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INVESTIGATION AND MODELING OF SPACE WEATHER EFFECT ON SPACE-BASED OBJECTS FOR ORBITAL SUSTAINABILITY IN LOW EARTH ORBIT

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DLR

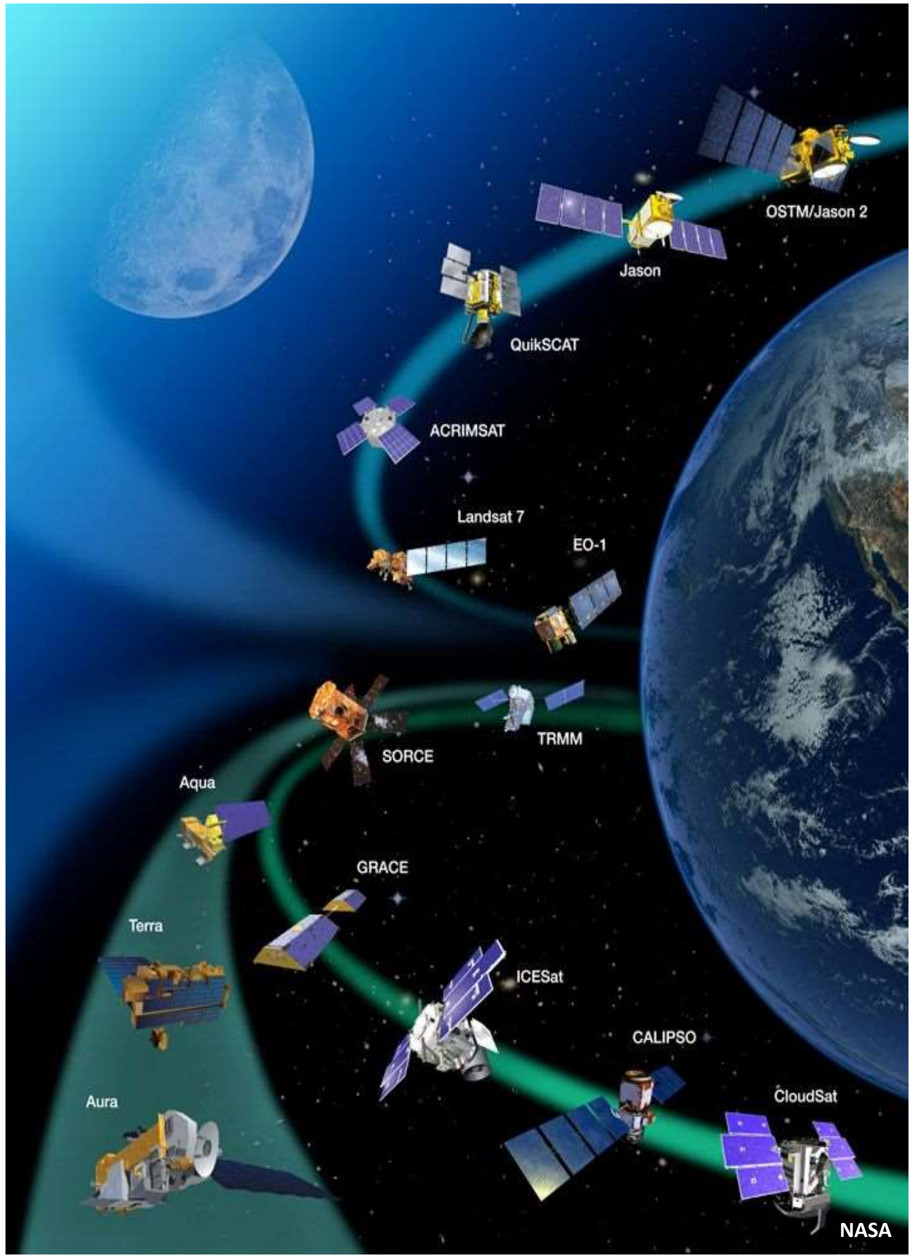
Introduction

- ❑ Atmospheric drag is the strongest force affecting the motion of satellites in low Earth orbit (LEO), especially at altitude $h \leq 800$ km
- ❑ Atmospheric drag detriments include:
- Retardation of space objects' motion and orbit shape alterations.
- Premature re-entry
- Increases the risk of spacecraft collisions due to the increased margins of error in spacecraft positioning - e.g.. 2009 Iridium - Cosmos collision
- Uncertainties in the re-entry location of deorbiting spacecrafts - e.g.. NASA's UARS and DLR's ROSAT re-entries in October 2011.
- Difficulty in manuvering, Identifying, tracking - e.g., temporal loss of 2500 space objects being monitored by tracking systems during the great geomagnetic storm of 13-14 March 1989.
- ❑ Space weather exacerbate the problem of atmospheric drag and consequently influence orbital debris population - e.g., storm-induced failure of 39 SpaceX Starlink satellites on 03.02.2022 (Dang et al., 2022)

Space weather contribution to debris population is both a matter of interest and concern globally – necessitating global space sustainability initiatives!!!

Some key factors for long-term sustainable use of the space include:

- Ability to monitor and understand the constantly changing space environment (achievable through improved SSA).
- Mitigation of debris production.
- Developing capabilities to remove existing debris [Jakhu, 2009; SWF, 2018].

