Dynamical study of the near-Earth space enviroment for passive debris removal

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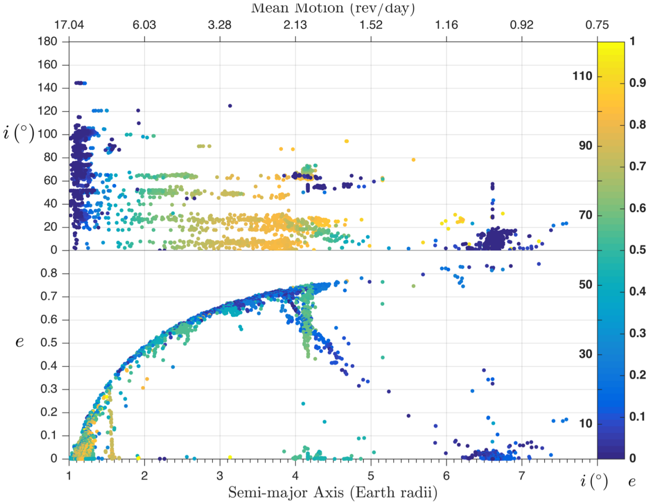
The Cataloged Space debris



NORAD RESIDENT SPACE OBJECT CATALOG (www.space-track.org | ASSESSED 26 OCT 2016)

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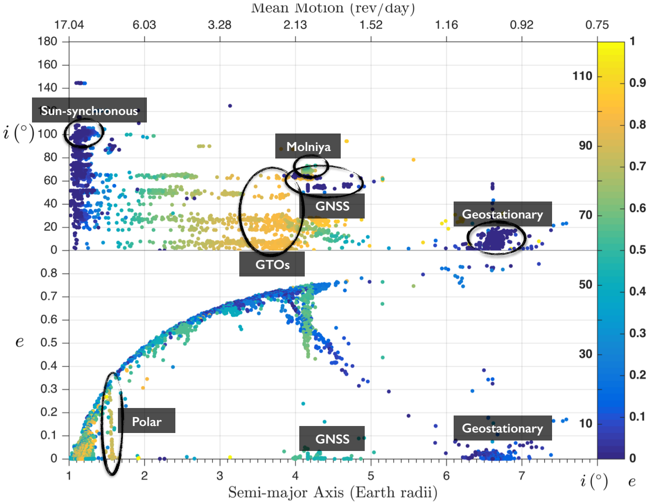

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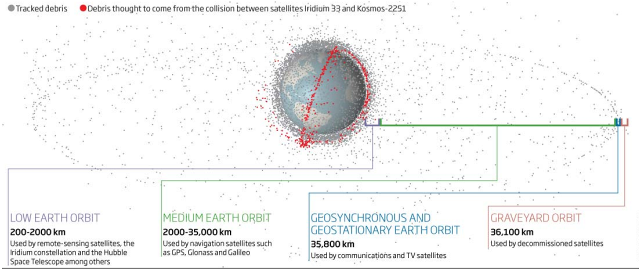
The problem of Space Debris

- Proliferation of debris has motivated deeper analysis of the dynamical environments occupied by satellites
- Studies on the long-term dynamics about Earth are relevant now
- A new paradigm in post-mission disposal: exploit resonant orbits to obtain relatively stable graveyards or highly unstable disposal orbits
- ReDSHIFT: identify dynamically interesting regions that harbor natural disposal trajectories on realistic timescales ($< 120 years$)
  - * provide dynamical survey of the whole, usable circumterrestrial space
  - * can increasing the satellite's area-to-mass ratio promote the deorbiting process?



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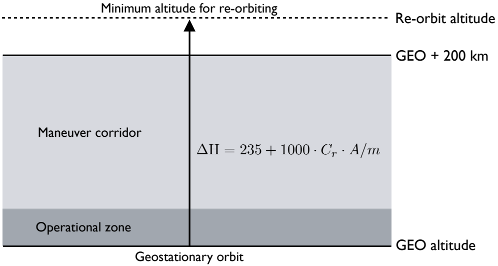

