An Evaluation of CubeSat Orbital Decay

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Contents

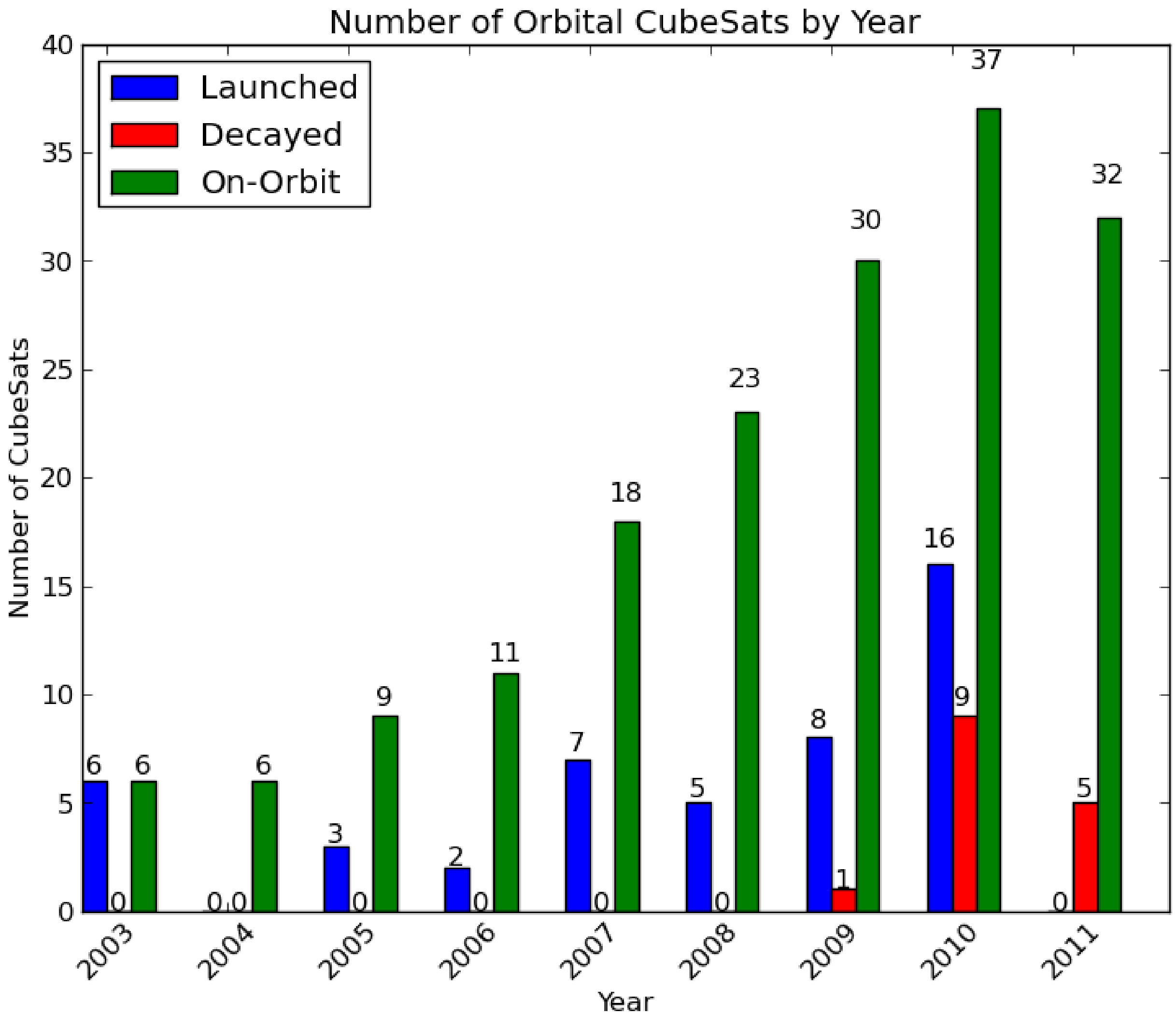
CubeSat Historical Manifest

Year	Name	Form-factor	Mass Est. (kg)	SCC #
2003	AAUSAT-1	1U	1	27846
2003	CanX-1	1U	1	27847
2003	Cute 1	1U	1	27844
2003	DTU-1	1U	1	27842
2003	QuakeSat	3U	4.5	27845
2003	XI-IV	1U	1	27848
2005	Ncube-2	1U	1	28897
2005	UWE-1	1U	1	28892
2005	XI-V	1U	1	28895
2006	**Cute 1.7+APD**	**2U**	**3.5**	**28941**
2006	**GeneSat**	**3U**	**5**	**29655**
2007	AeroCube-2	1U	1	31133
2007	CAPE-1	1U	1	31130
2007	CP3	1U	1	31129
2007	CP4	1U	1	31132
2007	CSTB1	1U	1	31122
2007	Libertad-1	1U	1	31128
2007	MAST	3U	3	31126
2008	AAUSAT-2	1U	1	32788
2008	CanX-2	3U	3.5	32790
2008	Compass-1	1U	1	32787
2008	Delfi-C3	3U	3	32789
2008	SEEDS-2	1U	1	32791

CubeSat Historical Manifest (Continued)

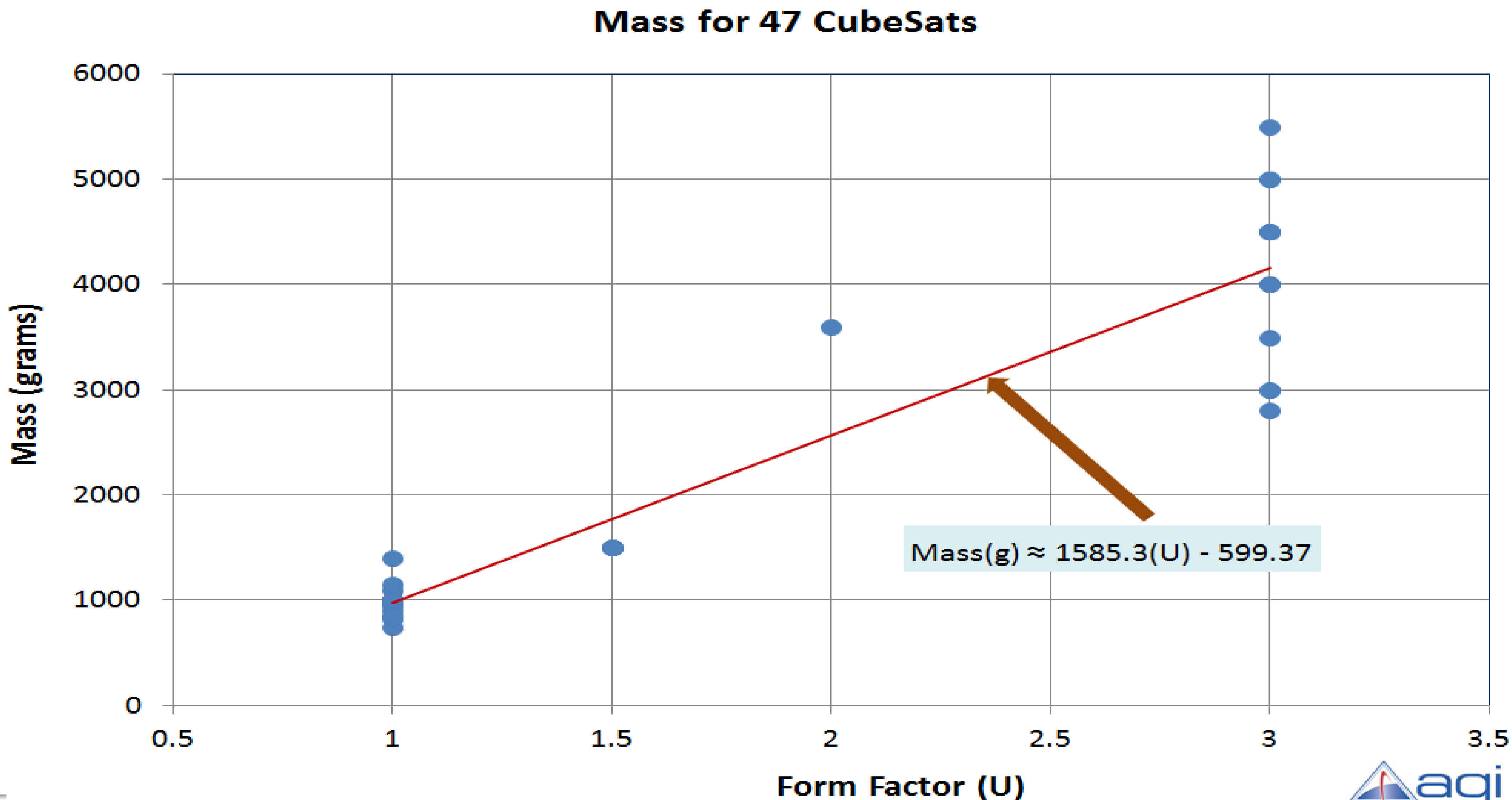
Year	Name	Form-factor	Mass Est. (kg)	SCC #
2009	**AeroCube-3**	**1U**	**1**	**35005**
2009	CP6	1U	1	35003
2009	HawkSat-1	1U	1	35004
2009	PharmaSat	3U	4.5	35002
2009	BeeSat	1U	1	35933
2009	ITU-pSat	1U	1	35935
2009	SwissCube	1U	1	35932
2009	UWE-2	1U	1	35934
2010	**Hayato (K-Sat)**	**1U**	**1.5**	**36573**
2010	**Negai**	**1U**	**1**	**36575**
2010	**Waseda-Sat2**	**1U**	**1**	**36574**
2010	StudSat	1U	1	36796
2010	Tisat-1	1U	1	36799
2010	NanoSail-D2	3U	4	37361
2010	**O/OREOS**	**3U**	**5.5**	**37224**
2010	**RAX**	**3U**	**3**	**37223**
2010	**MAYFLOWER (CAERUS)**	**3U**	**5**	**37252**
2010	**PERSEUS 000**	**1.5U**	**1.5**	**37251**
2010	**PERSEUS 001**	**1.5U**	**1.5**	**37248**
2010	**PERSEUS 002**	**1.5U**	**1.5**	**37250**
2010	**PERSEUS 003**	**1.5U**	**1.5**	**37247**
2010	**QbX1**	**3U**	**4.5**	**37249**
2010	**QbX2**	**3U**	**4.5**	**37245**
2010	**SMDC-ONE**	**3U**	**4**	**37246**