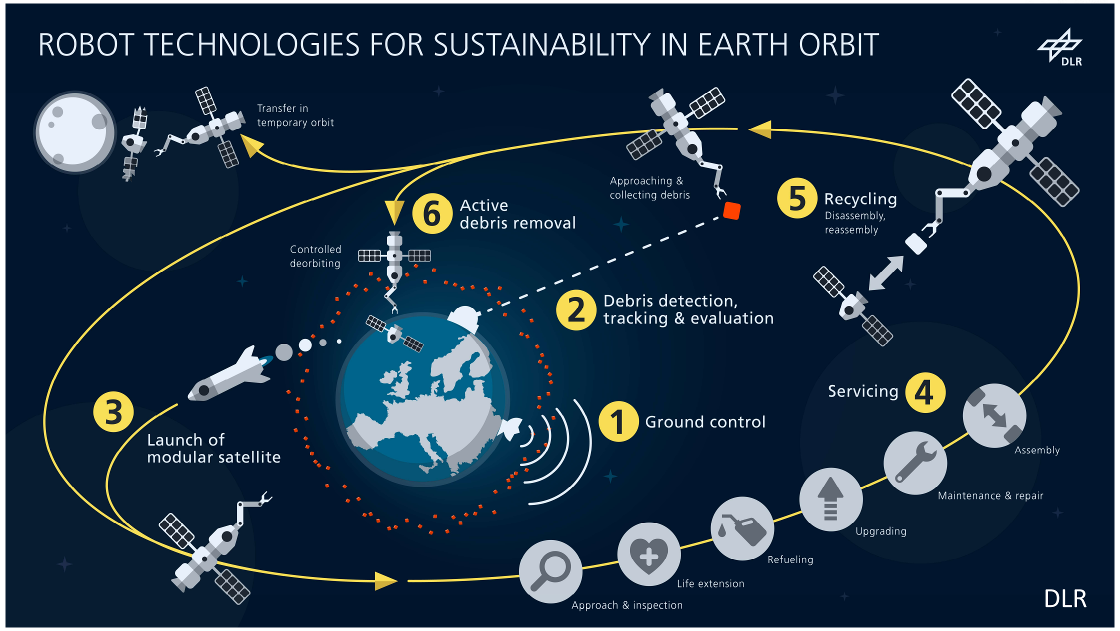


Technology-driven concepts for space sustainability

- Various concepts for space sustainability are being actively conceived, proposed and implemented in the areas of Space Situational Awareness (SSA), On-Orbit Servicing (OOS), Active Debris Removal (ADR) and On-Orbit Assembly (OOA) nationally and internationally.
- Some of the efforts (past and present) include:
  - The Laser Ranging Systems Evolution Study - LARAMOTIONS (Dreyer et al., 2021)
  - e.Deorbit (Biesbroek et al., 2017)
  - Deutsche Orbitale Servicing Mission - DEOS (Reintsema et al., 2010)
  - Mission Robot Vehicle MEV-1 and MEV-2 (Pyrak & Anderson 2022)
  - ELSA-d mission (Fujii et al., 2021)
  - Clearspace-1 (Biesbroek et al., 2021)
  - On-Orbit Servicing, Assembly and Manufacturing 1, OSAM-1 (Coll et al., 2020).
- The German Aerospace Center (DLR) is effectively addressing the concepts and technologies for increasing sustainability in Earth orbit within the framework of ION (Impulsprojekt Orbitale Nachhaltigkeit) Project.
- This work falls within the scope of a work package that provides SSA through technologies for the modeling of atmospheric drag force on LEO objects for the purpose of debris removal mission planning.

Specific objectives

1. Model/investigate the evolution of orbital decay of catalogued LEO objects as a function of observed solar indices (F10.7 and Ap) during this period of increasing solar activity.
2. Provide SSA for target space debris for mission planning purposes.



Theoretical considerations for Atmospheric drag model

- Our model was formulated from the equations of motion for a satellite moving under the attraction of a point mass planet with perturbations effect (Chobotov, 2002) as a function of solar activity indices.
- We applied the ephemeris data-assisted calibration (EDAC) aided modeling or simulation of long-term drag effect or decay rate of the semimajor axis – beyond the scope of this paper.

$$\frac{da}{dt} = -\frac{a^2 \rho A C_d}{m_s} \sqrt{\frac{GM_e}{a^3}} \, [\boldsymbol{r}_{mod}]$$

Representation in words [using terms]:

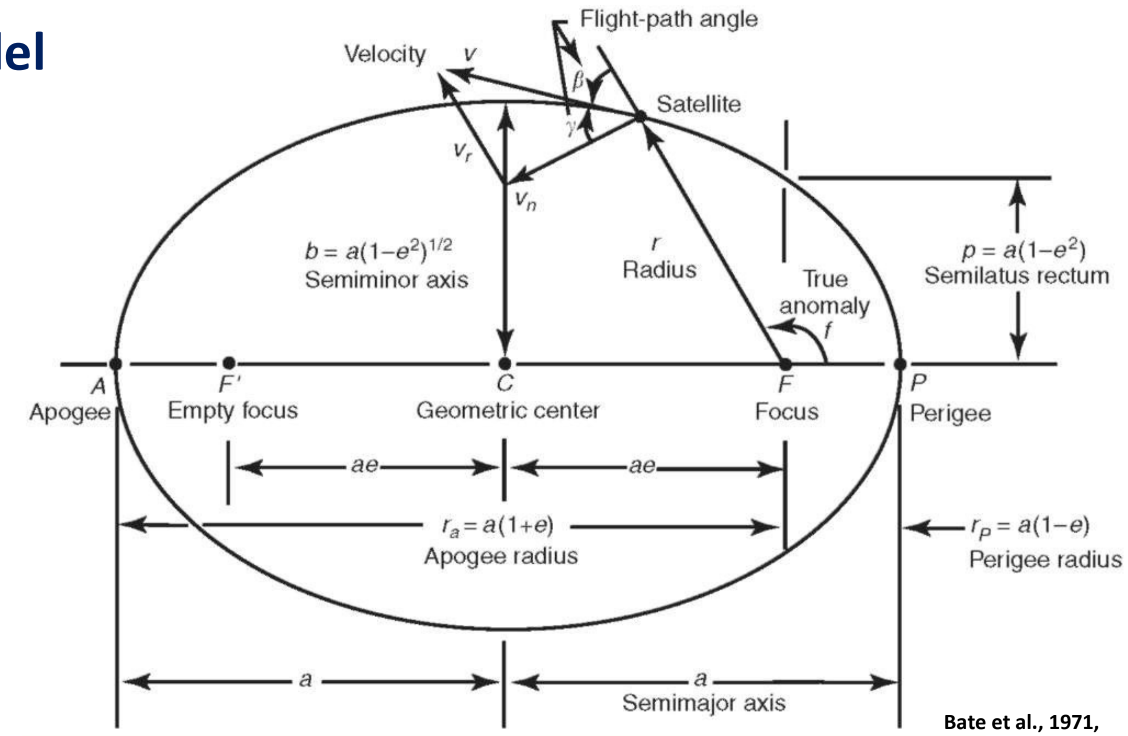
$$ODR = -\frac{SMA^2 \times Adensity \times SSA \times DCoef}{mass\ of\ satellite} \times \sqrt{\frac{GrConst \times Mass\ of\ Earth}{SMA^3}} \times [MSP]$$

ODR – orbit decay rate; SMA – semimajor axis; Adensity – atmospheric density; SSA – satellite surface or exposed area; DCoef – drag coefficient; GrConst – Earth's gravitational constant; MSP – modified satellite position.

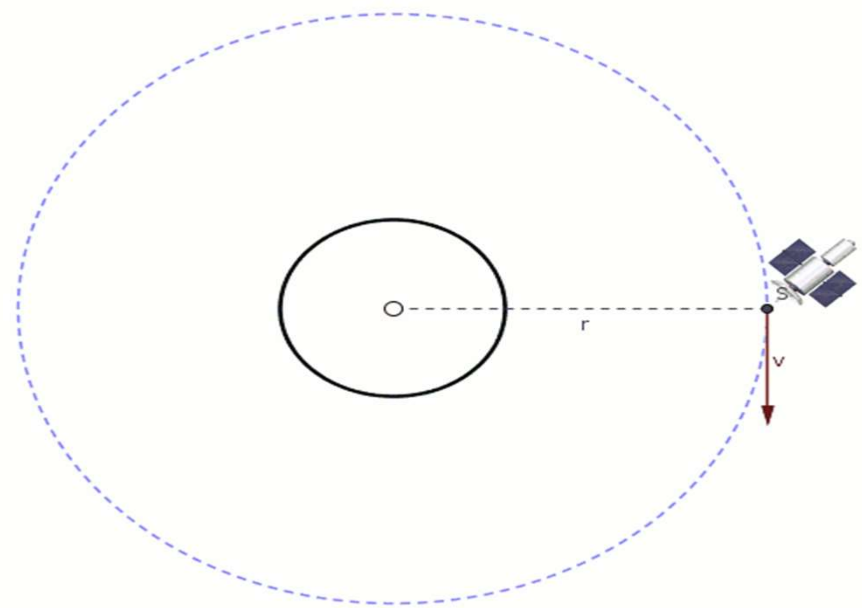
$$r_{mod} = \frac{\Delta r_e}{\Delta r_s},$$

$\Delta r_e = r_{te} - r_{ep}$, which is the difference of the actual mean r (based on ephemeris data), at time t (rt) and the epoch (rep).