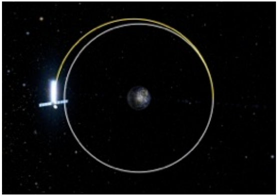

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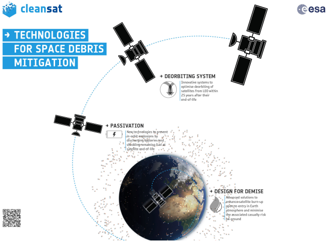
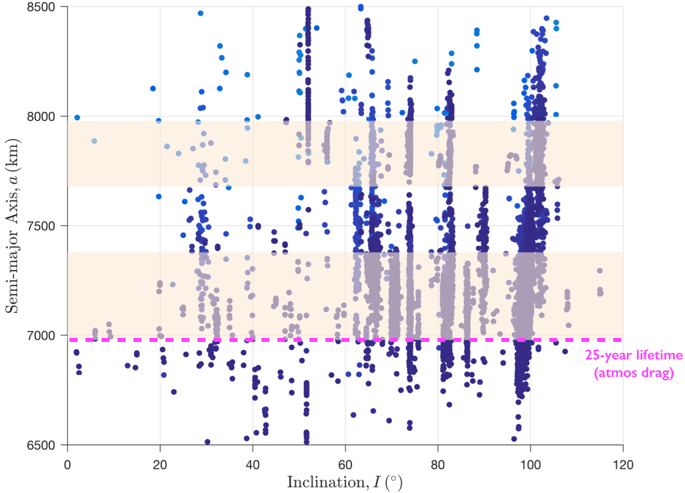


The problem of Space Debris - LEO diposal strategy



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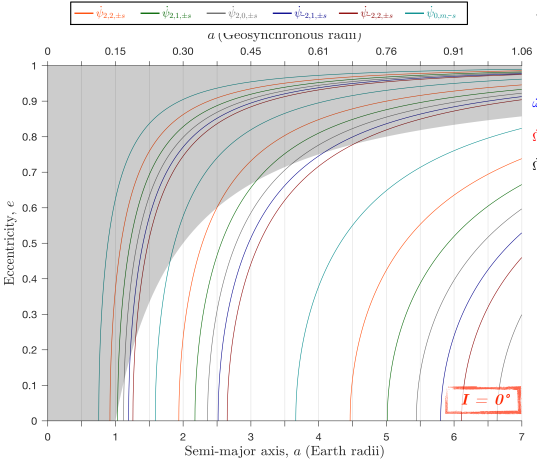
Resonances in near-Earth region



COOK, GJRAS (1962); HUGHES, PRSL (1981); BREITER, CEMDA (2001)
GKOLIAS, DAQUIN, GACHET & ROSENGREN, AJ (2016)

- The oblateness ***apsidal*** and ***nodal*** precession overshadows the lunisolar effects

$$\dot{\omega} \approx 4.98 (R/a)^{\frac{7}{2}} \frac{5\cos^2 I - 1)}{(1-e^2)^2} \,°/\mathrm{d}$$

$$\dot{\Omega} \approx -9.97 (R/a)^{\frac{7}{2}} \frac{\cos I}{(1-e^2)^2} \,°/\mathrm{d}$$

$$\dot{\Omega}_{\mathrm{M}} \approx -0.053°/\mathrm{d}, n_{\mathrm{S}} = 0.986°/\mathrm{d}, n_{\mathrm{M}} = 13.246°/\mathrm{d}$$

$$\alpha\dot{\omega} + \beta\dot{\Omega} + \gamma\dot{\Omega}_{\mathrm{Moon}} \approx 0$$
(lunar secular res)

$$\alpha\dot{\omega} + \beta\dot{\Omega} + \gamma n_{\mathrm{Sun}} \approx 0$$
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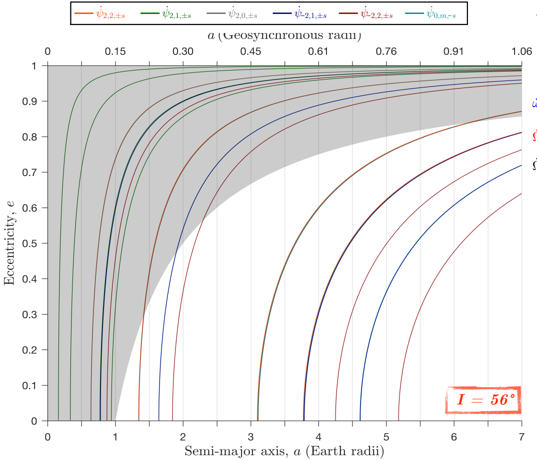

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Dynamical Model - Initial conditions

- Dynamical model:

* central body ⇒ Earth with gravity field up to degree and order 2 (i.e. $J_{2,0}$, $J_{2,2}$)

* perturbing bodies ⇒ Moon & Sun

* Solar Radiation Pressure (SRP):

  - mean (satellites): $1.5 \cdot 10^6\ km^3/s^2$ (SRP 1)
  - enhached: $1 \cdot 10^8\ km^3/s^2$ (SRP 2)