Orbital CubeSats By Year



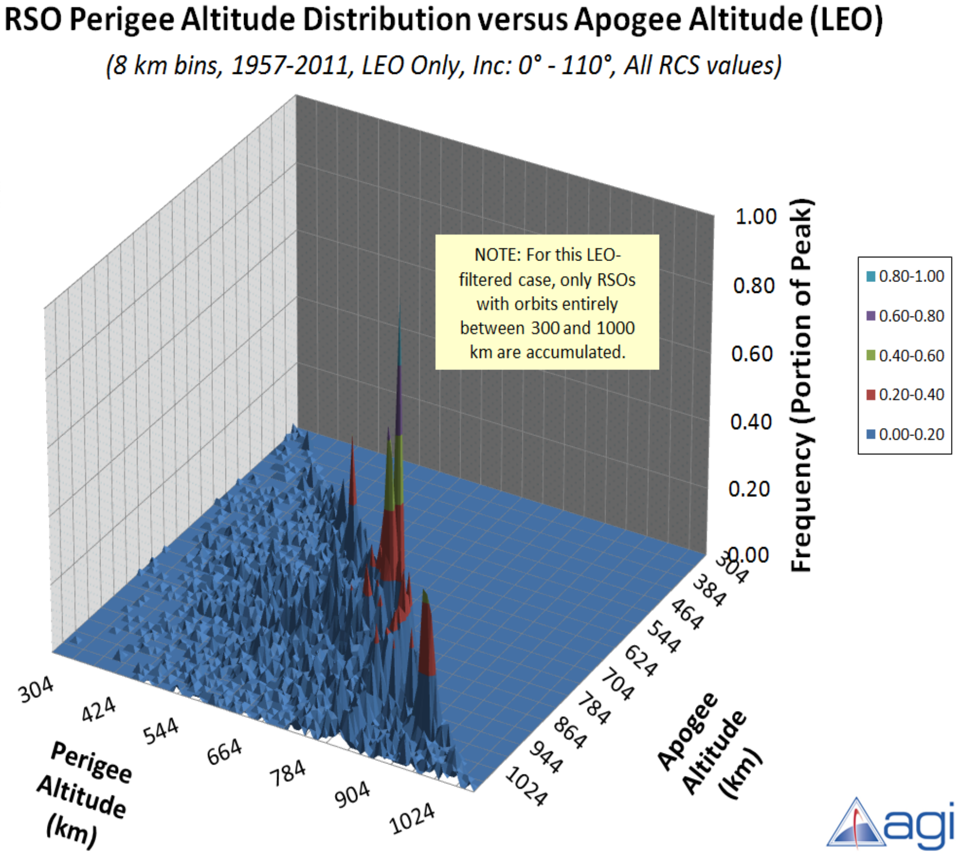
CubeSat Mass Statistic/Metric

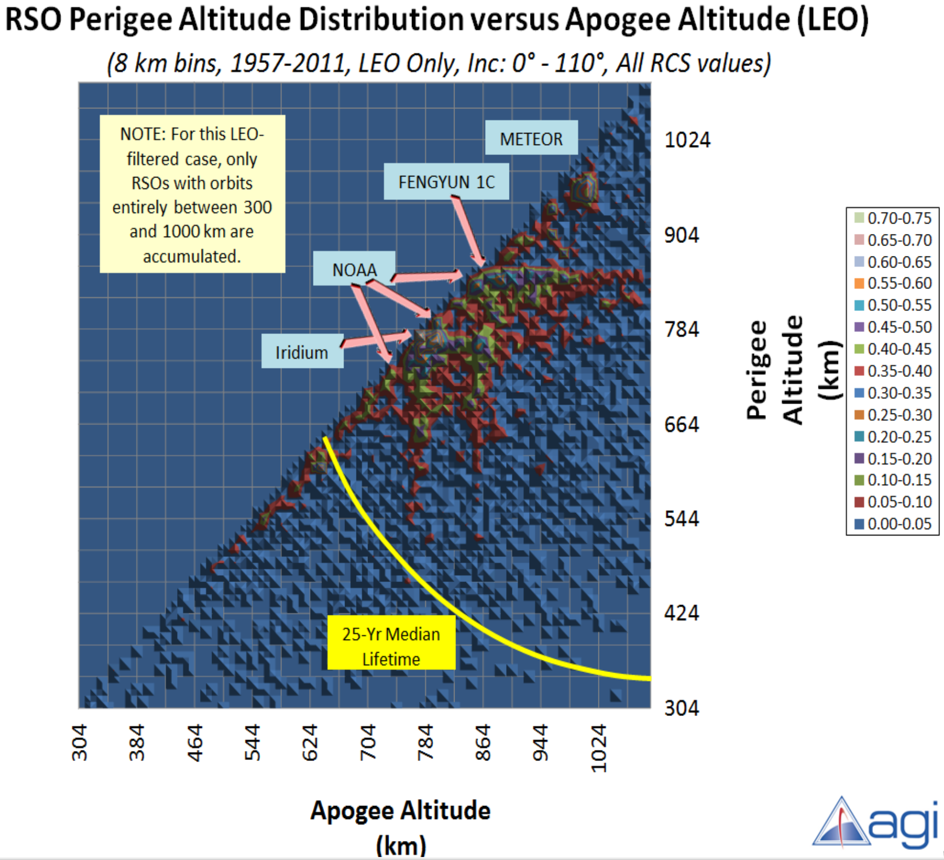
- Can evaluate “Mass-per-U” metric/trend



Resident Space Object (RSO) Population: Distribution Analysis

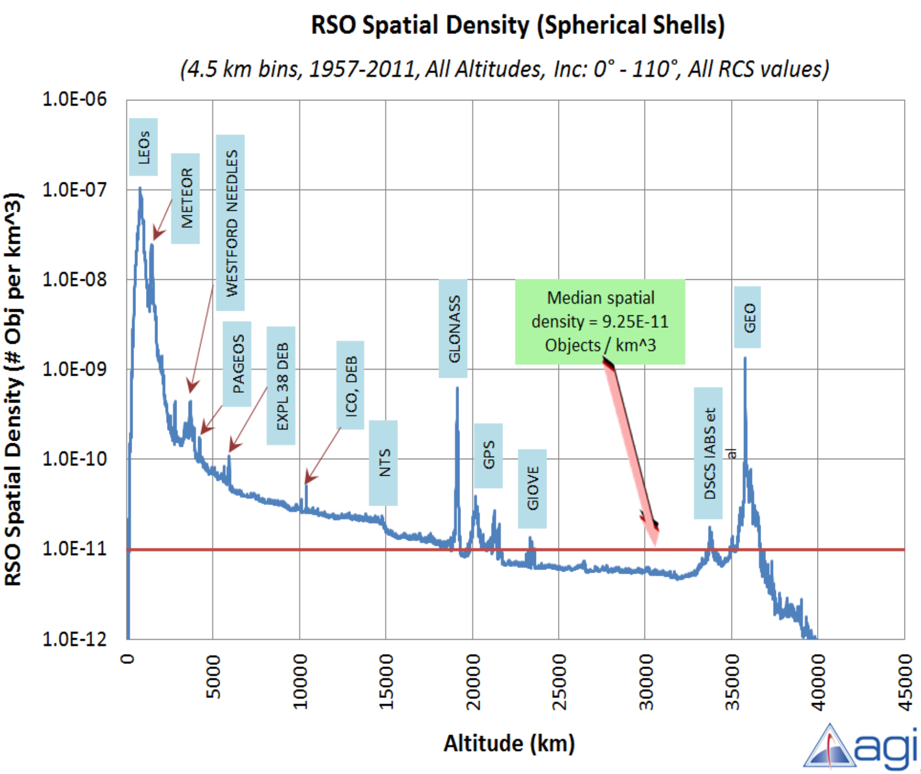
- Examination of the LEO region permits comparison of LEO population versus 25-year lifetime ISO standard