$\Delta r_s = r_{ts} - r_{ep}$, the difference of the [normalized] simulated mean position, r, at time t (rt) and the epoch (rep).



Bate et al., 1971, Chobotov, 2002



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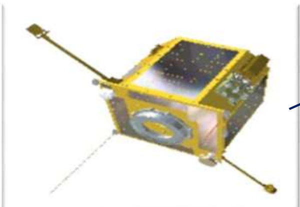
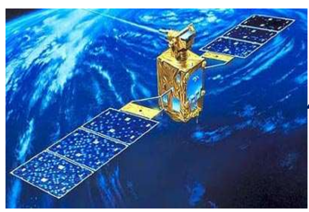
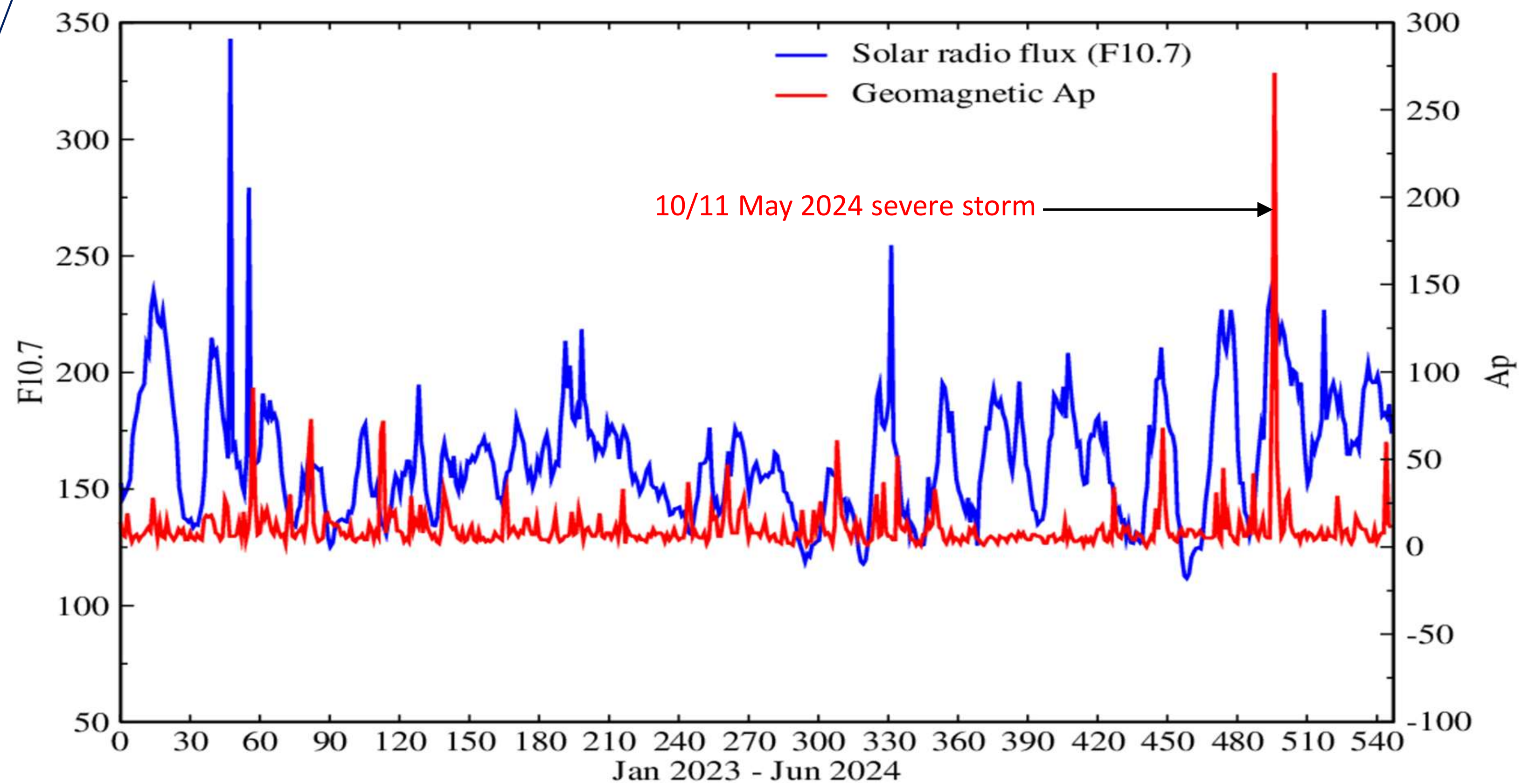
List of catalogued LEO objects of interest and their orbital and ballistic parameters [used for modeling]

