Thermospheric Space Weather and its Impacts to LEO Satellite Operations

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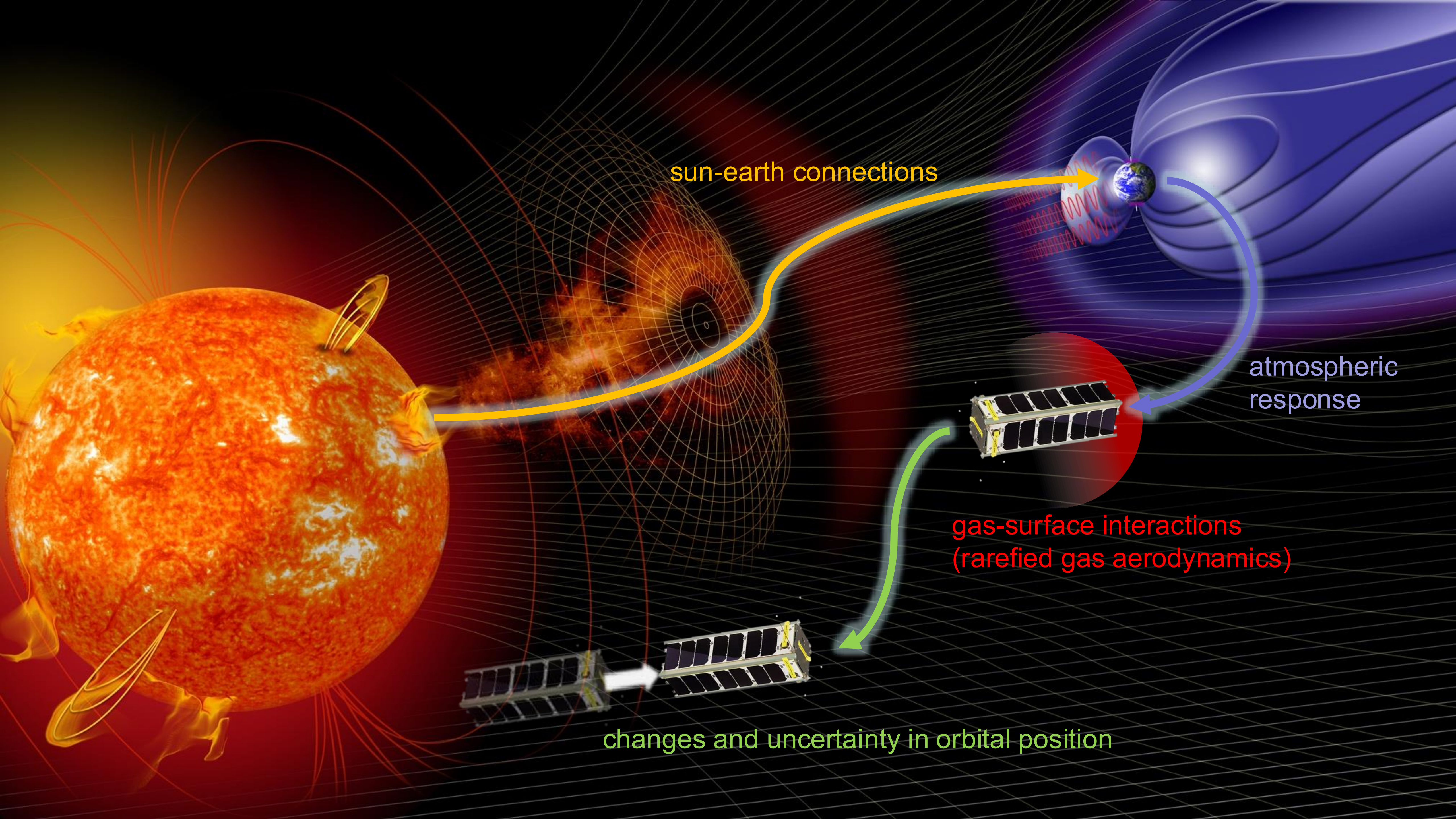
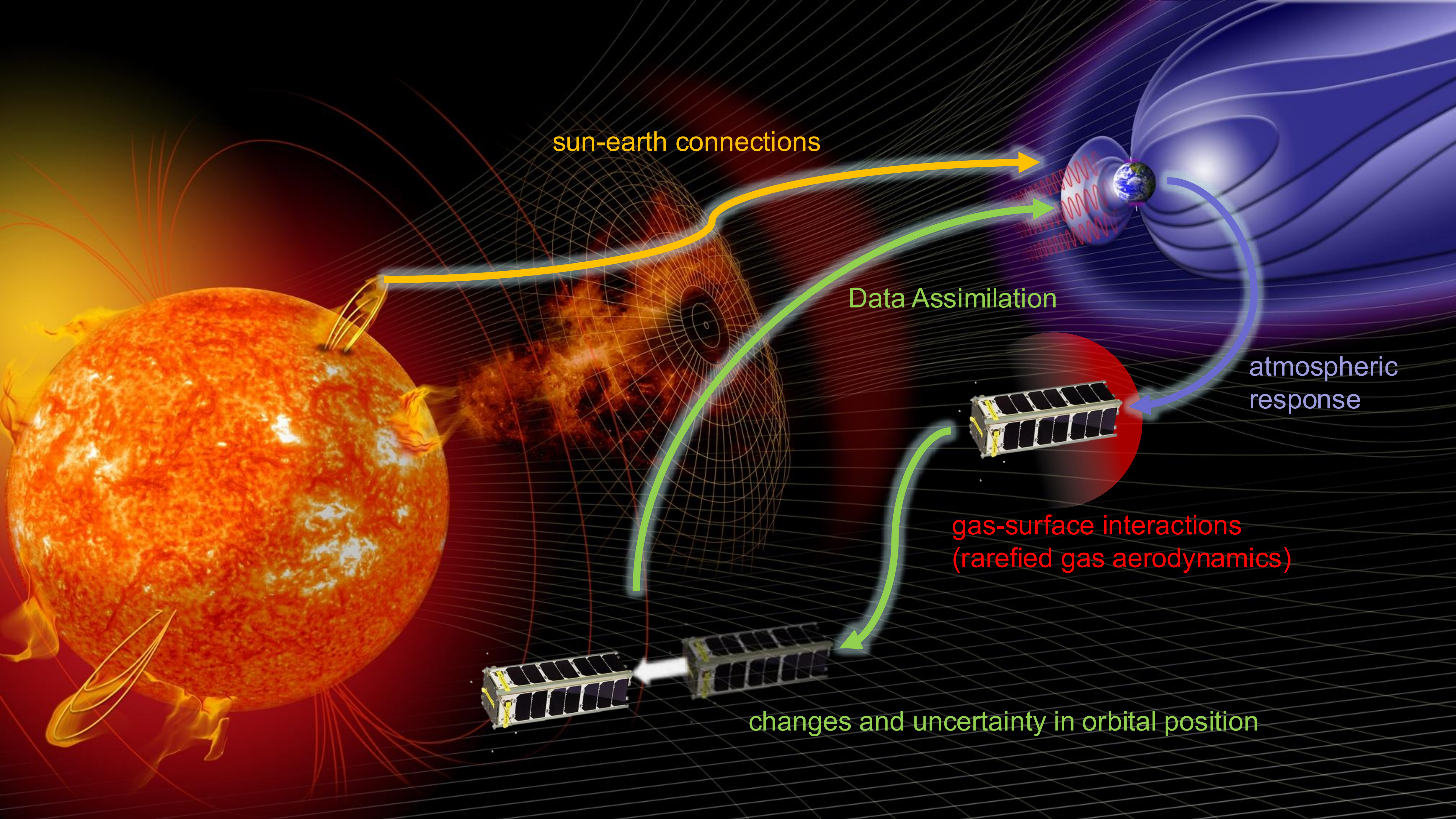
NASA 5th Eddy Cross Disciplinary Symposium, Boulder, CO