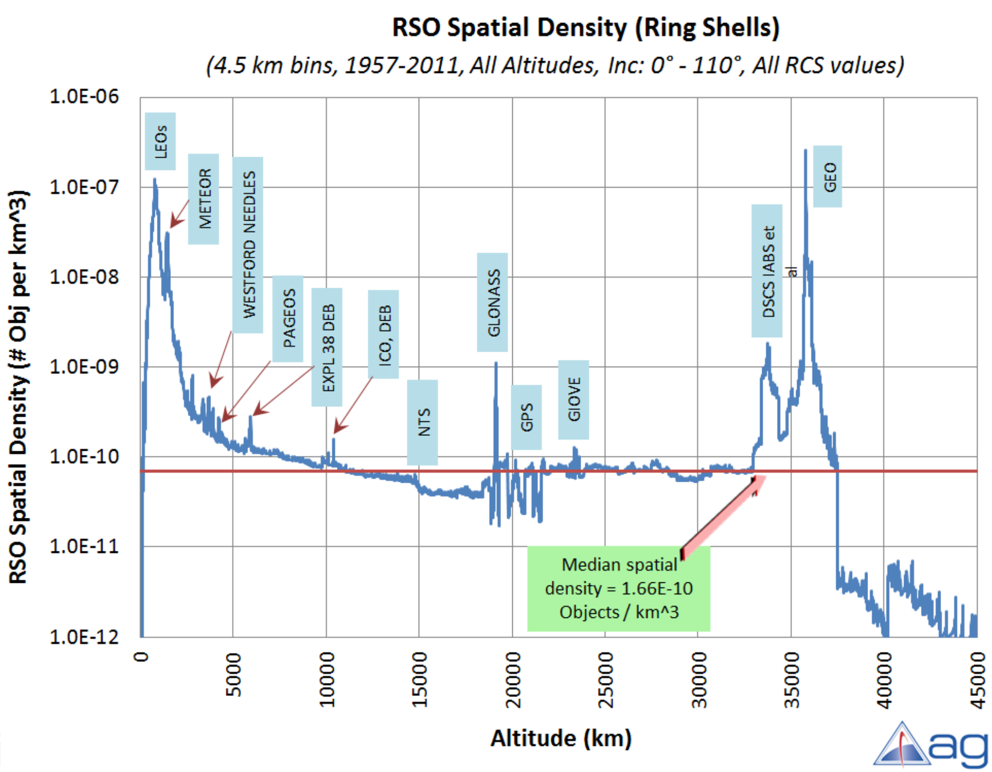


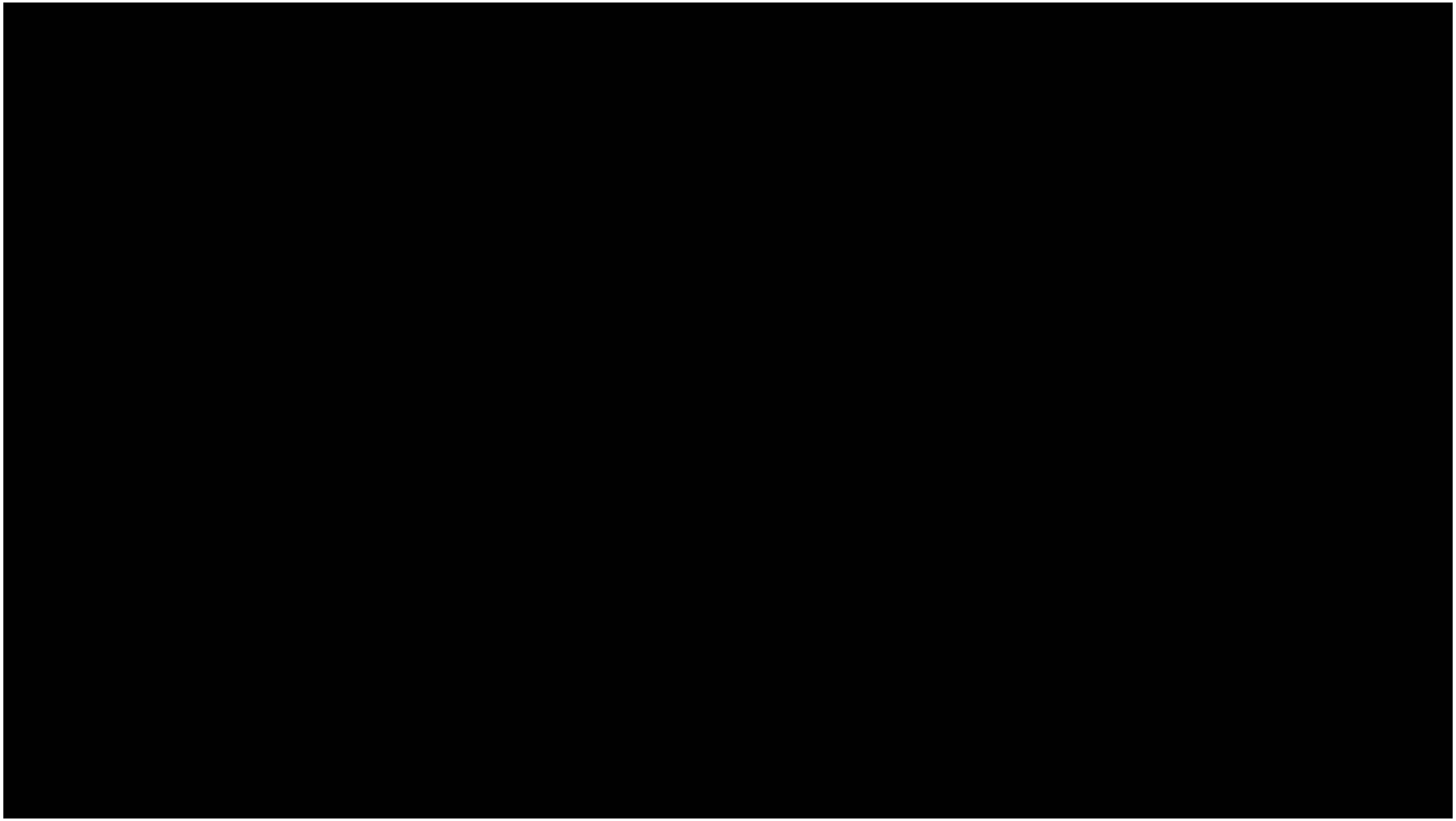


Spatial Density

- RSO spatial density generated assuming spherical shells
- The “Ring Shell” model is much more representative

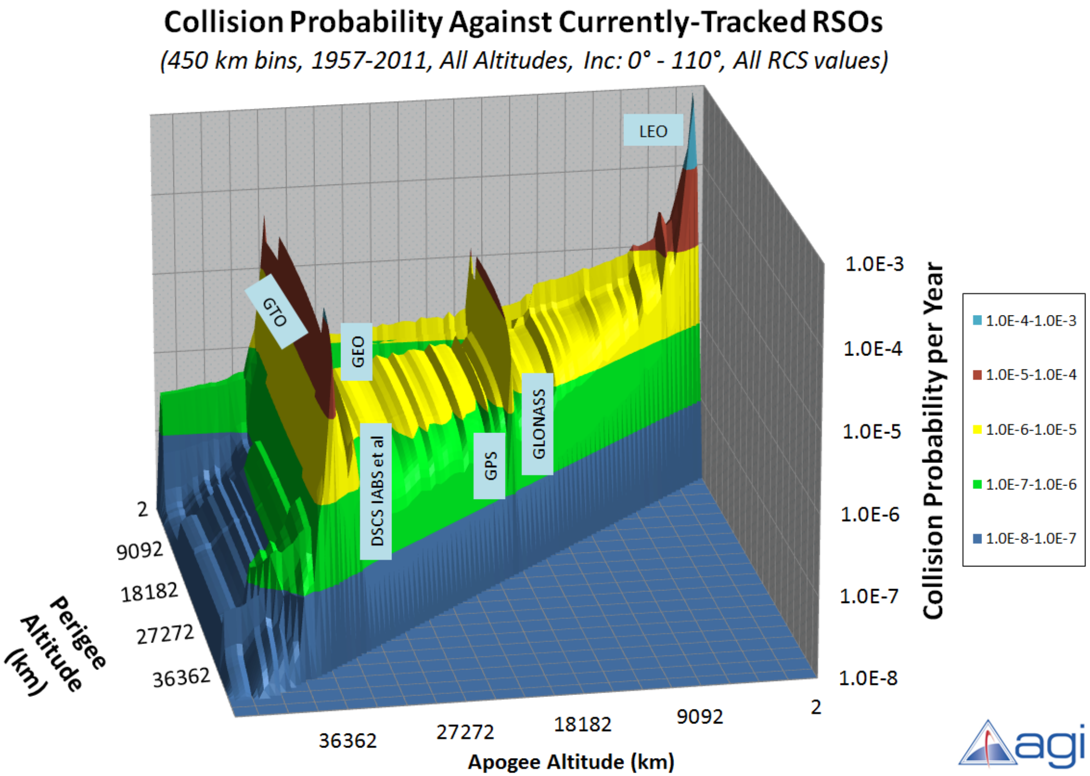


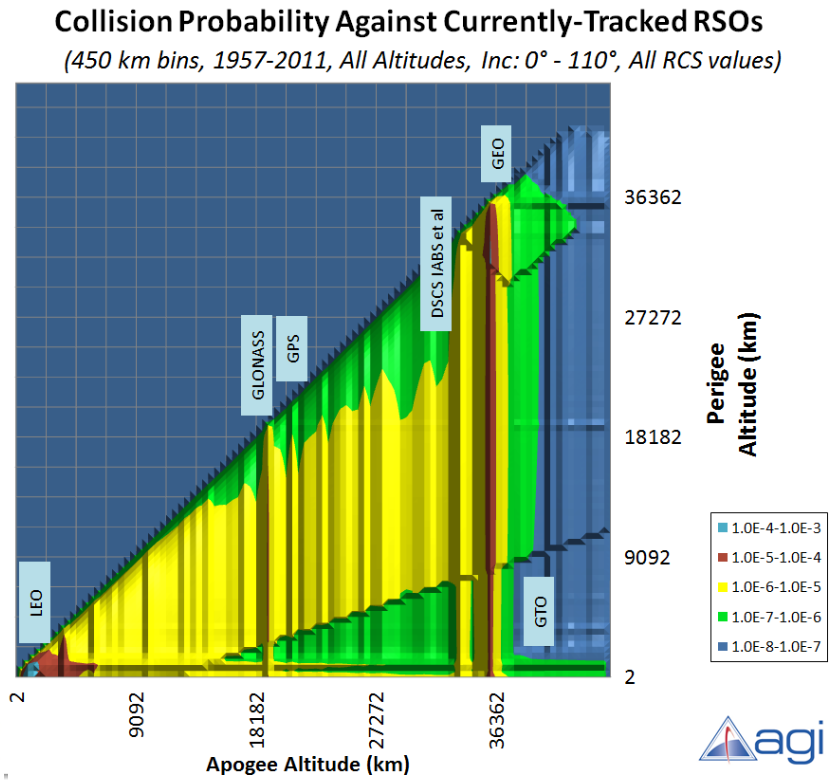




Collision Probability

- Can use median RCS, spatial density, and satellite orbit flight paths thru "Ring Shells" to obtain collision prob.
  - Presumes movement thru shells (i.e., GEO least accurate)