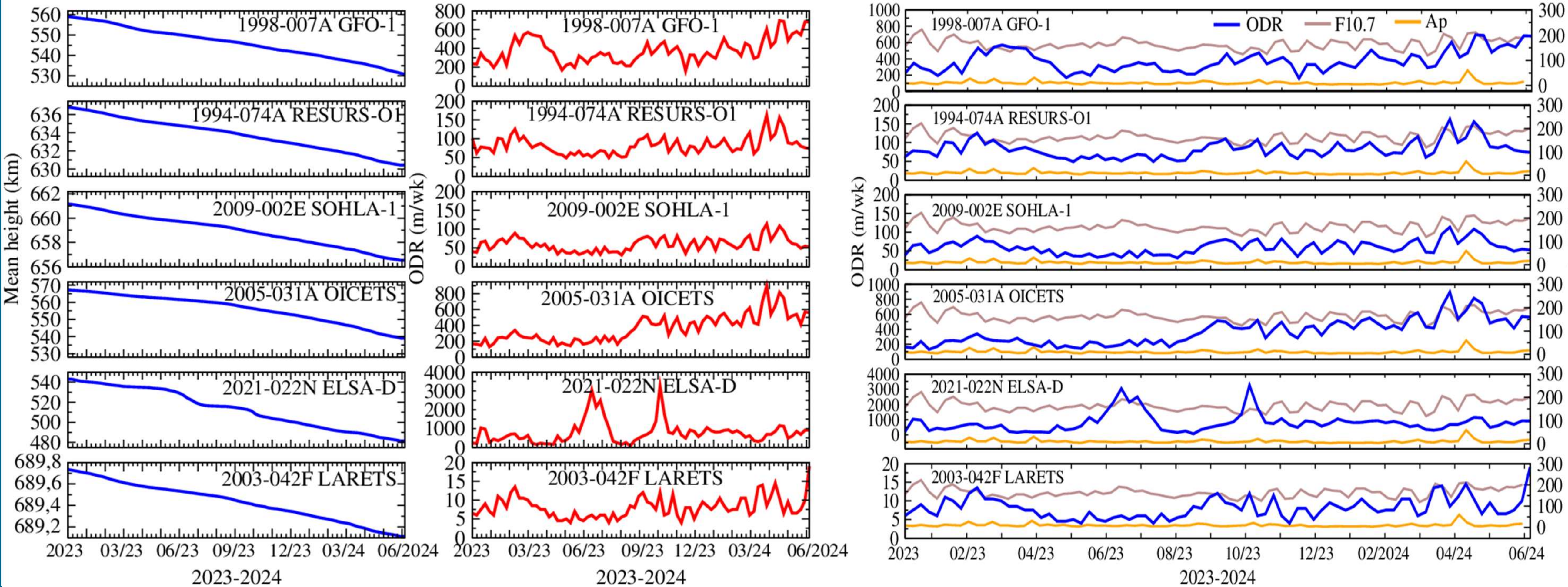


	LEO Object (NORAD#-COSPAR# Name)	h_a, h_p, h_m (km)	m (Kg)	A (m^2)	C_d	B (m^2/kg)	Eccentricity, e	Inclination, i
5	25157 1998-007A GFO-1	622.1, 438.6, 530.3	361.74	2.513	3.090	0.0214661	0.01329	108.032°
6	36037 2009-059B PROBA-2	729.5, 711.8, 720.7	130.00	0.81	2.124	0.0132341	0.00124	98.225°
7	23342 1994-074A RESURS-O1	633.2, 631.3, 632.3	1900.00	11.656	3.253	0.0199562	0.00013	97.754°
8	33496 2009-002E SOHLA-1	664.2, 653.8, 659.0	50.00	0.375	2.124	0.0159300	0.00074	98.231°
9	28809 2005-031A OICETS	562.0, 544.6, 553.3	570.00	5.823	2.354	0.0240479	0.00126	98.142°
10	38046 2012-001A Zi Yuan-3	495.6, 488.5, 492.1	2650.00	10.304	2.354	0.0091530	0.00052	97.275°
11	47944 2021-022N ELSA-D	521.4, 499.3, 510.3	175.00	1.284	2.354	0.0172716	0.00161	97.479°
12	27944 2003-042F LARETS	698.4, 680.2, 689.3	10.00	0.031	2.123	0.0013162	0.00129	98.287°



Solar activity indices (F10.7 and Ap) during the interval objects were monitored - January 2023 to June 2024.

Analysis of objects’ orbital history – mean height (h_m) and orbit decay rate (ODR) compared with observed solar activity indices [7-day mean] during January 2023 to June 2024

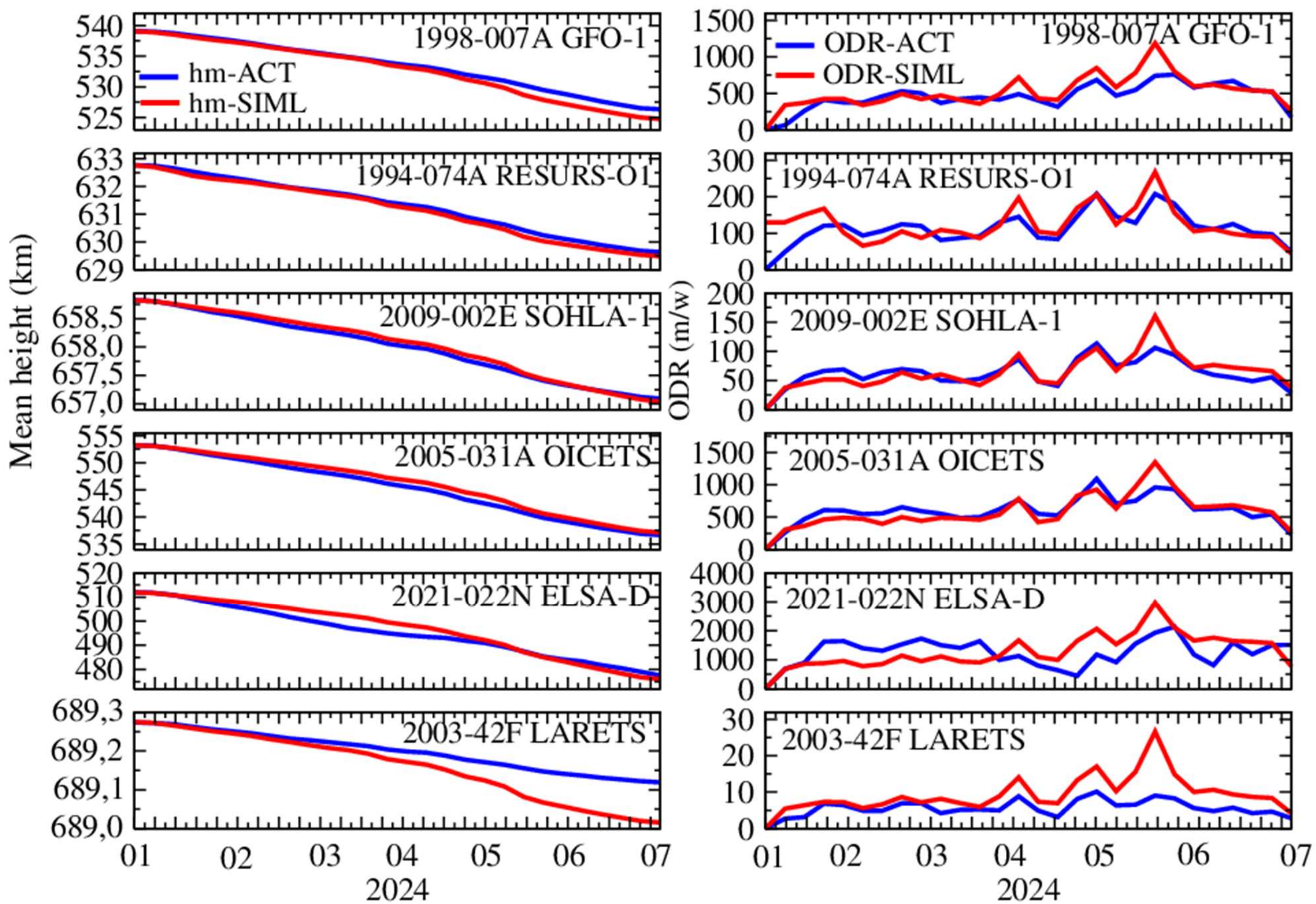


- ODR was calculated from the equation of the semimajor Axis decay rate (da/dt).
- Severity of solar activity impact varied from object-to-object – depend on their height, ballistic parameters (*A, Cd, m*) and operational dynamics per time.
- There are trajectory pattern that appear not to be completely related to solar activity e.g., case of ELSA-D.
- High Object’s ODR (and h) appear to correlate well with elevated [or strong fluctuation in] F10.7 and/or Ap - proxies of thermospheric heating by EUV radiation and geomagnetic activity.