sun-earth connections
atmospheric
response
gas-surface interactions
(rarefied gas aerodynamics)
changes and uncertainty in orbital position


sun-earth connections
Data Assimilation
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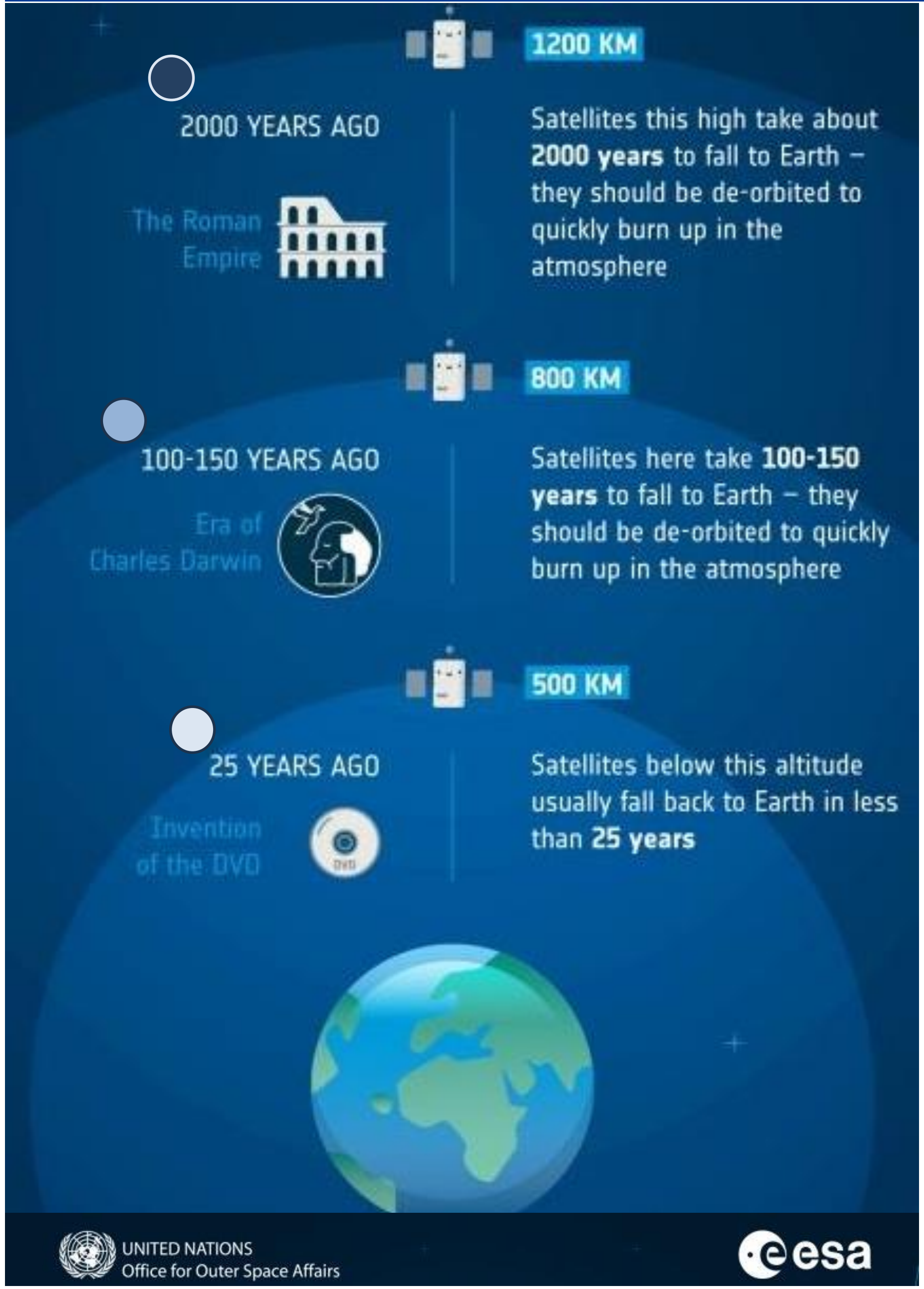
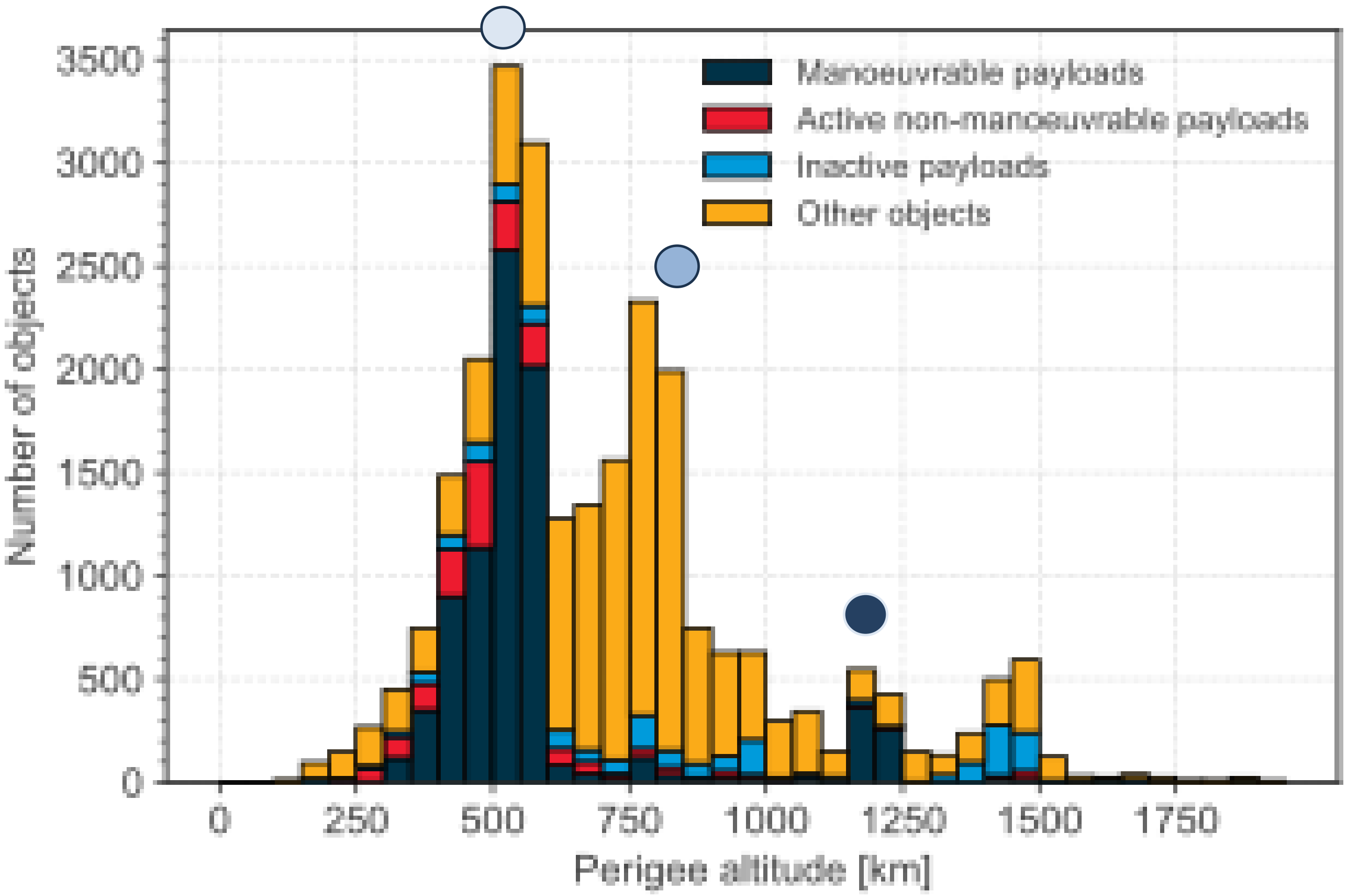
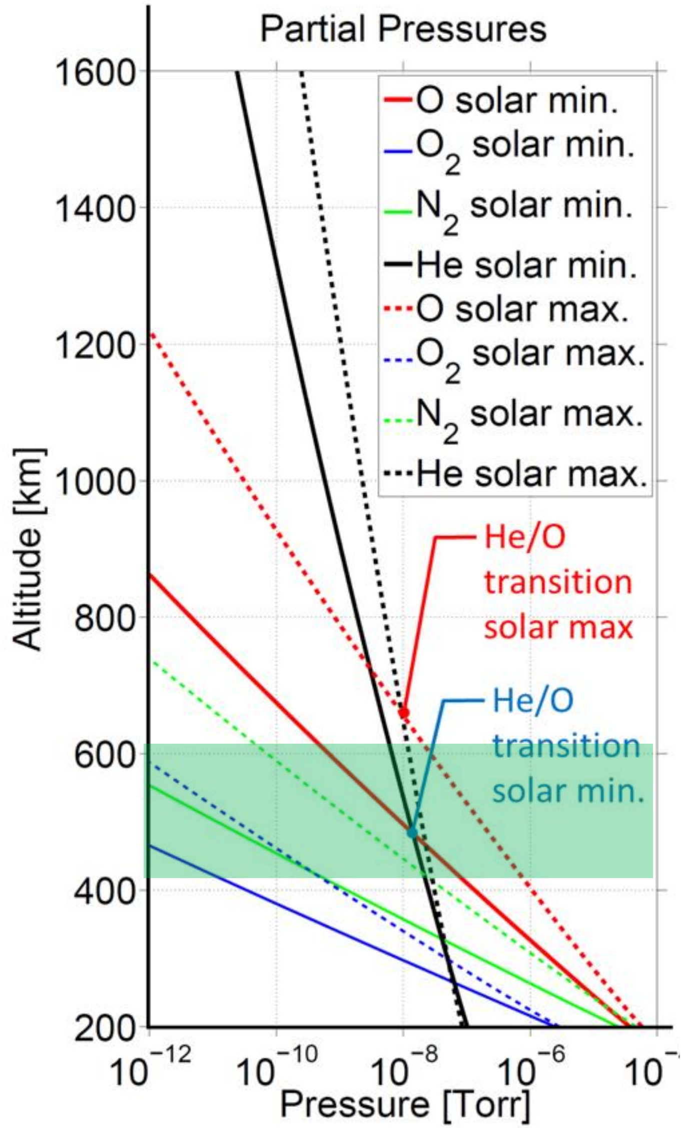
Resident Space Object Population