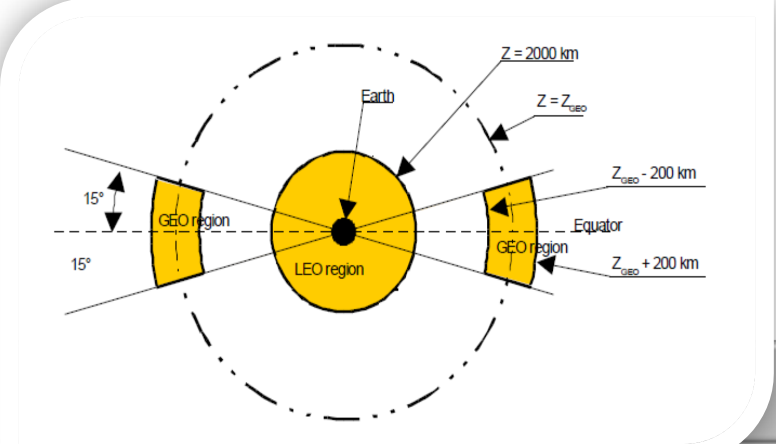


Orbit Lifetime and Space Standards

- Inter-Agency Space Debris Coordination Committee (IADC) recommends:
  - Spacecraft exit LEO-crossing regime (0 - 2000km) within 25 years of EOL
    - De-orbit or maneuver to suitably reduce orbit lifetime;
    - Dispose in orbit where drag/perturbations will limit lifetime;
  - ***IADC 'guidelines' are only that, with no regulatory requirement.***
- International Standards Organization (ISO)
  - ISO TC20/SC14/Working Group 3 creates Space Operations standards
- Orbital Debris Coordination Working Group (ODCWG) created to help coordinate conversion of IADC guidelines into ISO WG standards
- 'Orbit Lifetime' identified by ODCWG as ISO TC20/SC14/WG3 topic
  - ISO New Work Item Proposal (NWIP) for Orbit Lifetime standard
    - Approved 5 May 2006, with no dissenting votes
    - Assigned international team, led by Dan Oltrogge, to draft this standard
- Working Draft ISO Standard submitted for international comment 30 April 2007
- Approved for publication Fall 2010

IADC Guideline

- "A spacecraft or orbital stage should be left in an orbit in which, using an accepted nominal projection for solar activity, atmospheric drag will limit the orbital lifetime after completion of operations. ***A study on the effect of post-mission orbital lifetime limitation on collision rate and debris population growth*** has been performed by the IADC. This IADC and some other studies and a number of existing national guidelines have found 25 years to be a reasonable and appropriate lifetime limit."



Unique CubeSat Orbit Lifetime Aspects

- IADC, ODCWG, ISO and Engineering Best Practices [recommend/dictate] a 25-yr post-mission orbit lifetime
  - Compliance requires accurate orbit lifetime assessment
- CubeSats provide unique opportunity for lifetime studies
  - 47 CubeSats placed in orbit since 2003
  - 1U, 2U & 3U standardized form factors and mass properties
- CubeSat missions are being examined to:
  - Evaluate IADC guidelines and ISO standards compliance
  - Evaluate predicted and actual orbital decay profiles
- Implications for future CubeSat h/w design, concepts of operation and orbital decay modeling are being studied.

Orbital Debris Mitigation is Our Responsibility!

- Long-term vitality and viability of CubeSat community may depend upon ability to actively address:
  - ***Real and perceived orbital debris threat posed by CubeSats to government and industry operations***
- Can be addressed by:
  - Taking leadership roles in orbital debris assessment
  - Ensuring all current and future orbital debris mitigation standards, guidelines and directives are met
  - Invoking effective mitigation strategies:
    - Avoid mission orbits that prevent near-term natural decay
    - Limit post-mission orbit lifetime to prevent debris population growth using sophisticated modeling incorporating environmental uncertainty

Why Estimate Orbit Lifetime?

- 3 reasons:
  - Demonstrate compliance with Standards or Best Practices
  - Predict a future (actual) orbit demise
  - Post-decay forensic analysis and ballistics characterization
- Type of analysis dictates best space weather profile
  - "Typical" atmosphere useful for Stds compliance and design
  - Worst-case lifetime predictions useful to ensure compliance
- ISO orbit lifetime standard doesn’t require spacecraft redesign or remanufacture depending upon launch date within 11-year solar cycle

Orbit Lifetime Analysis Tools

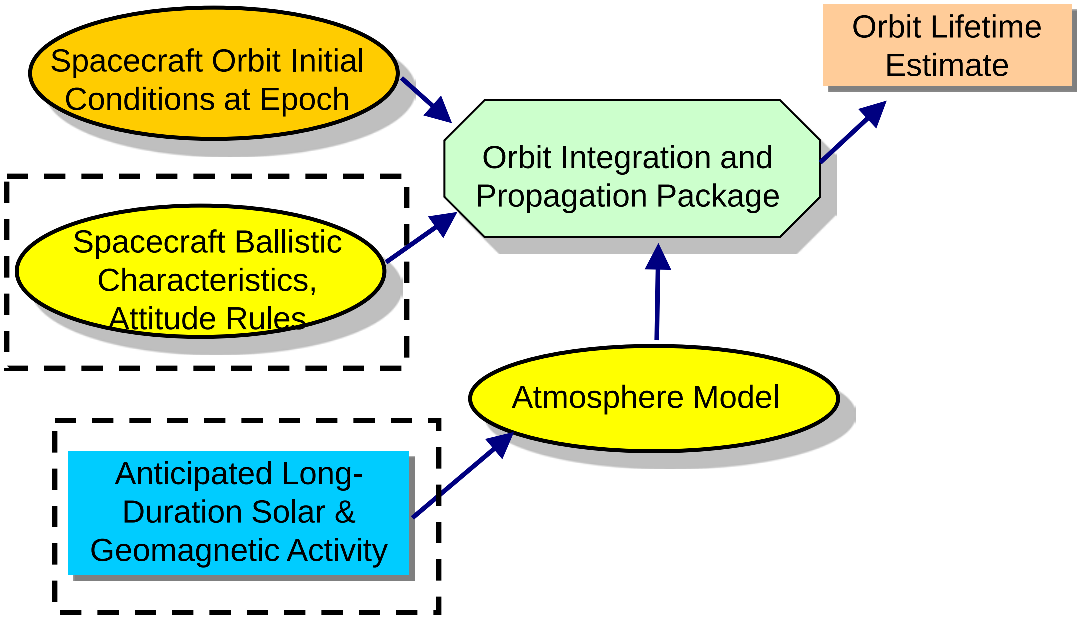
- Numerous models exist …
- Orbit lifetime prediction models we're using include:
  - QuickProp (QProp) propagator, supporting published ISO Standard 27852, "Space systems — Estimation of orbit lifetime."
    - Forthcoming digital orbit lifetime database on www.CelesTrak.com
  - STK
  - Detailed numerical integration
  - NASA Debris Assessment Software (DAS)

Lifetime Estimation Approaches

- Three primary methods to estimate orbit lifetime:
  - Method 1: Direct numerical integration of accelerations in Cartesian space
    - Detailed gravity model (addresses resonance effects);
    - Third-body effects and solar radiation pressure,;
    - Satellite ballistic coefficient =f (attitude rules, angle-of-attack)
  - Method 2: Semi-analytic propagation of mean orbit elements influenced by gravity zonals J2 and J3 and selected atmosphere models
  - Method 3: Use summary tables, graphs, and/or fit equations produced using Methods 1 &/or 2
- Method 1 longer to run than Methods 2 & 3
  - e.g., 1700 seconds vs 1 sec for a 30-year propagation.