EDAC aided simulation of Atmospheric drag effect on catalogued LEO objects trajectory

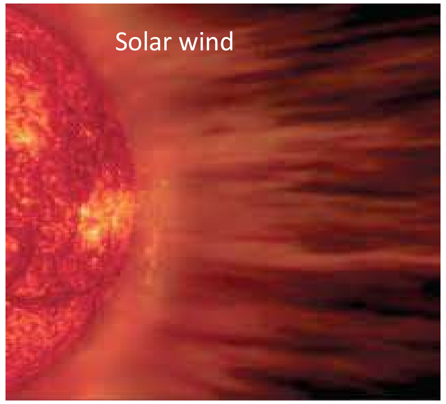
LEO objects actual mean height (hm-ACT) and orbit decay rate (ODR-ACT) during Jan 2024 to Jun 2024, compared with simulated hm (hm-SIML) and ODR (ODR-SIML).

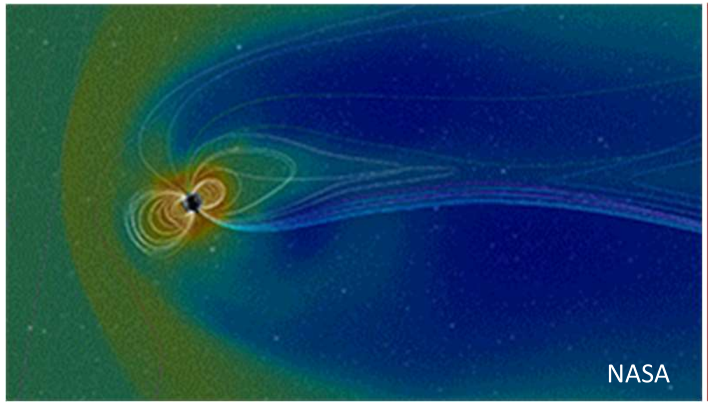
- Simulated hm and ODR show a remarkable correspondence (and consistency) with the actual orbital history of the LEO objects (except ELSA-D)
- ELSA-D exhibit trajectory pattern that appear to be related to its attitude (in addition to solar activity impact).
- Significant deviation of simulated parameters (hm, ODR) from the objects actual values for LARETS – to be investigated further!!!
- **Notwithstanding, the simulated hm/ODR in the OSI regime compared well with the actual values and solar activity indices for the interval (Jan-Jun 2024).**

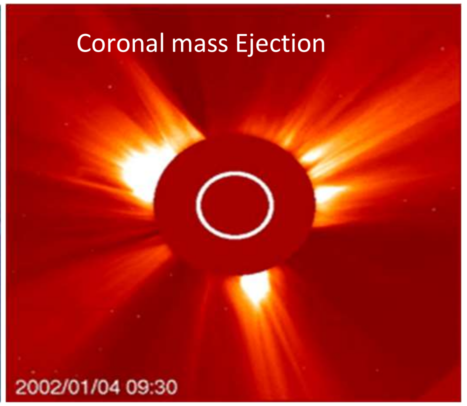


EDAC aided simulation of Atmospheric drag impact of May 10-11 storm on LEO objects trajectory

- On 10 May 2024 the Earth witnessed the largest geomagnetic storm in over 20 years.
- The event brought about the best [fascinating] auroras display in 2 decades but also left trails of adverse impact (on ground- and space-based technology) in its wake.
- An analysis of open-access data from the US Space Force revealed more than 5,000 satellites were manoeuvred (for collision avoidance) during the storm (ABC News, 2024).
- Geomagnetic storm is a major disturbance of the Earth's magnetosphere that occurs when there is a very efficient transfer of energy from the solar wind to the magnetosphere or space environment surrounding Earth.
- Storms are more frequent and intense during the maximum phase of the solar cycle and the 2 leading drivers are:
  - High speed solar wind & stream-stream interaction (creating CIR)
  - Coronal mass ejections (CMEs) – most geo-effective!!!
- **The trajectory of the 6 catalogued objects were also impacted by the storm, leading to a significant orbit decay.**

