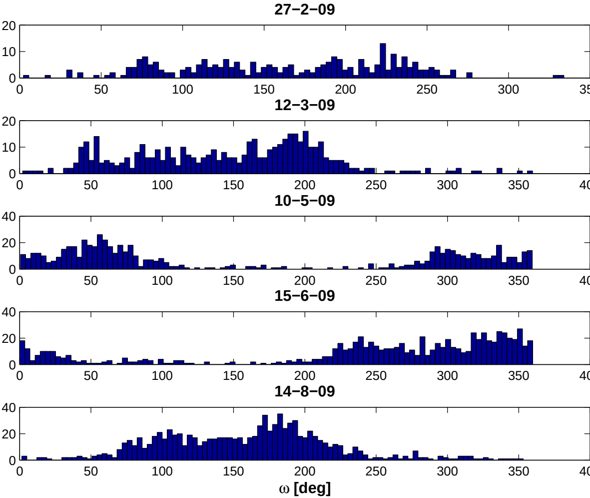
Iridium cloud ω evolution

- The Iridium fragment cloud is not locked in the frozen regime
- Nonetheless it remains compact in terms of ω since it is very close to the frozen regime



Cosmos cloud ω evolution

- The Cosmos fragment cloud is not locked in the frozen regime
- Nonetheless it remains compact in terms of ω since it is very close to the Type I frozen regime (critical inc. @ $63°$)



Collision avoidance within a debris cloud

- The Minimum Orbital Intersection Distance (MOID: minimum distance between the osculating orbits of two objects) is the parameter commonly used in NEOs studies to evaluate the PHA status of an object.
- It is possible to evaluate the MOID also in the case of debris clouds.
- The nodal distance (d_n) gives the difference between the geocentric distance of the projectile, when it crosses the target orbital plane, and geocentric distance of the target at that longitude.
- Provided that the inclination of the projectile orbit w.r.t. the target one is different from zero, a collision takes place only if $d_n = 0$.

Collision avoidance within a debris cloud

- How to compute d_n?
- Given two sets of orbital elements, one relative to the target $(a_*, e_*, i_*, \omega_*, \Omega_*, f_*)$, and the other relative to the projectile $(a, e, i, \omega, \Omega, f)$.
- We need to compute $\cos i_r$ and $\cos \omega_r$ of the projectile in a reference frame in which the orbit of the target has equatorial inclination equal to zero and where the x-axis coincides with longitude of the ascending node of the target (w.r.t. the equator).

How to compute the relative elements?

The computation exploits the orbital angular momentum:

$$h = \sqrt{Gm_{\oplus}a(1-e^2)}\,.$$

and eccentricity vectors:

$$\vec{\varepsilon} = GM\vec{e}$$

leading to expression for the relative elements of the form:

$$\begin{aligned}
\cos i_r &= \cos i \cos i_* + \sin i \sin i_* \cos \Delta\Omega \\
\cos \omega_r &= \frac{\sin i \cos i_* \cos \omega + \sin i_* (\sin \omega \sin \Delta\Omega - \cos i \cos \omega \cos \Delta\Omega)}{\sqrt{1-(\cos i \cos i_* - \sin i \sin i_* \cos \Delta\Omega)^2}} \\
\sin \omega_r &= \frac{\sin i \cos i_* \sin \omega - \sin i_* (\cos \omega \sin \Delta\Omega + \cos i \sin \omega \cos \Delta\Omega)}{\sqrt{1-(\cos i \cos i_* - \sin i \sin i_* \cos \Delta\Omega)^2}} \\
\cos \Omega_r &= -\frac{\cos i \sin i_* - \sin i \cos i_* \cos \Delta\Omega}{\sqrt{1-(\cos i \cos i_* - \sin i \sin i_* \cos \Delta\Omega)^2}} \\
\sin \Omega_r &= \frac{\sin i \sin \Delta\Omega}{\sqrt{1-(\cos i \cos i_* - \sin i \sin i_* \cos \Delta\Omega)^2}}\,.
\end{aligned}$$

Nodal distance

- Geocentric distances of the nodal points:

$$
\begin{aligned}
r_a &= \frac{a(1-e^2)}{1+e\cos(-\omega_r)} = \frac{a(1-e^2)}{1+e\cos\omega_r} \\
r_d &= \frac{a(1-e^2)}{1+e\cos(180^\circ-\omega_r)} = \frac{a(1-e^2)}{1-e\cos\omega_r}\,.
\end{aligned}
$$