Lifetime Estimation Components

- Purpose of Orbit Lifetime standard is to:
  - standardize ballistic coefficient & solar/geomagnetics modeling approaches
  - Provide users with access to plots and tabular orbit lifetime data

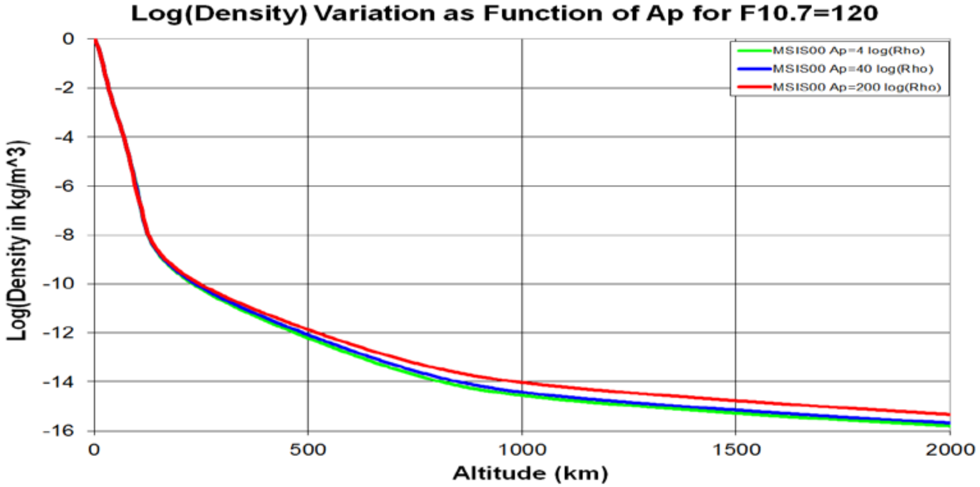


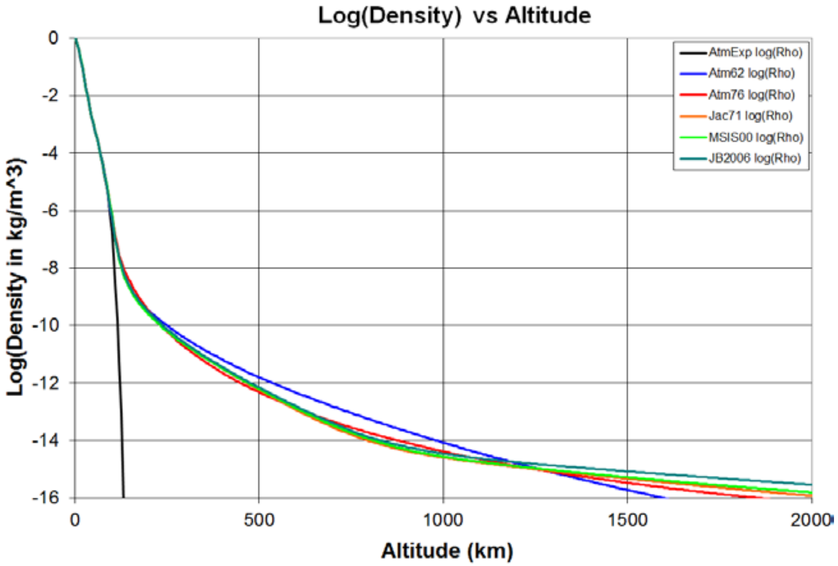
For one million model evaluations:

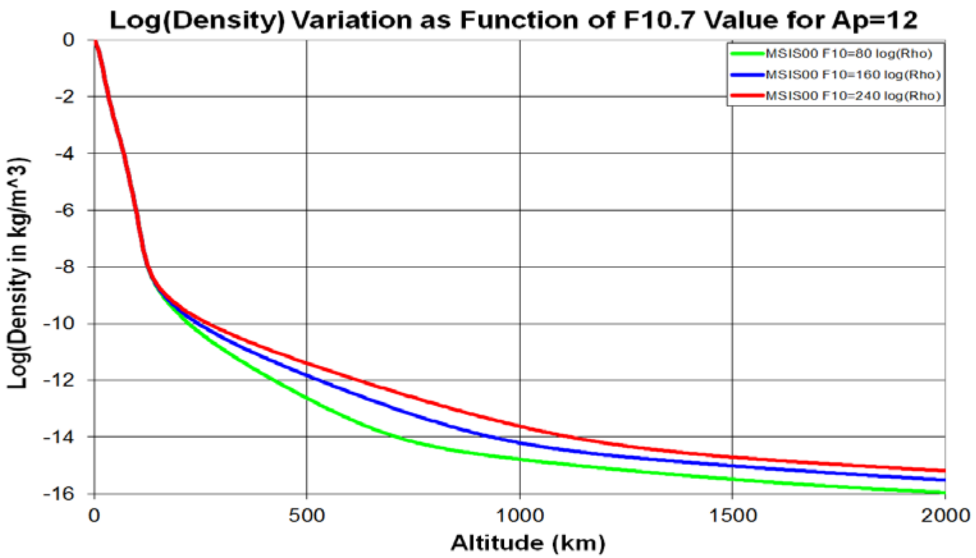
Atmosphere Model	CPU sec 0<Alt<5000 km	CPU sec 0<Alt<1000 km
Exponential	0.578	0.547
Atm1962	0.829	0.828
Atm1976	0.89	0.844
Jacchia 1971	7.906	9.468
MSIS 2000	81.547	121.875
JB2006	395.266	319.704

Model, Solar & Geomag Impact on Density

- Selected atmosphere model and profiles for Radio Flux and geomagnetic activity impact density predictions
- Newer models ~ better