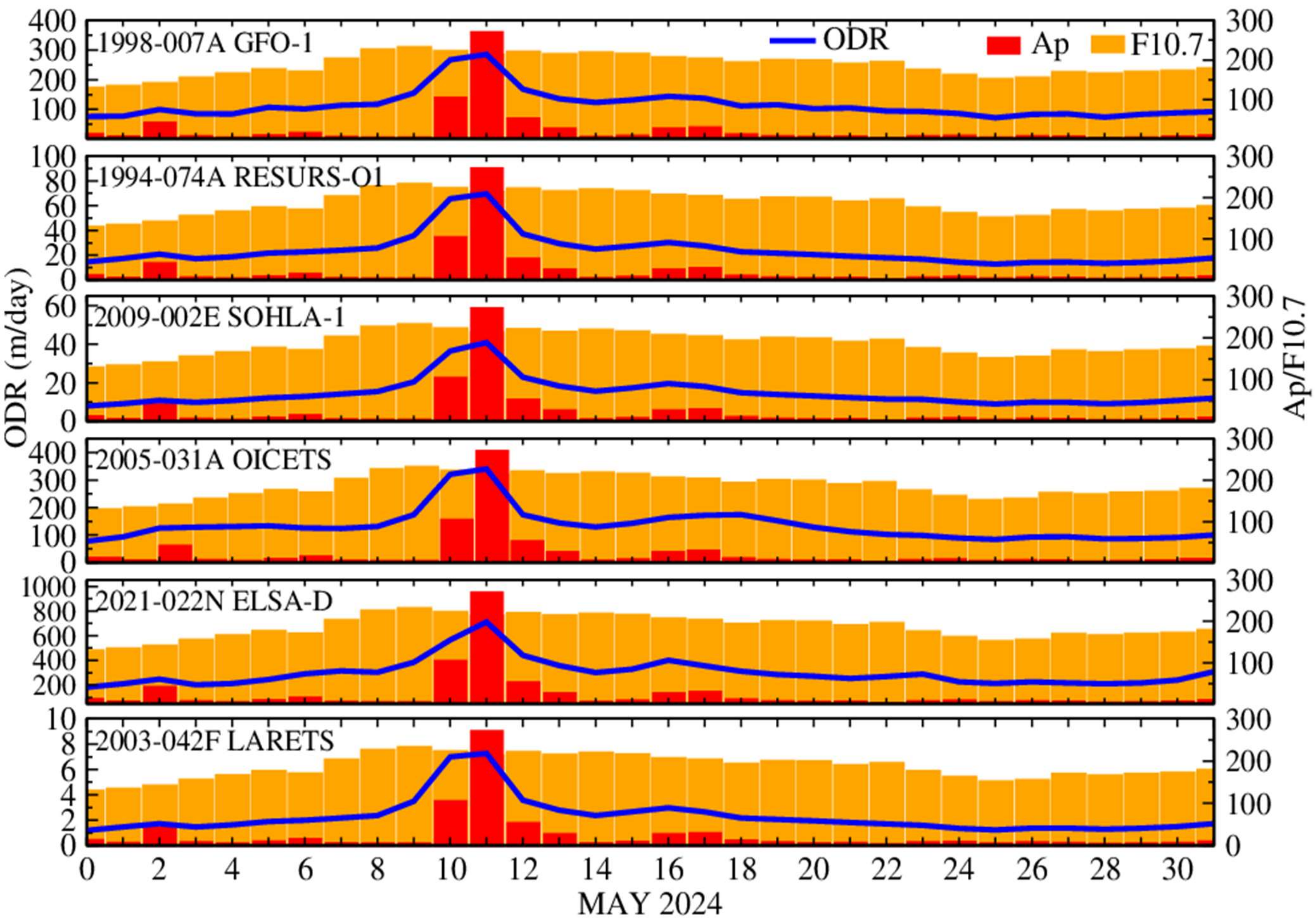






Geostorm-induced accelerated orbital decay: 10-11 May 2024 extreme storm Impact

Objects' orbit decay rate (ODR) for May 2024 [simulated], highlighting severe storm of 10-11 May.



How were they affected...

- ❑ **h** ~ 492 km (ELSA-D) up to 700 m/day
- ❑ **h** ~ 530 km (GFO-1) up to 285 m/day
- ❑ **h** ~ 544 km (OICETS) up to 340 m/day
- ❑ **h** ~ 630 km (RESURS up to 69 m/day
- ❑ **h** ~ 657 km (SOHLA-1) up to 40 m/day
- ❑ **h** ~ 689 km (LARETS) up to 7 m/day

Specific storm-induced ODR (SSIO)

Objects' orbit decay rate (ODR) for 9-16 May 2024 [simulated] – highlighting severe storm of 10-11 day of the month (DOM).

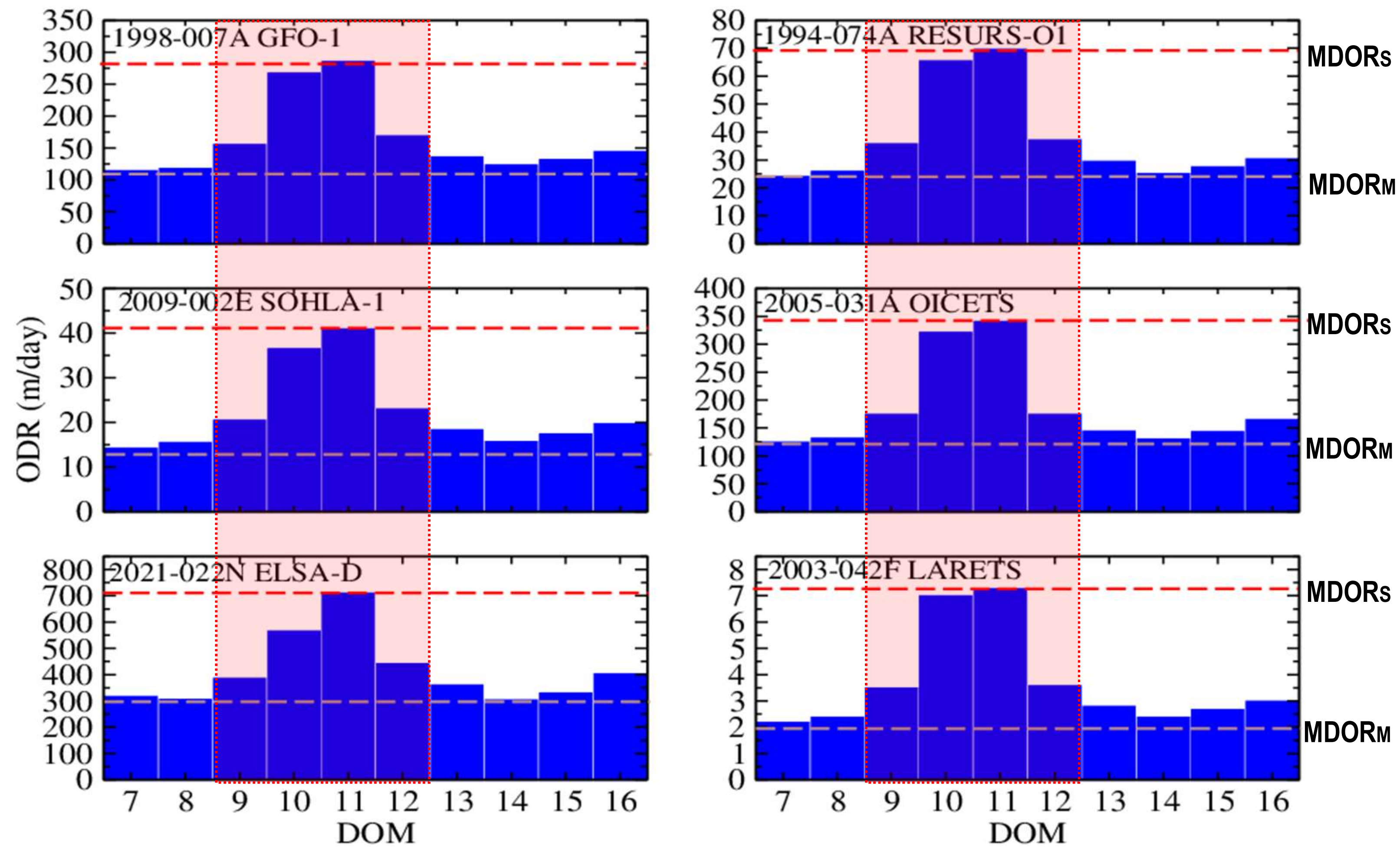
The SSIO per day can be estimated using the expression:

$$ODR_S = MODR_{SD} - MODR_M$$

Where $MDOR_M$ is baseline for the mean ODR for month (i.e. May), $MDOR_{SD}$ is the mean ODR on storm day.