LEO area → IFAC group, Italy

GEO area→ POLIMI group, Italy

- Initial two epochs:
  22.74/12/2018
  21.28/06/2020
- $t_{max} = 120\ yr$
- $r > R_{Earth} + 400km$

	ALL*	GTO†	MEO
$a\ (a_{GEO})$	0.150 – 1.050	0.498 – 0.664	0.600 – 0.710
Δa	0.0050	0.00475	0.0025
e	0 – 0.9	0.5 – 0.8	0 – 0.88
Δe	0.015	0.015	0.02
$i\ (^\circ)$	0 – 120	0.235 – 10.235 23.533 – 33.533 41 – 51	0 – 90
Δi	2	1	2
$\Delta\Omega\ (^\circ)^\dagger$	{0, 90, 180, 270}		
$\Delta\omega\ (^\circ)^\dagger$	{0, 90, 180, 270}		
$C_R(A/m)$ (m²/kg)	{0.015, 1}		

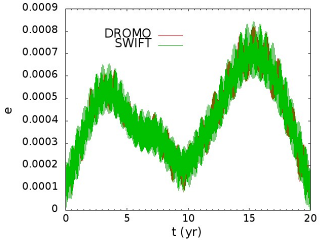
∼ 18M of simulations

Symplectic integrator - Validation

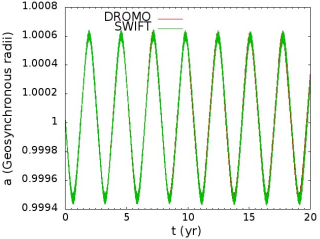
SWIFT-SAT:

* based on Mixed Variable Symplectic Integrator (Wisdom and Holman, 1991)
* suitable for bodies of negligible mass
* full non-averaged equations of motion
* validation with DROMO: a regularized method for evaluation of orbital elements (Davide Amato, UPM group)

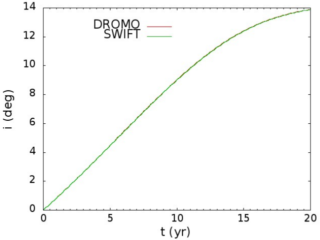
$t - e$



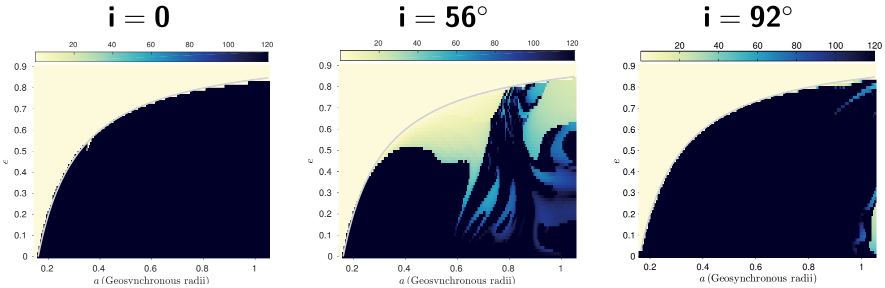
$t - a$



$t - i$



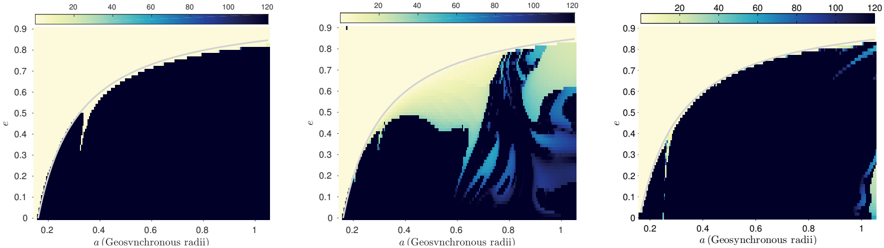
Circumterrestrial phase space (**SRP1**)



- **LEO**: Possible disposal routes at high-altitude LEO, related to solar gravity and radiation pressure resonances. Escape times comply with the IADC 25-year rule
- **MEO**: For the GNSS region, intricate escape hatches are carved by lunisolar secular resonances and widened by SRP.
- **GEO**: Natural deficiency of reentry solutions, except for high-I (BeiDou).