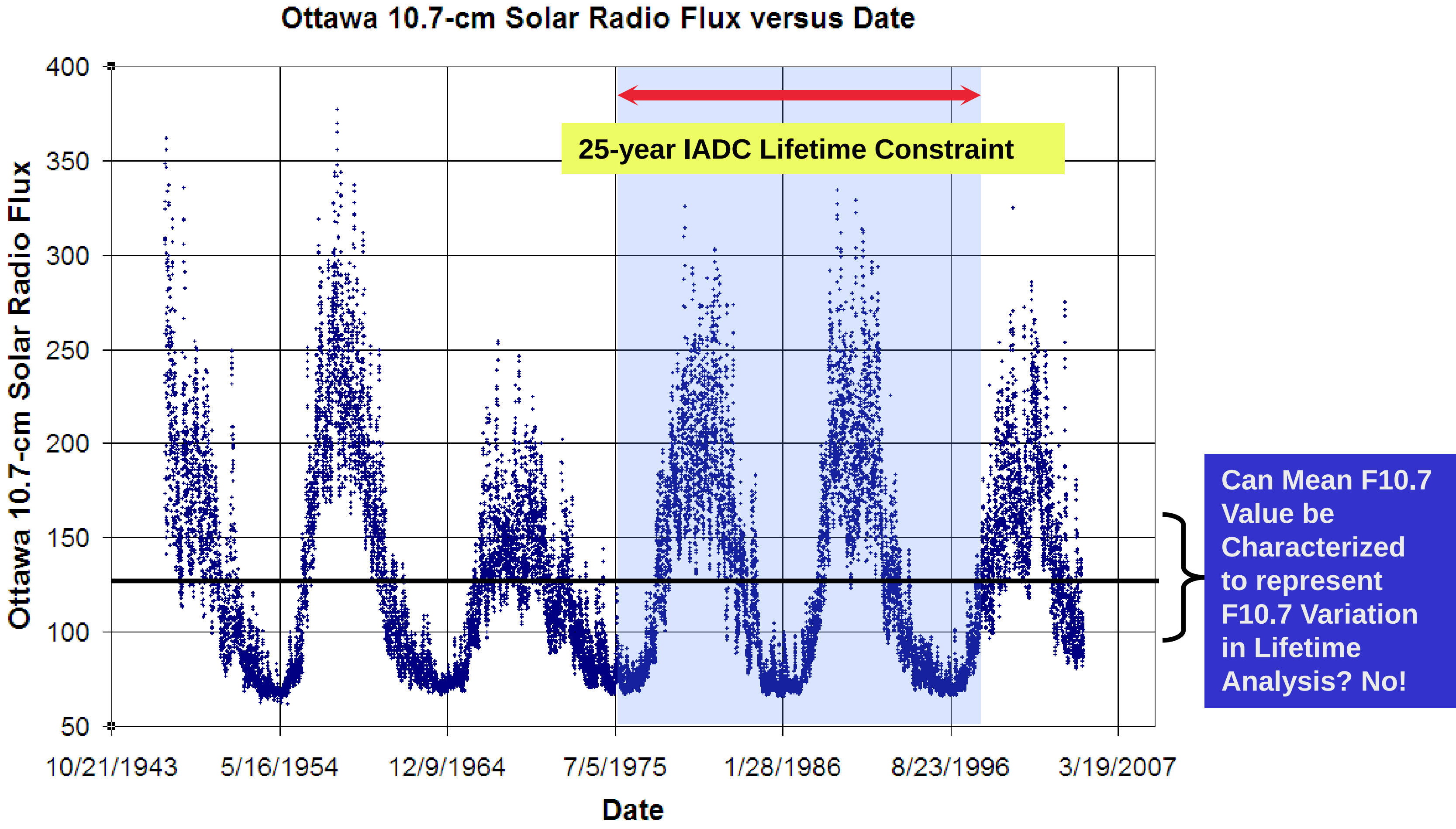






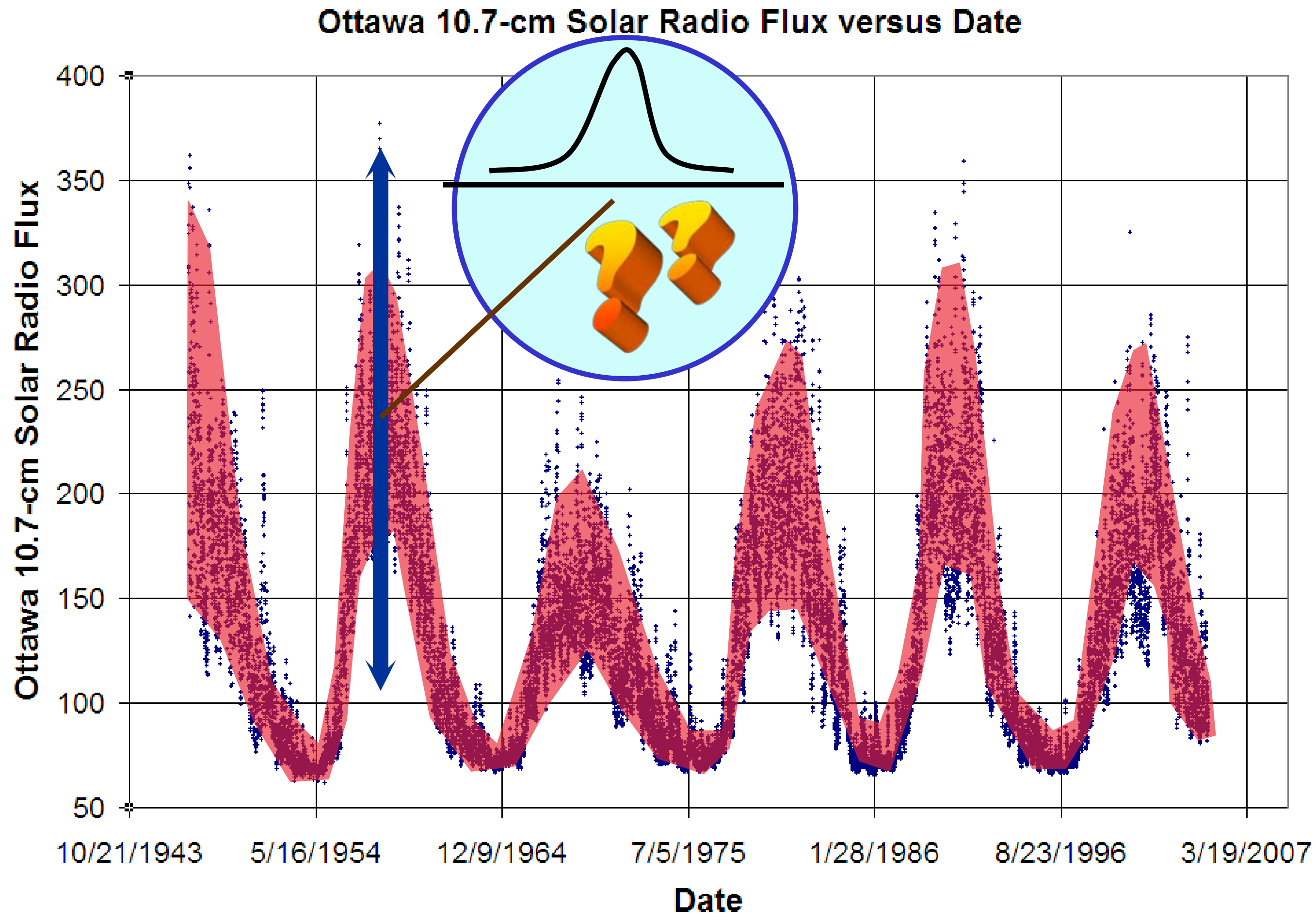
Space Weather Considerations for Orbit Lifetime

- Examination of all available F10.7 Solar Radio Flux Index (1947 – 2006) illustrates unpredictable nature of values



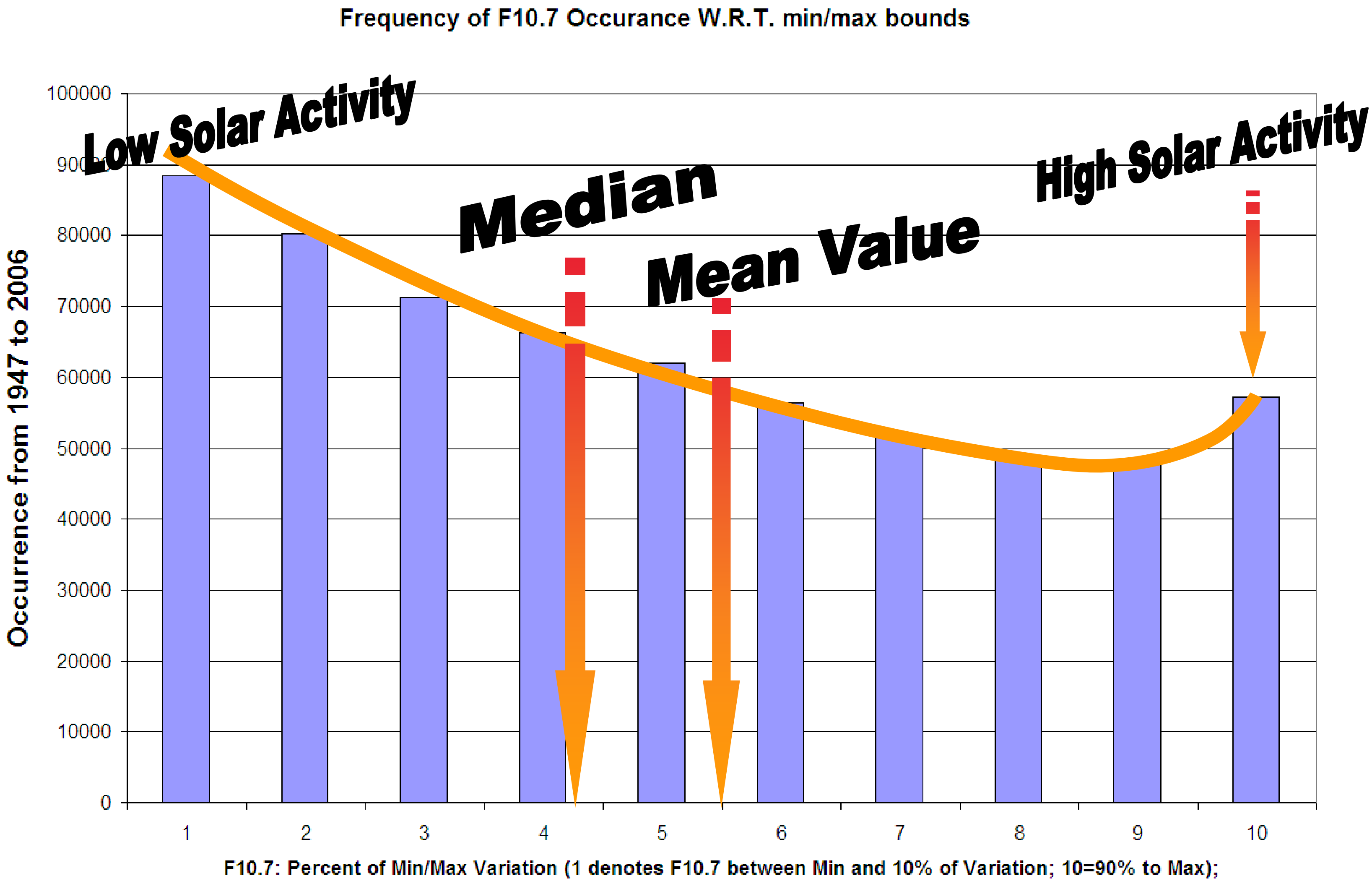
Background: F10.7 Bounds vs Time

- F10.7 values range from floating minimum and maximum bounds
- What about the distribution of F10.7 values across these bounds?



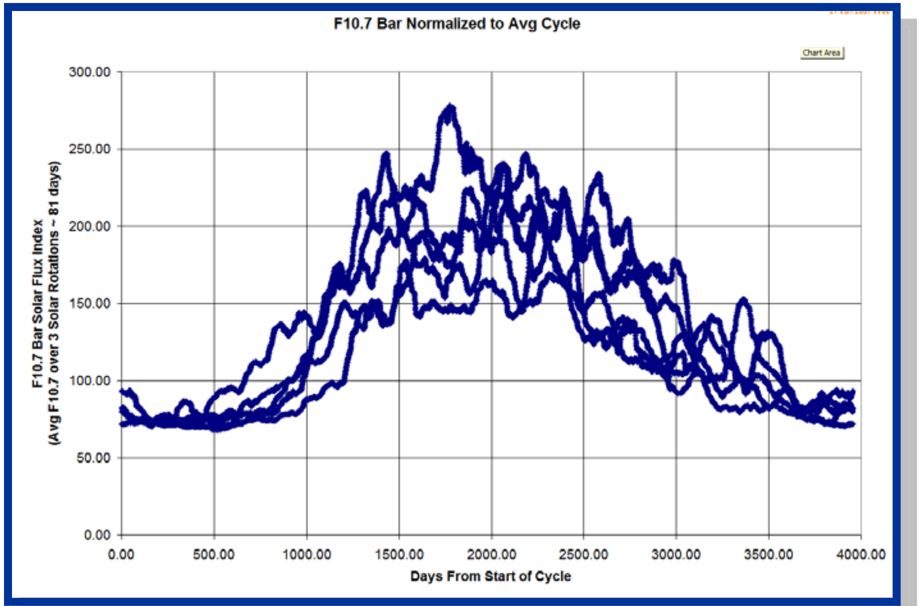
Background: F10.7 Distribution

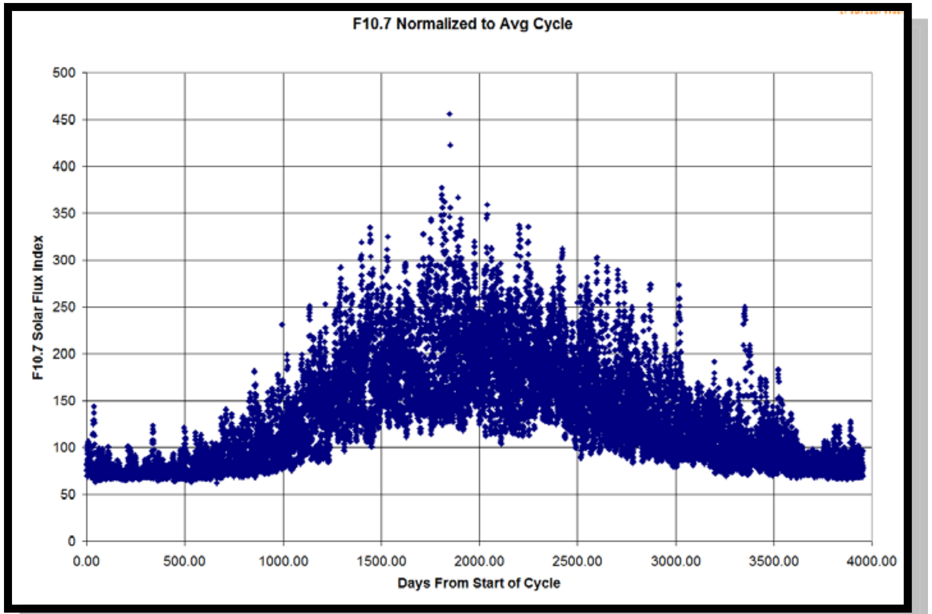
- F10.7 values not distributed from low to high in even fashion