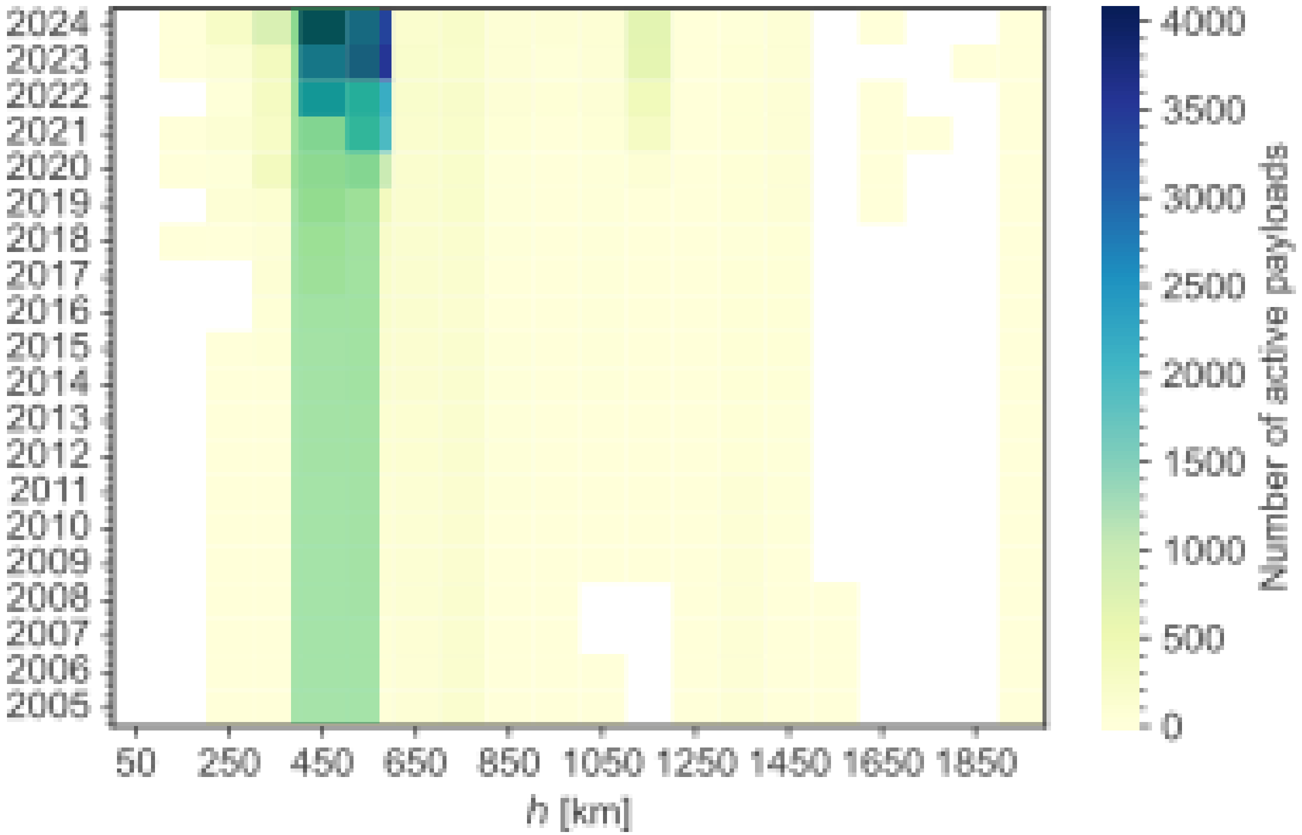




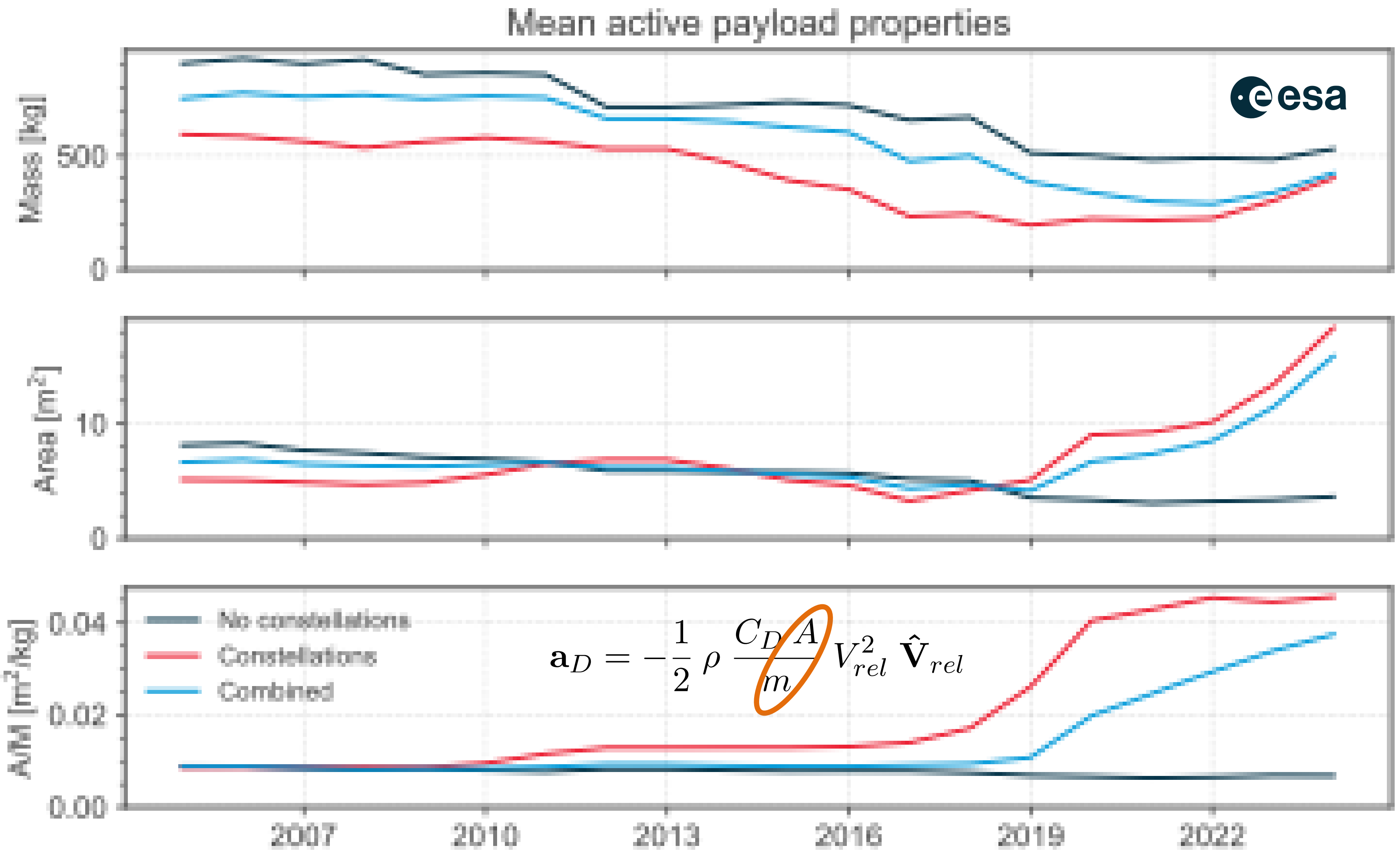
Resident Space Objects and the LEO Environment