Circumterrestrial phase space (**SRP2**)

$\mathbf{i = 0}$ $\mathbf{i = 56^{\circ}}$ $\mathbf{i = 92^{\circ}}$



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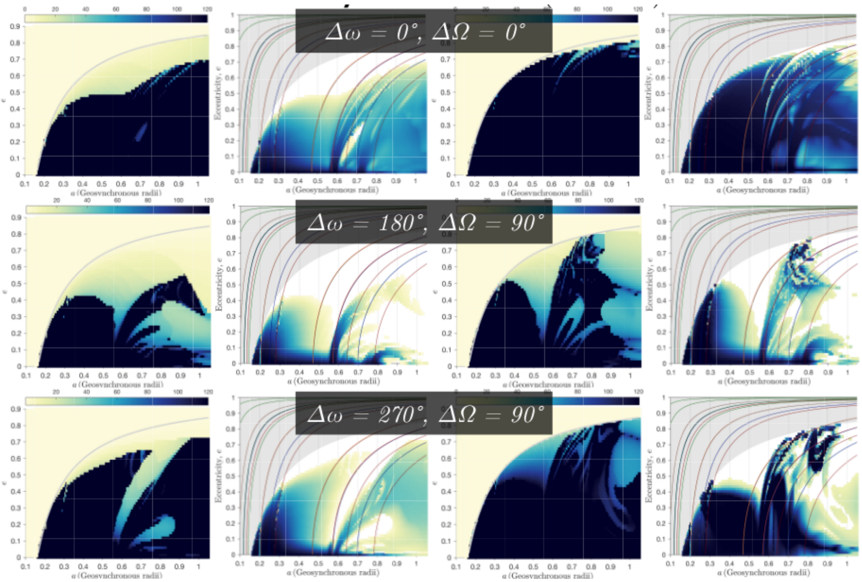
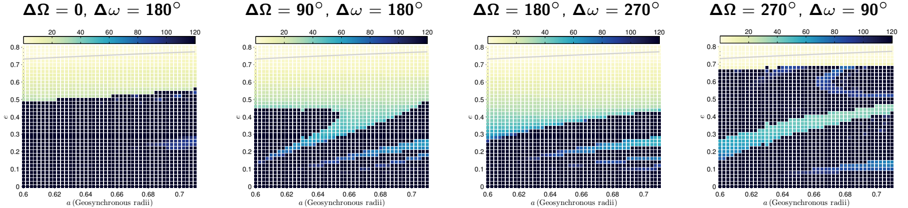
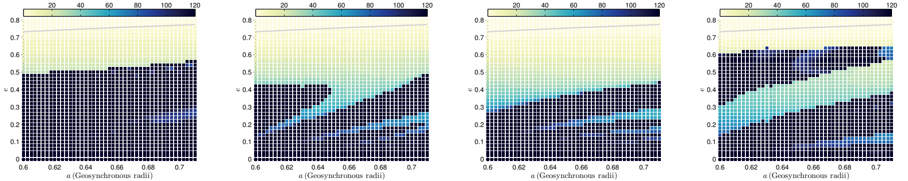
Circumterrestrial phase space



GNSS phase space - **i = 56**$^\circ$



SRP1

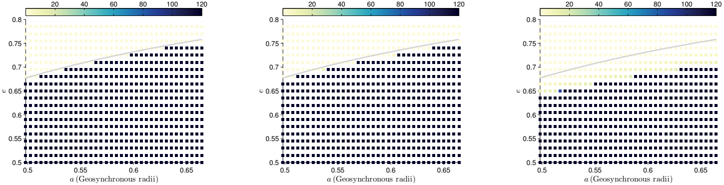


SRP2

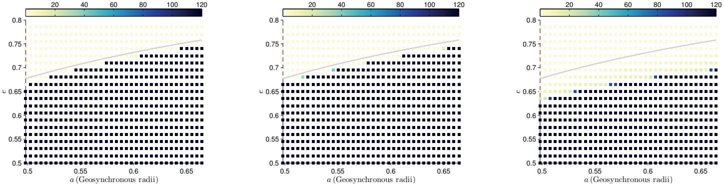
- Re-entry solutions feasible, but not for $t < 25$ *yrs*
- Results depend on secular orientation angles and epoch
- Enhanced A/m can widen the re-entry regions

GTO phase space

i = **5.235**° (Kourou) **i** = **28.533**° (Cape Carneval) **i** = **46**° (Baikonur)



SRP1



SRP2

- SRP is not very important, but helps
- Re-entry is easier at high inclinations

Conclusions

- We have successfully completed a massive campaign of simulations, encompassing the whole circumterrestrial region ($\sim$ 18M orbits)
- We have constructed the most complete to date dynamical atlas, both for the nominal and the 'enchached' A/m satellite cases
- GNSS:
    - Re-entry times of $40 - 60$ *yr* feasible
    - Design of maneuvers to reach the optimal diposal orbit for each initial operational orbit
- GTO:
    - Enhanced SPR is not enough for natural re-entry
    - Atmospheric drag may help - need to check

Thank you for your attention!