- Geocentric distances of target at ascending and descending node of projectile orbit relative to the orbital plane of the target:

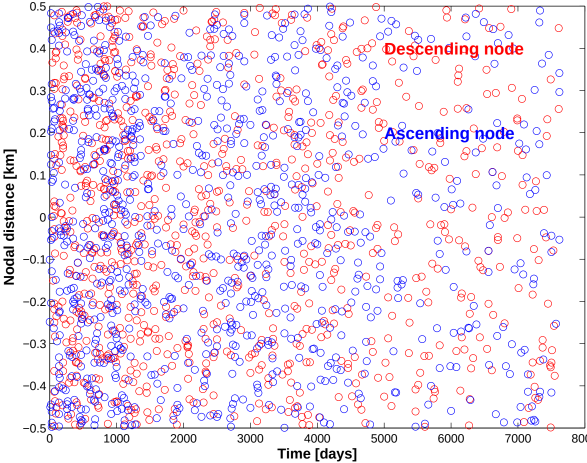
$$
\begin{aligned}
d_a &= \frac{a_\star(1-e_\star^2)}{1+e_\star\cos(\omega_\star-\Omega_r)} \\
d_d &= \frac{a_\star(1-e_\star^2)}{1+e_\star\cos(\omega_\star+\Omega_r)}\,.
\end{aligned}
$$

Nodal distance

- The nodal distance (d_n) gives the difference between the geocentric distance of the projectile, when it crosses the target orbital plane, and geocentric distance of the target at that longitude:
    - Ascending node: $d_n = r_a - d_a$
    - Descending node: $d_n = r_d - d_d$

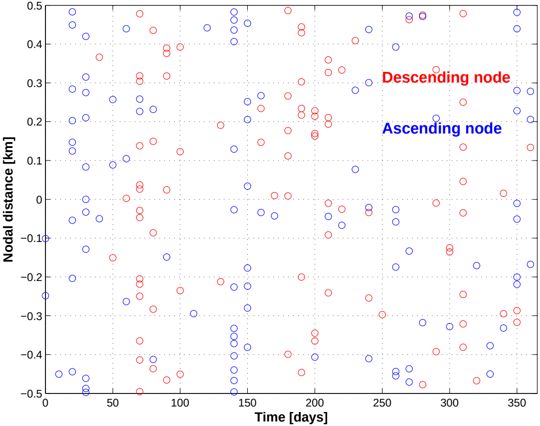
Nodal distance

- Iridium satellite against Iridium cloud
- Density decreasing with time as cloud spreads.
- Still a high density of close nodal passages after 10 years!



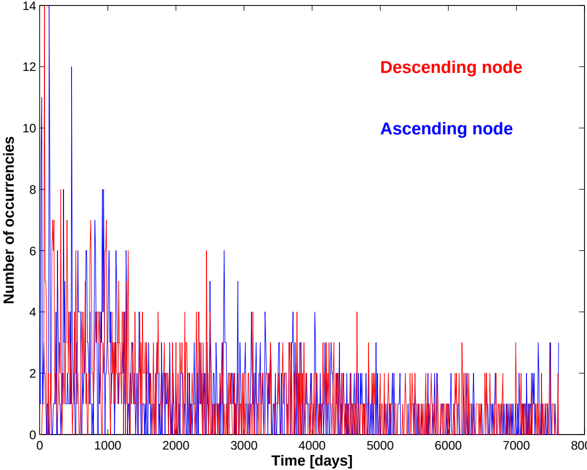
Nodal distance

- Iridium satellite against Iridium cloud
- Batches of ascending and descending node close approaches separated by about 100 days.



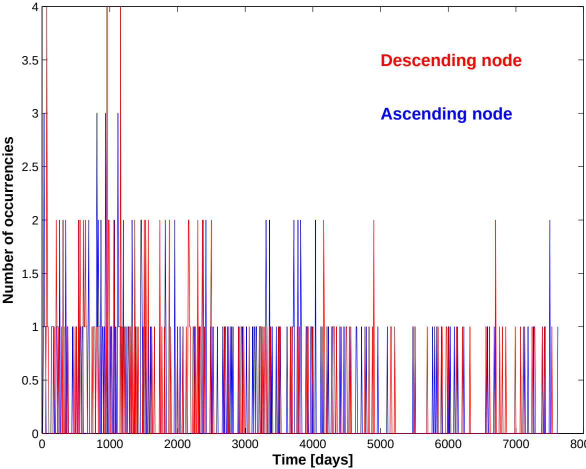
Nodal distance < 500 m as a function of time