ESA'S ANNUAL SPACE ENVIRONMENT REPORT

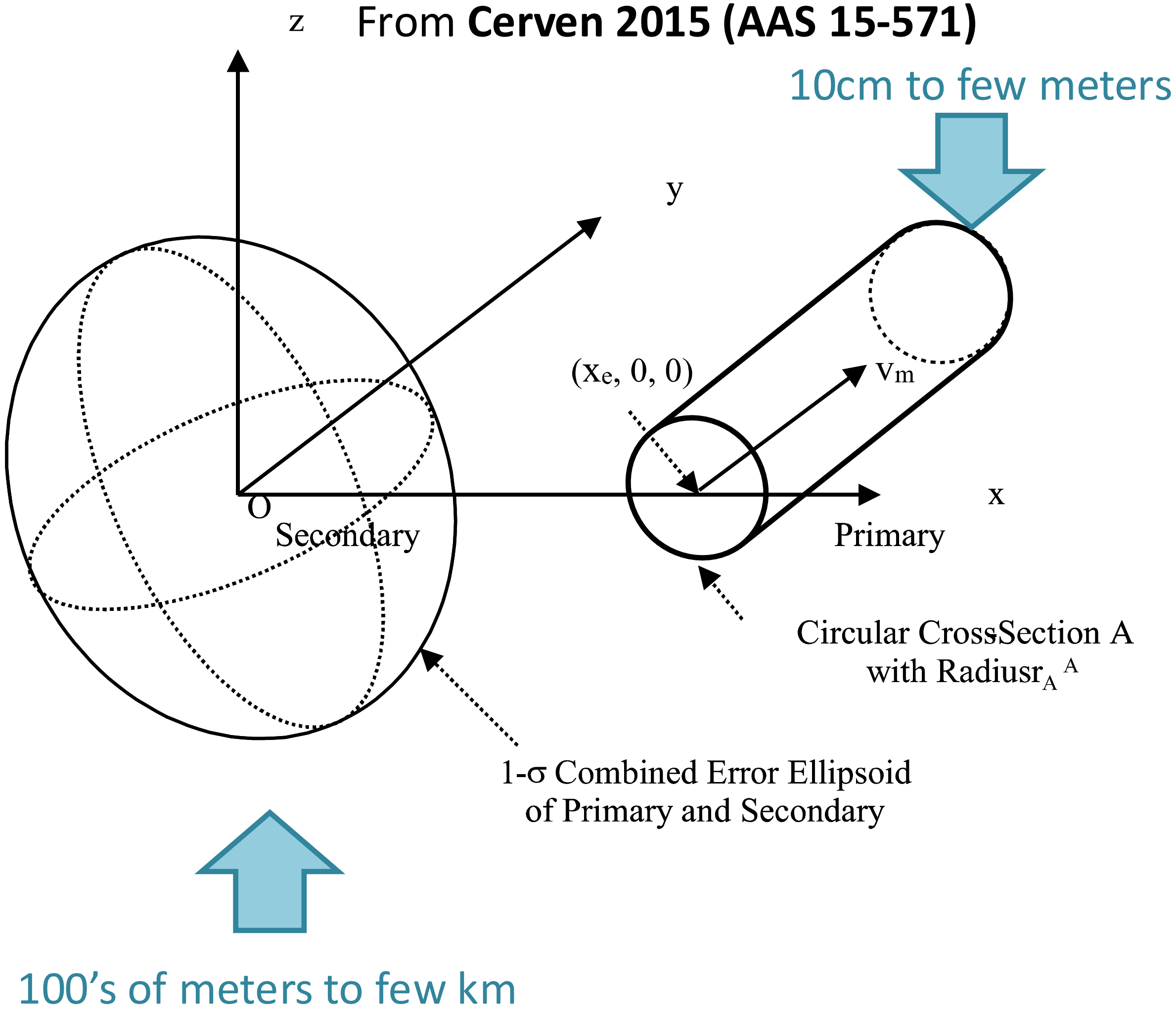


Average Properties of Active Payloads



$$\mathbf{a}_D = -\frac{1}{2}\,\rho\,\frac{C_D\,A}{m}\,V_{rel}^2\;\hat{\mathbf{V}}_{rel}$$

Predicting Collisions: Conjunction Assessment



From **Cerven 2015 (AAS 15-571)**

$$Pc = \iiint_V \frac{1}{\sqrt{(2\pi)^3 |C|}} e^{-\frac{1}{2}\mathbf{r}^T C^{-1} \mathbf{r}} \, dx \, dy \, dz$$

- Collision Probabilities (P_c) determine the threshold for operational action
- General Assumptions
  - Two spheres
  - Gaussian probability distributions
- P_c is the "integral of the combined positional **error distribution** (C) within the tube swept out by the relative motion of the primary with respect to the secondary (v_m) given a combined hard body radius (r_a)" (Cerven 2015)