The total SSIO for the considered interval (duration of impact) can be estimated using the expression:

$$Total\ ODR_S = \sum_{i=0}^{n} ODR_S$$



Total SSIO/ODRS…

- ❑ **h** ~ 492 km (ELSA-D) – 1004.23 m
- ❑ **h** ~ 530 km (GFO-1) – 439.96 m
- ❑ **h** ~ 544 km (OICETS) – 508.50 m
- ❑ **h** ~ 630 km (RESURS – 109.96 m
- ❑ **h** ~ 657 km (SOHLA-1) – 66.64 m
- ❑ **h** ~ 689 km (LARETS) – 21.95 m

STORM EFFECT ANALYSIS FOR 09-16 MAY 2024

	Object	H_{ST} (km)	Monthly mean ODR	09.05.2024		10.05.2024		11.05.2024		12.05.2024		Overall impact (4Ds)
			$\overline{ODR_F}$ (m/d)	ODR_{D1}	ODR_{S1}	ODR_{D2}	ODR_{S2}	ODR_{D3}	ODR_{S3}	ODR_{D4}	ODR_{S4}	ΣODR
1	GFO-1	530.85	108.93	155.21	46.28	267.08	158.15	285.20	176.27	168.19	59.26	439.96
2	RESURS	630.62	24.51	35.78	11.27	65.49	40.98	69.54	45.03	37.19	12.68	109.96
3	SOHLA-1	657.79	13.51	20.47	6.96	36.46	22.95	40.84	27.33	22.91	9.40	66.64
4	OICETS	543.94	125.54	174.31	48.77	321.22	195.68	340.92	215.38	174.21	48.67	508.5
5	ELSA-D	492.12	274.12	384.96	110.84	564.78	290.66	709.54	435.42	441.33	167.21	1004.13
6	LARETS	689.12	2.15	2.36	3.48	3.48	2.22	7.26	11.95	3.57	4.30	21.95

Conclusion & Recommendation

Conclusion

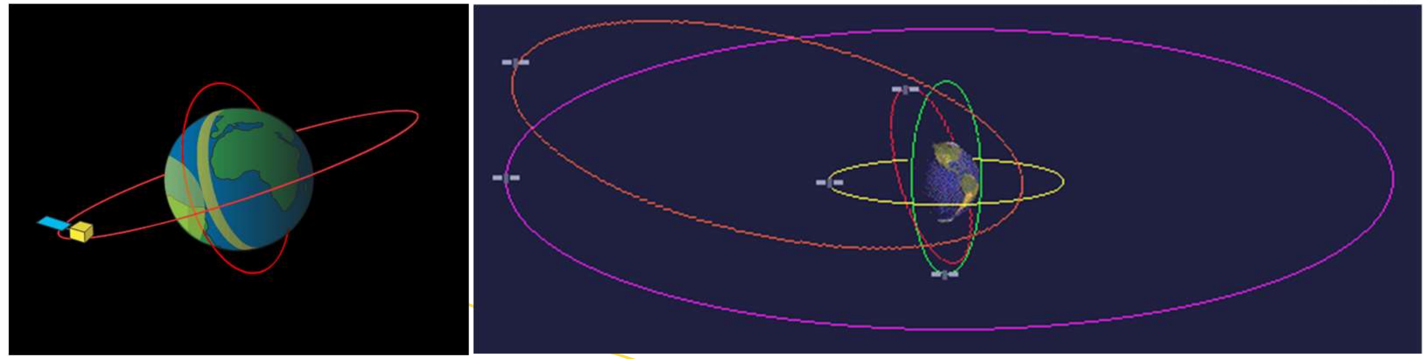
- ❑ Large variability in the Object's ODR and h (based on their orbital history) correlated well with elevated [or strong fluctuation in] F10.7 and/or Ap – used as proxies for thermospheric heating by EUV radiation and geomagnetic activity.
- ❑ The EDAC simulated decay evolution of catalogued LEO objects [selected] in the observed solar indices (OSI) regime compared well with the orbital history of the objects - an indication that a long-term model-driven SSA for LEO objects is achievable.
- ❑ May 10-11 (2024) storm had profound impact on the trajectory of the catalogued LEO objects and the impact level was influenced by objects altitude, position, orientation and ballistic parameters (A, Cd, m) at the time of the event.

Recommendations

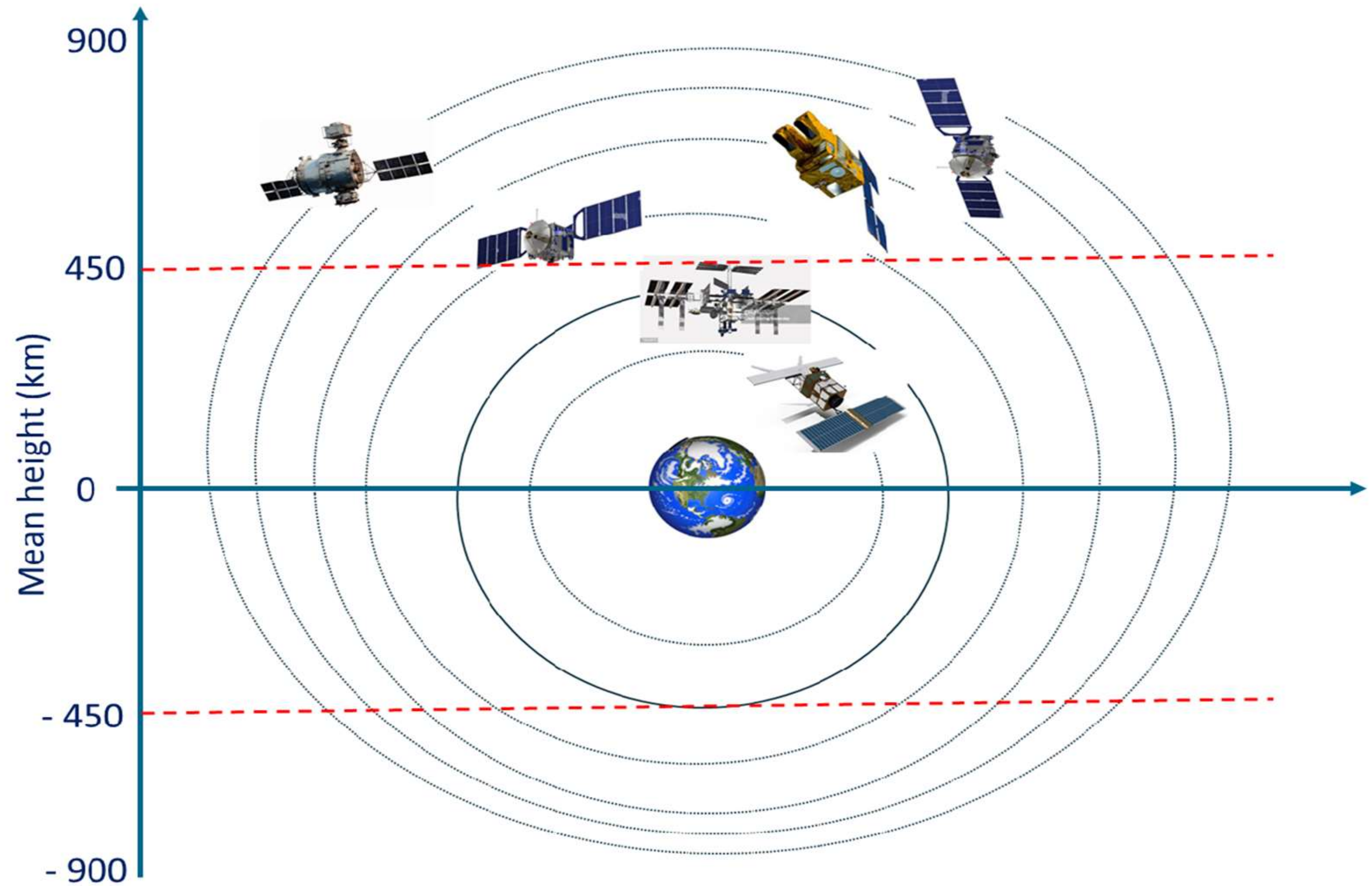
- ❑ Advocacy for more aggressive and enhanced actions/initiatives to increase the margin of safety for space operations.
- ❑ To increase compliance (to space debris mitigation guidelines & technical standards), agencies intending a new launch should be made to submit a comprehensive blueprint of how/when to take off their spacecraft [junk] from orbit (at the end of their mission) and subsequently sign an undertaking to that effect, before launch (or even design) approval is given.
- ❑ [Buttressing on the suggestion of David (2009)] the UN Member States should consider the imposition of fees for every launch and penalty for those who ignore their floating debris. Such fees can be used as compensation for operational spacecraft destroyed in future collisions and to partially fund R&D for space debris mitigation or active removal technologies.
- ❑ Advocacy for every satellite [for future launch] to be designed/equipped with controlled re-entry capability. This will facilitate timely deorbiting of debris (even if they fail before the end of mission).