- Iridium satellite against Iridium cloud
- Number of nodal distances lower than 500 m as a function of time



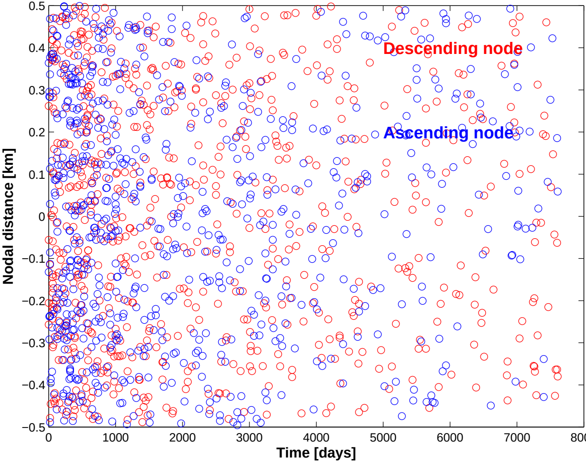
Nodal distance < 100 m as a function of time

- Iridium satellite against Iridium cloud
- Number of nodal distances lower than 100 m as a function of time



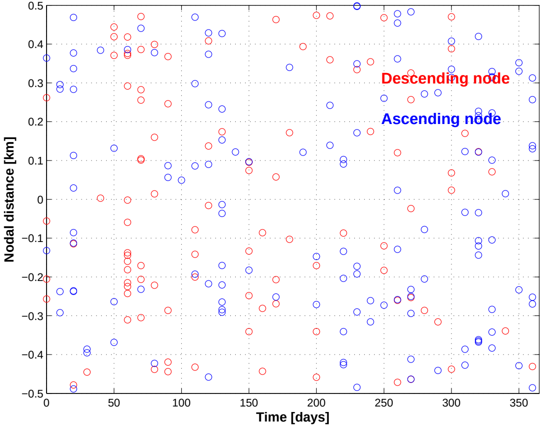
Nodal distance

- Iridium satellite against Cosmos cloud
- Density decreasing with time as cloud spreads.
- Lower number of close approaches.



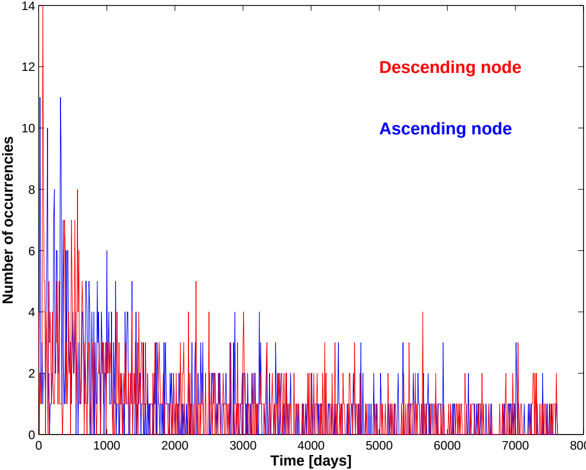
Nodal distance

- Iridium satellite against Cosmos cloud
- No grouping of nodal close approaches.



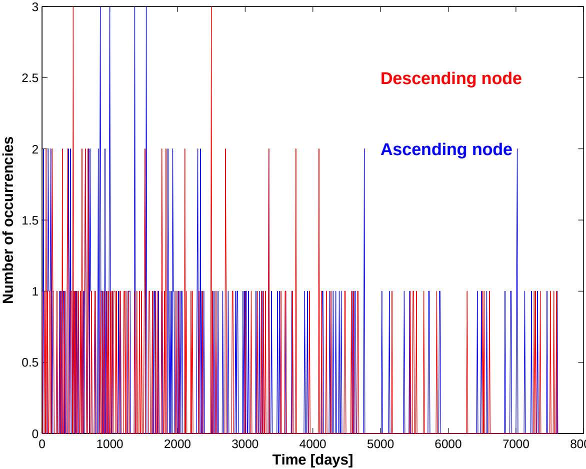
Nodal distance < 500 m as a function of time

- Iridium satellite against Cosmos cloud
- Number of nodal distances lower than 500 m as a function of time