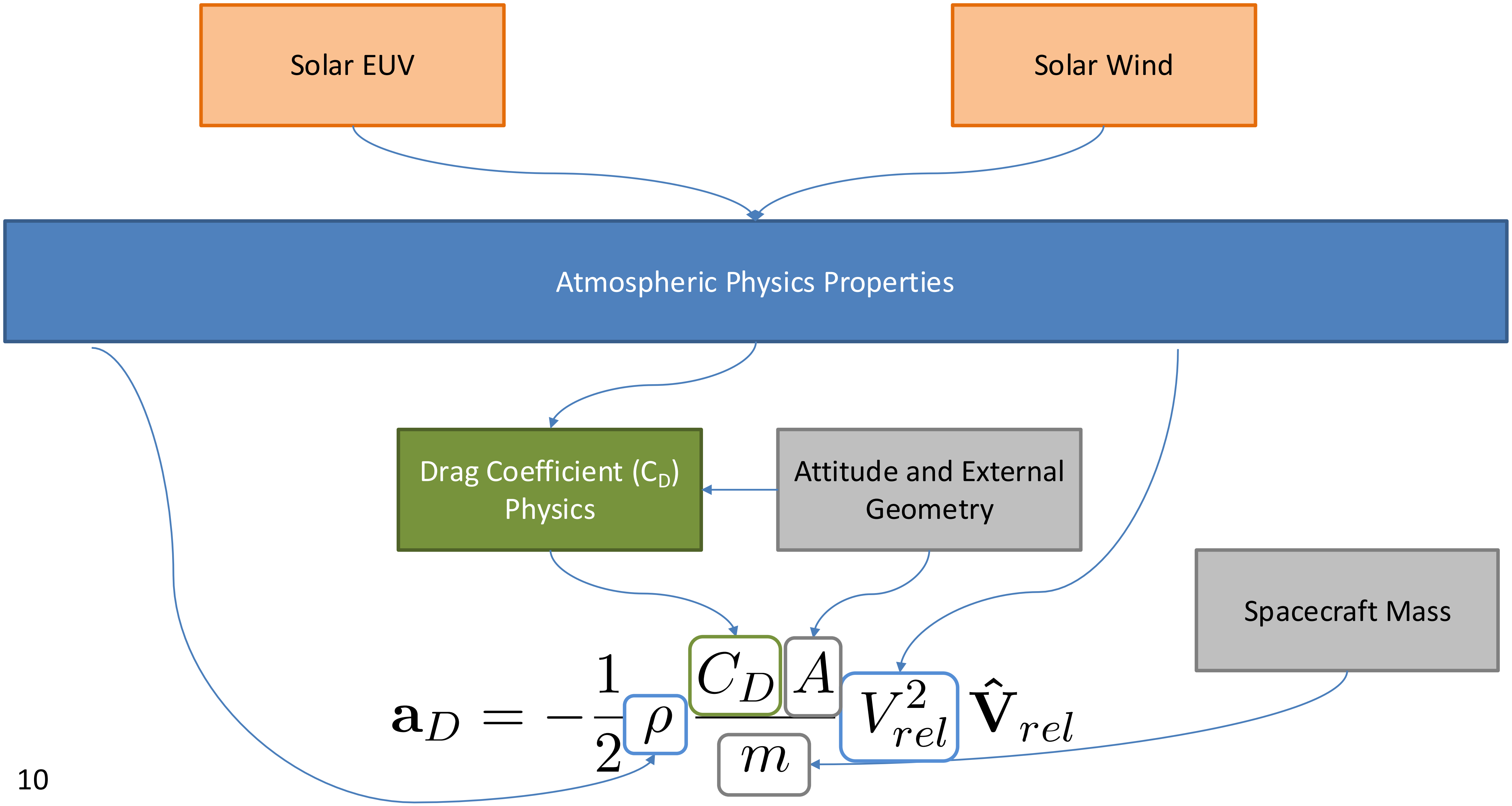
Conjunction Assessment

- To do well at CA
  - Need accurate initial state vector (position and velocity)
  - Need accurate orbit forecast (24-72 hrs)
  - Need for uncertainty specification (Hejduk and Snow 2018)
- Satellite drag has a significant impact on P_c of LEO objects via orbital forecasting
  - Combined positional probability distribution
  - Estimate of relative positions
- With the growing numbers of RSO's, number of warnings based on Pc is starting to be "not actionable"

Aerodynamic Drag Acceleration

$$\mathbf{a}_D = -\frac{1}{2}\,\rho\,\frac{C_D\,A}{m}\,V_{rel}^2\,\hat{\mathbf{V}}_{rel}$$

Aerodynamic Drag Acceleration



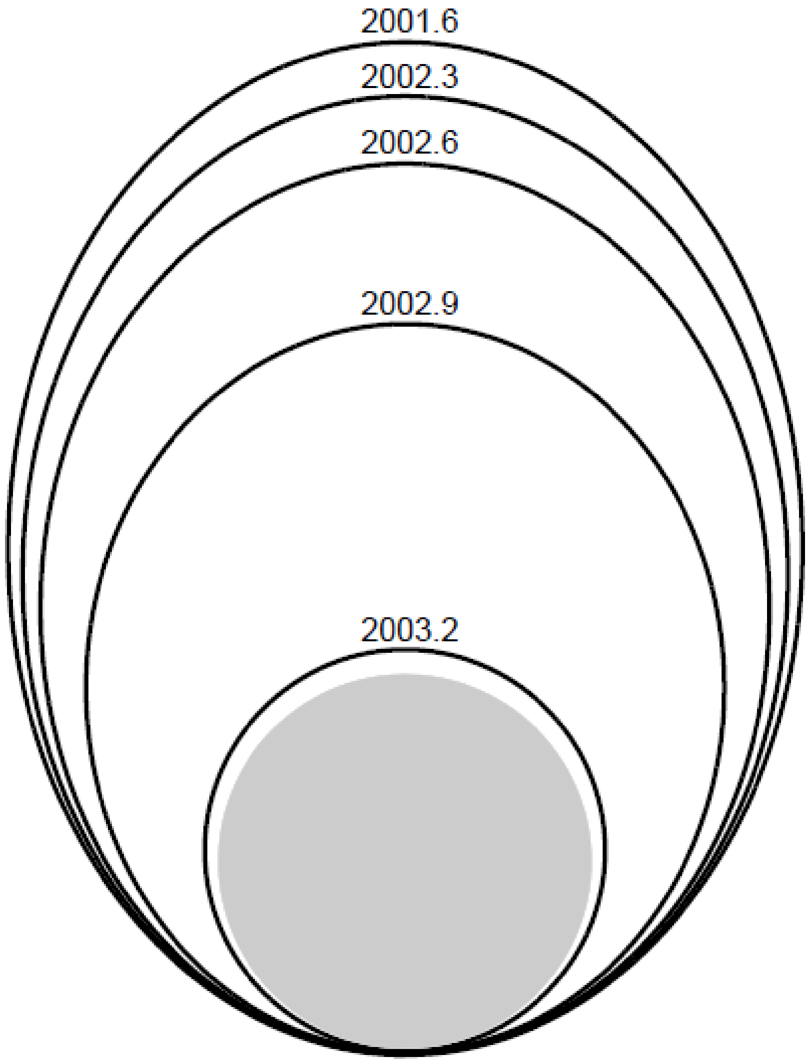
Aerodynamic Drag Scaling

$$\mathbf{a}_D = -\frac{1}{2}\,\rho\,\frac{C_D\,A}{m}\,V_{rel}^2\,\hat{\mathbf{V}}_{rel}$$

	Air Density (400 km altitude)	A/m	C_D	V^2	a_D (F_D)	Dist. Traversed in 90 minutes	Work Done by Drag (90 minutes)	Change in In-Track Position after 24 hours (vs. no drag)
LEO satellite (solar max)	2.7 x 10^{-12} kg/m^3	0.01 m^2/kg	2.5	6.4x10^7 m^2/s^2	2.12x10^{-6} m/s^2 **(0.02 μg)**	**4.3x10^7 m**	**9,120 J**	160 km (21 seconds)
Bike Ride (10 mph*)	1.0 kg/m^3	0.005 m^2/kg	0.8	20 m^2/s^2	0.04 m/s^2 **(4000 μg)**	**2.4x10^4 m**	**76,800 J**	-