OUTLOOK

- Development of a demonstrator in the Ionosphere Monitoring and Prediction Center (IMPC) of DLR-SO for the calculation of the atmospheric drag effect for selected analyzed and parameterized objects in their orbits [2025].
- Development and implementation of concept for simulation of Time to Debris Approach (TDA) to predefined Risk Zone (RZ) of an Active satellite as a function of predicted solar activity in the 25th solar cycle [2025].
- Model-driven collision risk analysis for active satellites in debris field [2025].



Point of high collision risk



Thank you very much for your attention!

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Theoretical considerations for Atmospheric drag model

The general equation of motion for a satellite moving under the attraction of a point mass planet with perturbations effect is given by the equation (Chobotov, 2002),

$$\frac{d^2\boldsymbol{r}}{dt^2} = -\frac{\mu \boldsymbol{r}}{r^3} + a_p$$

where, **r** is the position vector of the satellite, **μ** (=*GMe)* is the Earth's gravitational parameters, $\mathbf{a_p}$ is the resultant vector of all perturbing accelerations caused by perturbing forces in the adverse space or near-Earth environment.

- $\mathbf{a_p}$ is usually a result of two main types of forces:
  - Gravitational forces - Earth, solar and lunar attraction and Earth's oblateness (J2) and its triaxiality
  - Non-gravitational forces - atmospheric drag, solar radiation pressure, outgassing and tidal effects
- Our model accounts for the effect of Earth's gravity/attraction and atmospheric drag effect.

The drag or negative acceleration, $\mathbf{a}_p$, (in m/s²) experienced by the satellite is given as:

$$\mathbf{a}_p = \frac{1}{2}\rho B v_s^2$$

where **ρ** (in kg/m³) is the altitude-dependent atmospheric density, $\mathbf{v}_s$ (in m/s) is the satellite velocity (King-Hele, 1987),

B (in m²/kg) is satellite's ballistic coefficient given by:

$$\boldsymbol{B} = \frac{\boldsymbol{A_s C_d}}{\boldsymbol{m_s}}$$

where $\boldsymbol{C_d}$ is the unitless atmospheric drag coefficient, $\boldsymbol{A_s}$ (in m²) is the satellite's projected area in the direction of motion, and $\boldsymbol{m_s}$ (in kg) is the satellite mass.

The velocity of a satellite in elliptical orbit is given by the equation:

$$v_s = \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)}$$

The general equation for the radius *r* (satellite's position) is given by:

$$r = \frac{P}{1 + e\cos\gamma}$$

$$P = semilatus\ rectum = a(1-e^2) = r_p(1+e) = r_a(1-e)$$

$$a = semimajor\ axis = \frac{r_a + r_p}{2}$$

$$e = eccentricity = \frac{r_a + r_p}{r_a - r_p}$$

$$r_a = apogee\ radius = a(1+e)$$

$$r_p = perigee\ radius = a(1-e)$$

$$\boxed{\gamma = true\ anomaly \quad \Big| \quad \tan\frac{\gamma}{2} = \left[\frac{1+e}{1-e}\right]^{\frac{1}{2}} \tan\frac{E}{2} \quad \Big| \quad E = ae = r_a - r_p}$$

The decay rate of the satellite's semimajor axis *a* is given by:

$$\frac{da}{dt} = -a^2 \rho B \sqrt{\frac{\mu}{a^3}}$$

Bate et al., 1971, Chobotov, 2002

BACKUP Slides

Theoretical considerations for Atmospheric drag model

We used the numerical integration method in spherical coordinate system (r, θ and Ø) we computed the orbital decay as a consequence of changes in the radial distance (r) and the azimuthal angle (Ø) as a function of solar activity (represented by F10.7, Ap proxies).

$$\dot{v}_r = -\dot{\phi} r^{\frac{1}{2}} \rho B,$$
$$\dot{r} = v_r,$$
$$\ddot{\phi} = -\frac{1}{2} r \rho \dot{\phi}^2 B,$$
$$\dot{\phi} = \frac{v_\phi}{r},$$

	LEO Object (NORAD#-COSPAR# Name)	*Shape*	*Recommended Cd*	Max X-section	Min X-section	Avg X-section
1	23560 1995-021A ERS-2	Box + 1 pan	2.100	24.872	3.610	15.593
2	25977 1999-064A HELIOS 1B	Box + 1 pan	2.200	11.477	4.000	9.274
3	38013 2011-076G ASAP-S	Cyl	2.408	1.649	1.131	1.508
4	27421 2002-021A SPOT 5	Box + 1 pan	2.408	37.437	9.610	26.052
5	25157 1998-007A GFO-1	Cyl+1 dish+1 pan	3.120	2.812	0.785	2.513
6	36037 2009-059B PROBA-2	Box + 2 pan	2.124	1.201	0.360	0.810
7	23342 1994-074A RESURS-O1	Cyl + 2 pan	3.253	20.516	1.539	11.656
8	33496 2009-002E SOHLA-1	Box	2.124	0.433	0.250	0.375
9	28809 2005-031A OICETS	Box + 2 pan	2.354	11.377	1.210	5.823
10	38046 2012-001A Zi Yuan-3	Box + 2 pan	2.354	19.728	4.000	10.304
11	47944 2021-022N ELSA-D	Box + 2 pan	2.354	2.297	0.360	1.284
12	27944 2003-042F LARETS	Sphere	2.123	0.031	0.031	0.031