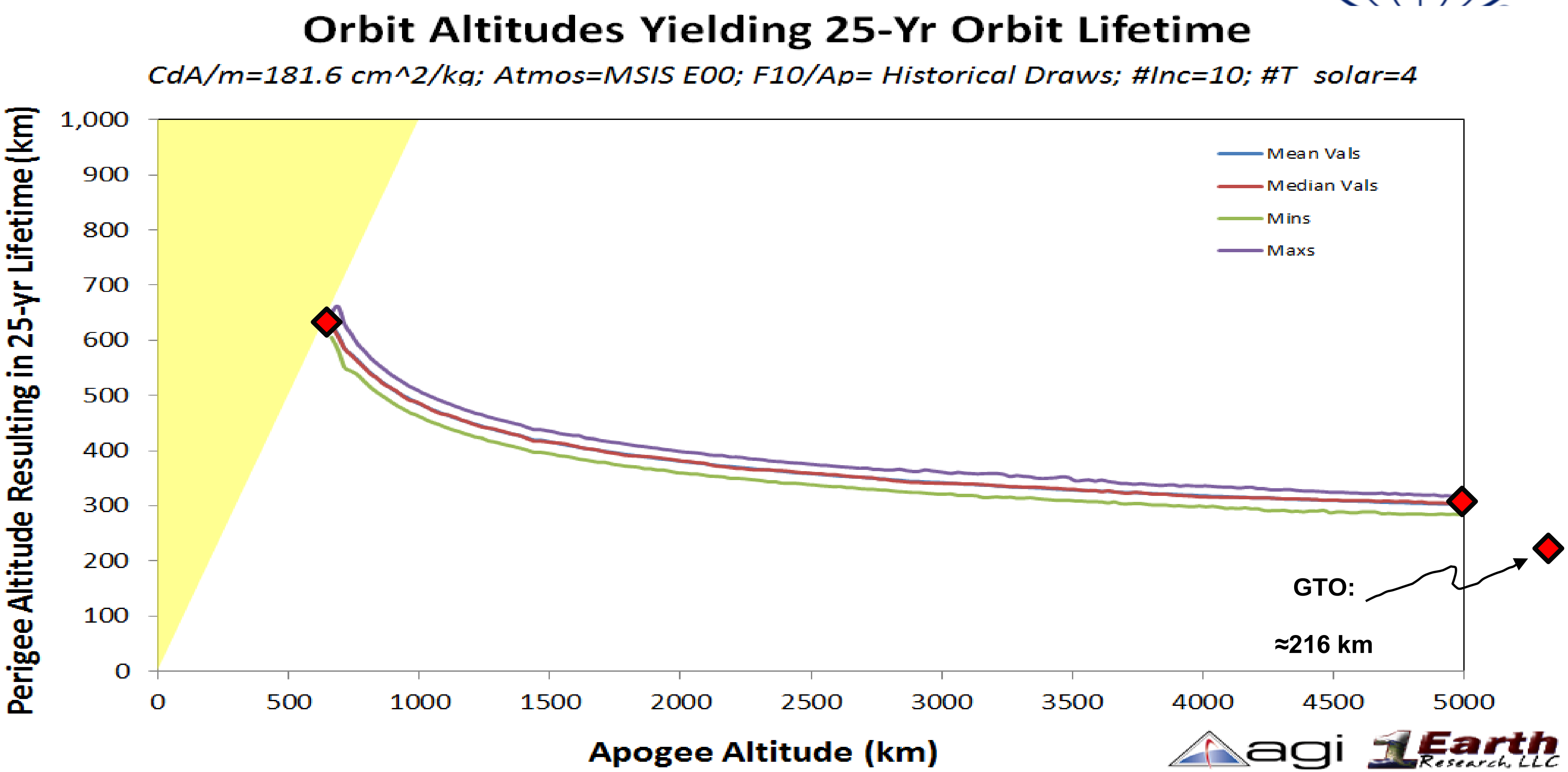
Space Weather Impacts on Orbit Lifetime

- Life=f(I.C., cycle time, β, **<u>solar/geomag activity</u>**)
- Modeled solar/geomag activity using recorded data random draw approach
  - Facilitates computation of median orbit lifetime





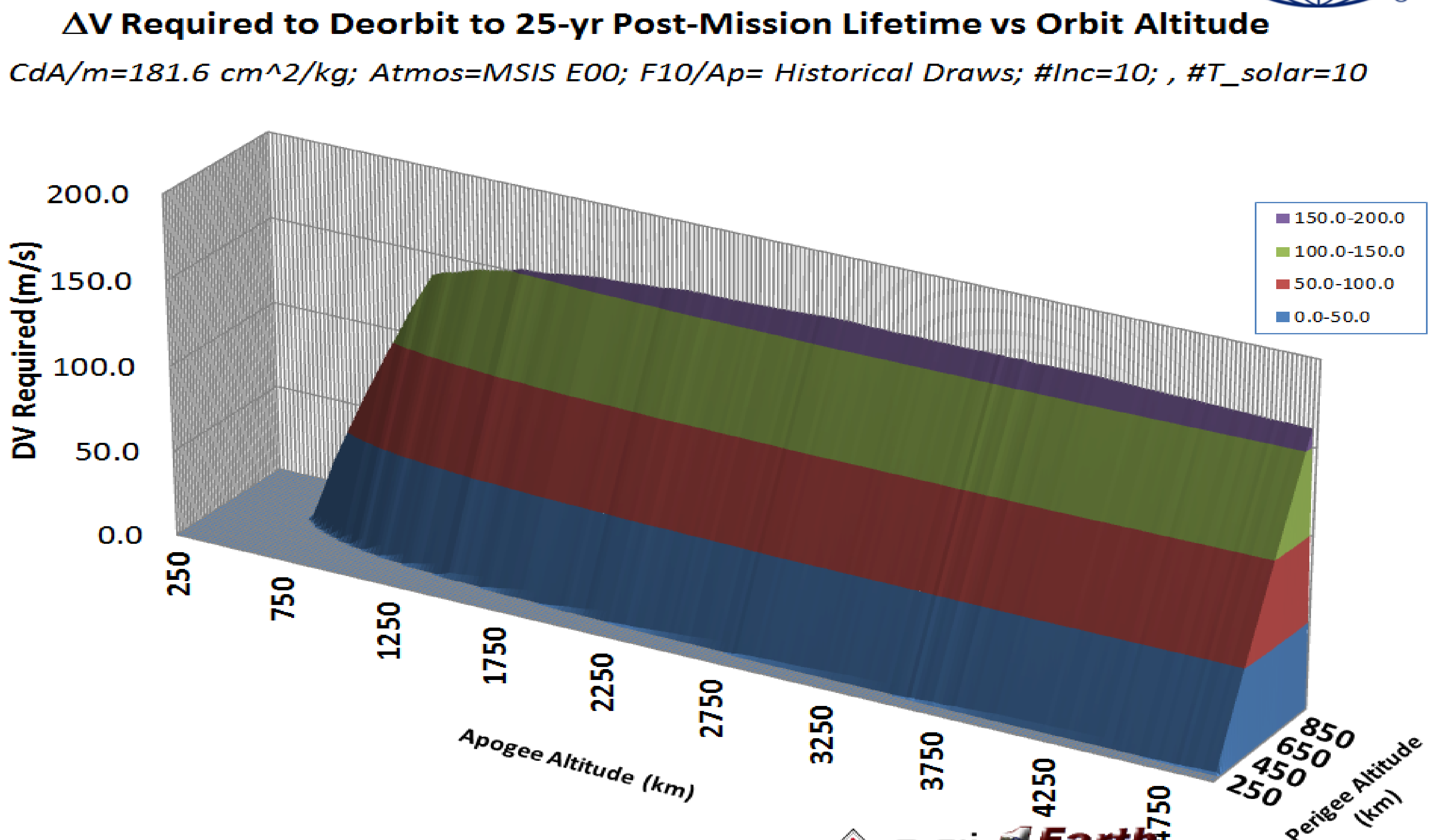
Orbits with 25-Year Life



Lifetime sensitivity to altitude in the LEO- and GEO-protected regions:

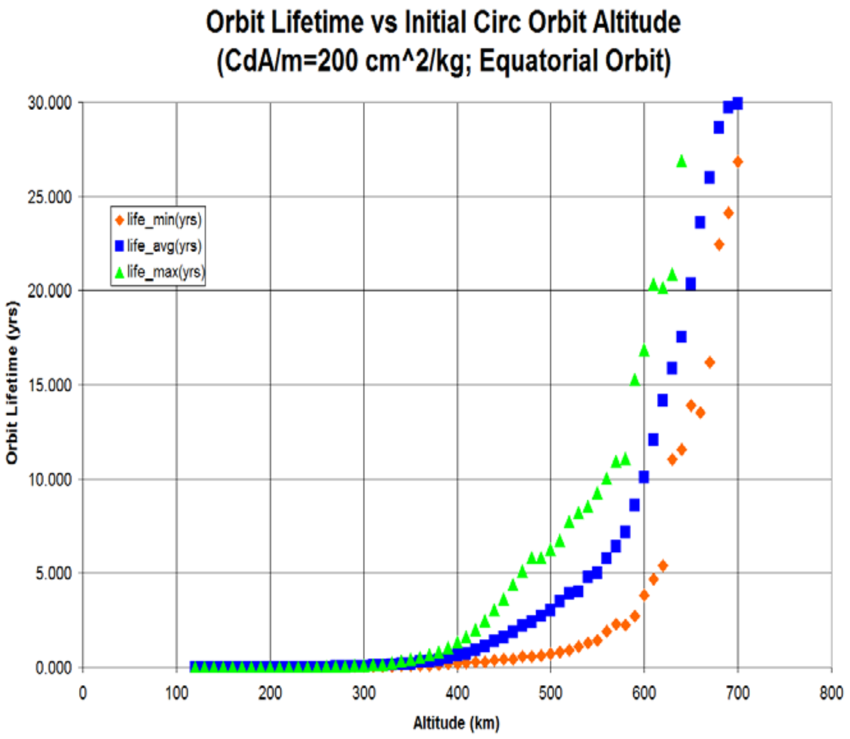
Circular Orbits at ≈640 km altitude experience a median orbit lifetime of 25 years, with perigee altitude decreasing monotonically for highly-elliptical orbits (≈300 at Ha=5000km and ≈215 km for GTOs)