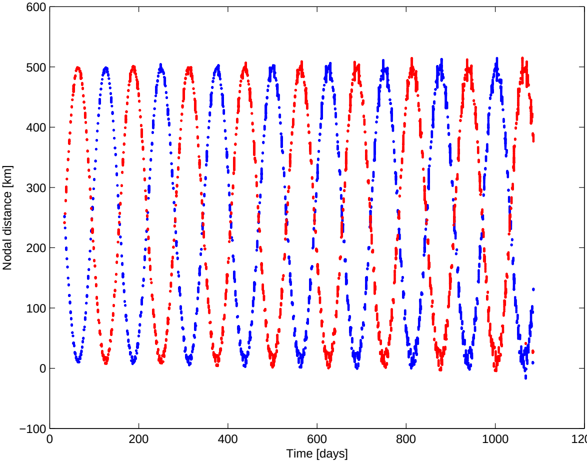
Nodal distance < 100 m as a function of time

- Iridium satellite against Cosmos cloud
- Number of nodal distances lower than 100 m as a function of time



Filtering the dangerous objects

- Nodal distance [in km] as a function of time, between selected fragments and an Iridium satellite plotted whenever the difference in true longitude is lower than 1 deg.
- The evolution of the nodal distance (MOID) can be used a filter for fragments that will have minimal or no interaction with the constellation in the future.



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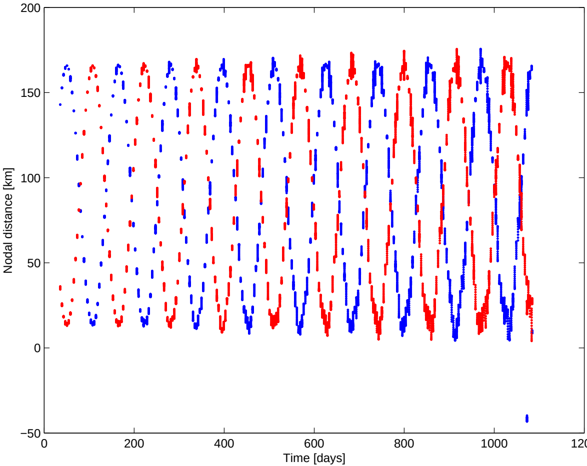

Debris vs NEOs collision monitoring

- You can move a target spacecraft...less easy is to move the Earth...
- In the debris case the collision is always the end point of a keplerian propagation (perturbed by geopotential and non-grav.), while in the NEO case the largest complexity is given by the chaoticity induced by planetary encounters (resonant returns).
- With NEOs there is one valuable target, while for debris there are many targets of interest that are active, but also a large number of non-valuable (and non active) targets that still are extremely dangerous in terms of the consequences they can engender.
- The time scales might be similar in terms of orbital revolutions but still are very different in terms of absolute times (i.e., days vs years).

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The Palermo scale for NEO impact hazard

- The Palermo Technical Impact Hazard Scale was developed to enable NEO specialists to categorize and prioritize potential impact risks spanning a wide range of impact dates, energies and probabilities [Chesley, Chodas, Milani, Valsecchi and Yeomans, “Quantifying the Risk Posed by Potential Earth Impacts”, *Icarus*, 159, 2002].
- The scale compares the likelihood of the detected potential impact with the average risk posed by objects of the same size or larger over the years until the date of the potential impact. This average risk from random impacts is known as the background risk.
- The scale is logarithmic. A Palermo Scale value of -2 means that the potential impact event is only 1% as likely as a random background event occurring in the intervening years, a value of zero indicates that the single event is just as threatening as the background hazard.

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A space debris Palermo-like scale for impact hazard

- Building on the NEO experience an index similar to the Palermo scale should be adopted to quantify the risk posed to the environment by a given spacecraft.
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- An *ad-hoc* combination of these different factors is being tested to device the most convenient formulation of the index.
- An Öpik-like approach to analytically screen the collision probabilities is used (other approaches are being also considered, e.g. CUBE).
- Such an index should accompany the TLE (or SSA TLE-like) orbital elements for each catalogued object.
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Conclusions and future work

- The Iridium - Cosmos collision is the first accidental collision between *large satellites* in orbit.
- The peculiar configuration of the Iridium constellation makes this collision particularly dangerous for the constellation itself.
- The altitude regime of the collision is already in a *critical* situation, i.e. a *collisional cascade* is possible between 800 and 1000 km.
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