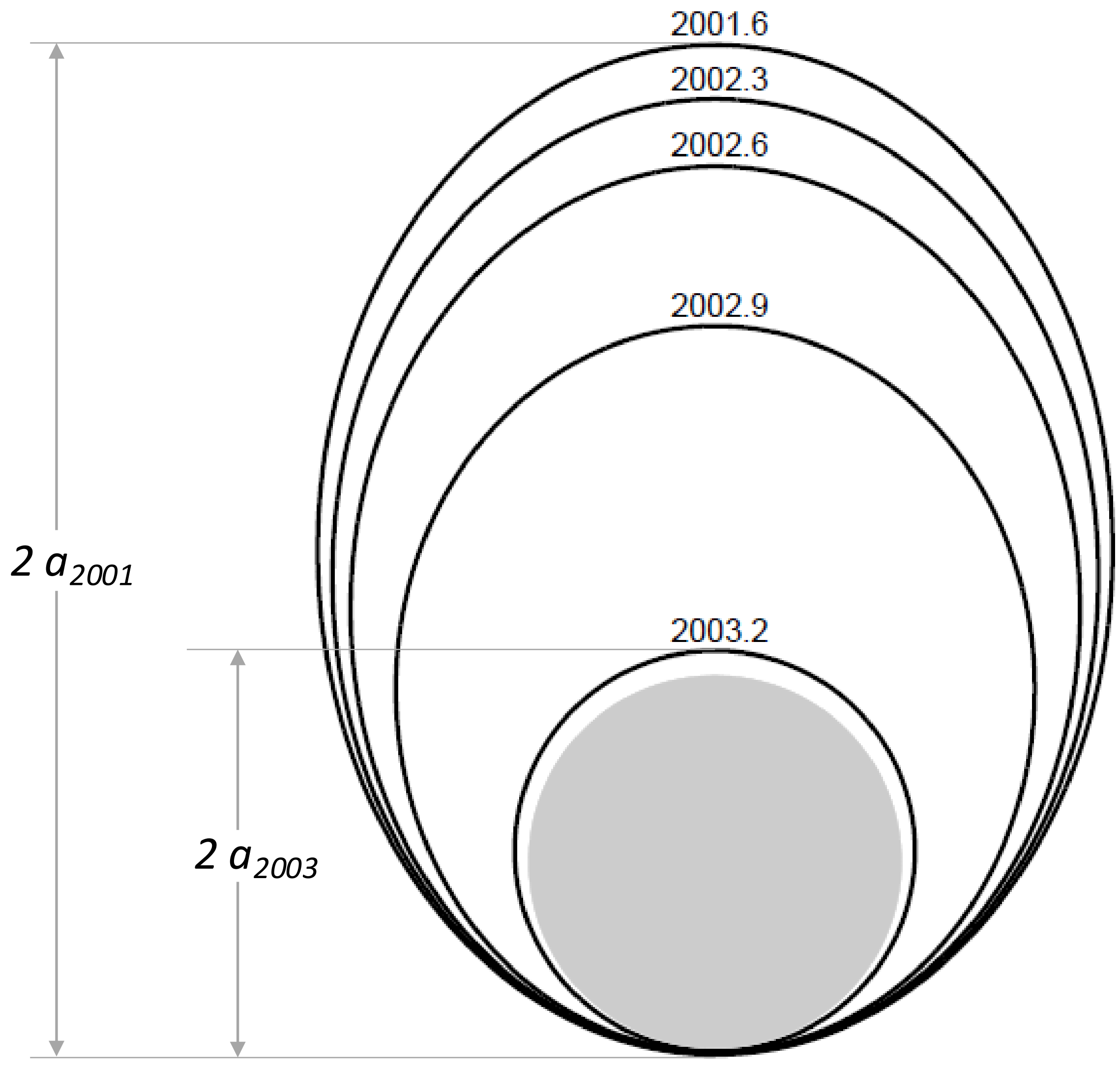
* … or 5 mph ground speed with 5 mph headwind

Thermospheric Influence on Satellite Orbits



$$\mathbf{a}_D = -\frac{1}{2}\,\rho\,\frac{C_D\,A}{m}\,V_{rel}^2\,\hat{\mathbf{V}}_{rel}$$

Thermospheric Influence on Satellite Orbits



Energy

$$E = \frac{-GmM}{2a}$$

Semi-major axis and orbital period

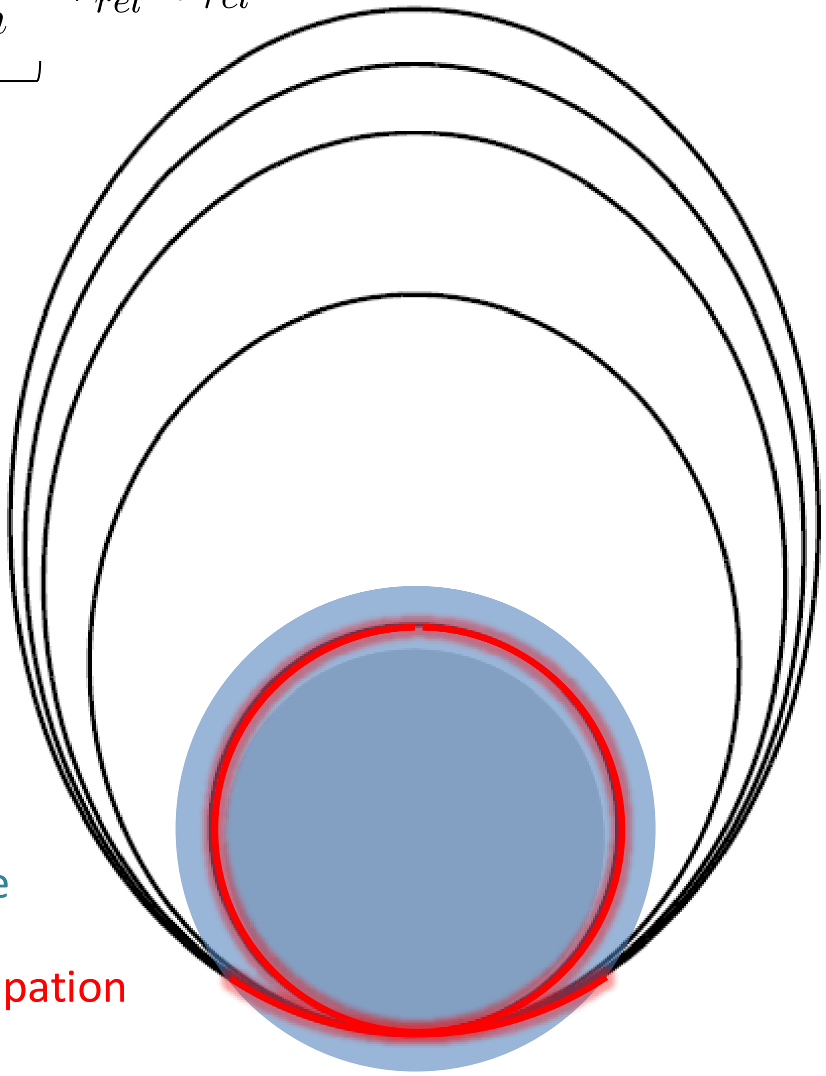
$$a^3 \propto P^2,$$

Mean-motion

$$n = \frac{2\pi}{P}$$

Thermospheric Influence on Satellite Orbits

$$\mathbf{a}_D = -\frac{1}{2}\,\rho\,\underbrace{\frac{C_D\,A}{m}}_{B}\,V_{rel}^2\,\hat{\mathbf{V}}_{rel}$$