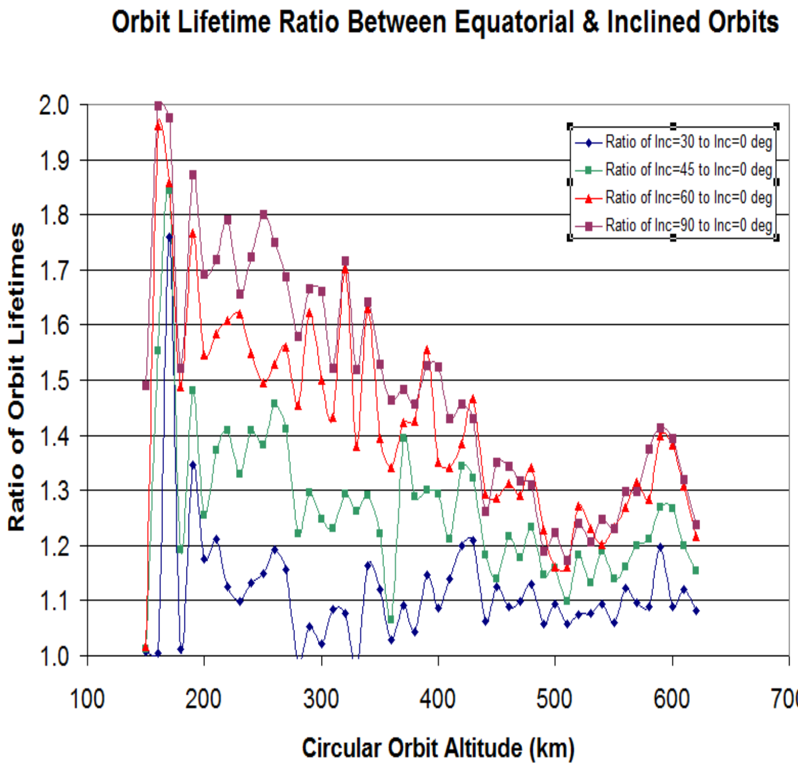
Energy Requirements to 25-Year Demise



Analysis Findings: Altitude & Inclination Studies

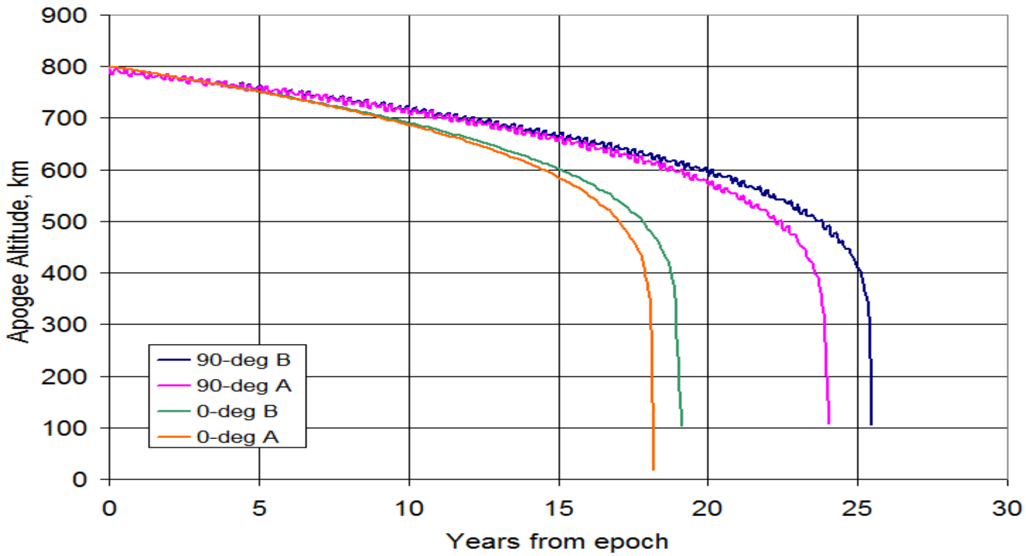
- Orbit lifetime dependencies upon orbit altitude, inclination:
  - Highly-inclined orbits have almost twice the orbit lifetime of equatorial orbits above 160 km.
  - Polar orbits spend less time in sub-solar (higher density) regions), and height above an oblate earth is higher at poles.





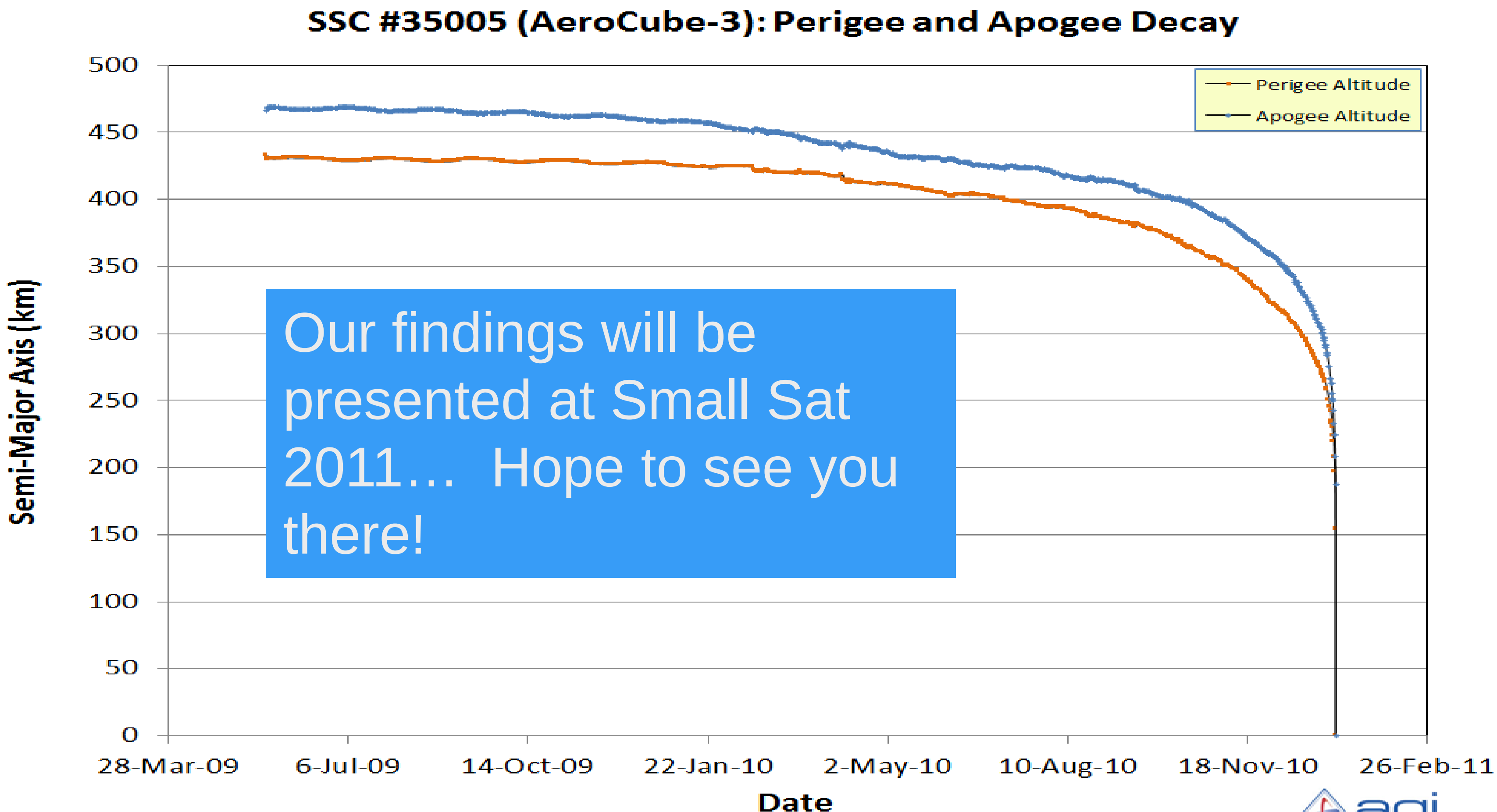
Impact of Thermospheric Cooling

- Recent satellite measurements and theoretical models indicate that the thermosphere is cooling off leading to lower densities
- Thermosphere (80 - 500 km) is a key part of LEO 25-yr lifetime regime
- Increased CO2 at alt < 30km causing upper atmosphere to cool down
- Examined orbit lifetime increase due to thermospheric cooling for an equatorial and polar orbit
  - Studies indicate that orbit lifetime may increase by 6 - 7%



Orbit Decay Profile

- For illustration, we show the AeroCube-3 decay
  - Has long-duration to permit estimation of avg ballistic coeff.



Our findings will be presented at Small Sat 2011… Hope to see you there!