Work done by aerodynamic drag along the orbital path l

$$\frac{B}{2}\rho\left\|\vec{V}_{rel}\right\|^2 l$$

Rewriting as a line integral, and dividing by a time interval results in the Energy Dissipation Rate (EDR)

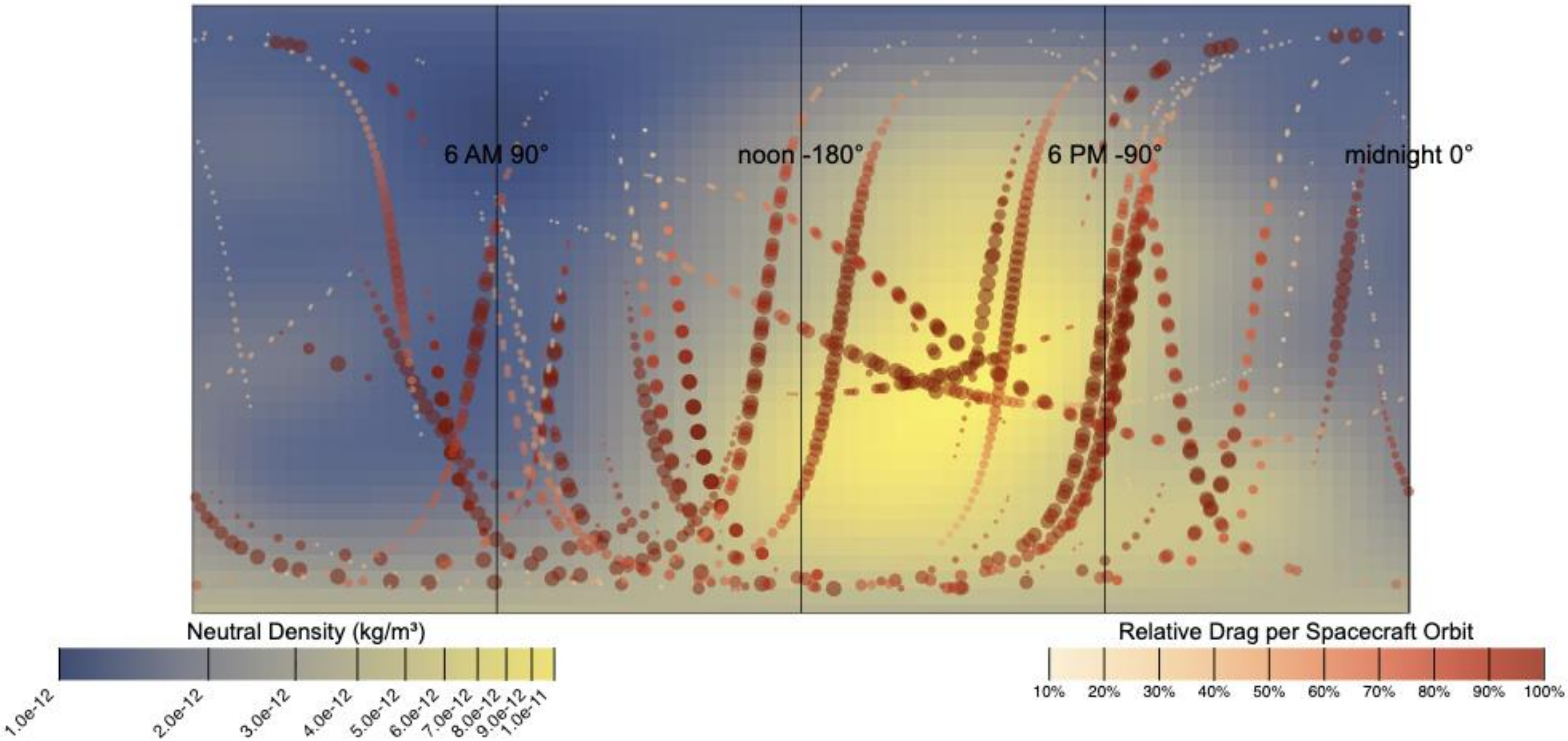
$$\dot{\varepsilon} = \frac{1}{2\Delta t}\int_{t_i}^{t_k} B\rho\left\|\vec{V}_{rel}\right\|\left(\vec{V}_{rel}\cdot\vec{V}_{sat}\right)dt$$

Assuming there are no significant in-track perturbations or that these can be removed, we can relate the EDR to change in mean-mean motion

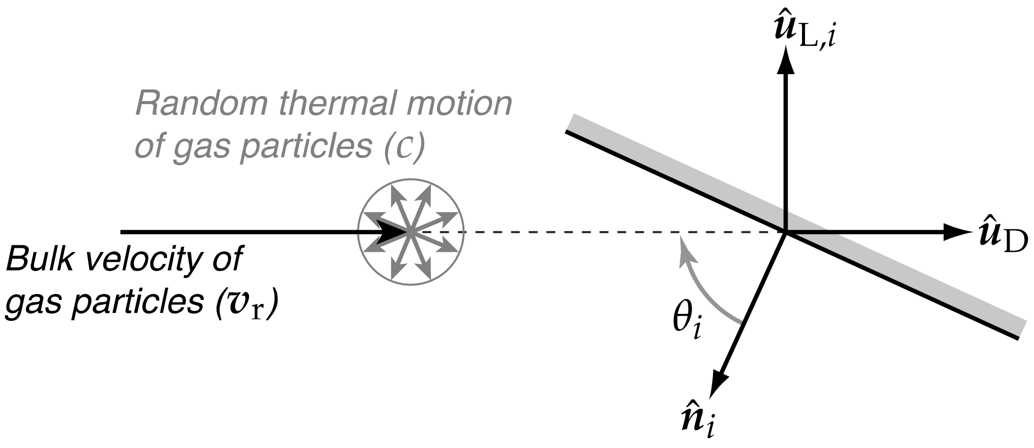
$$\dot{\varepsilon}_{\mathrm{obs}}\left(t_{ik}\right) = \frac{\Delta n}{3n_A^{1/3}\mu^{-2/3}\Delta t}$$

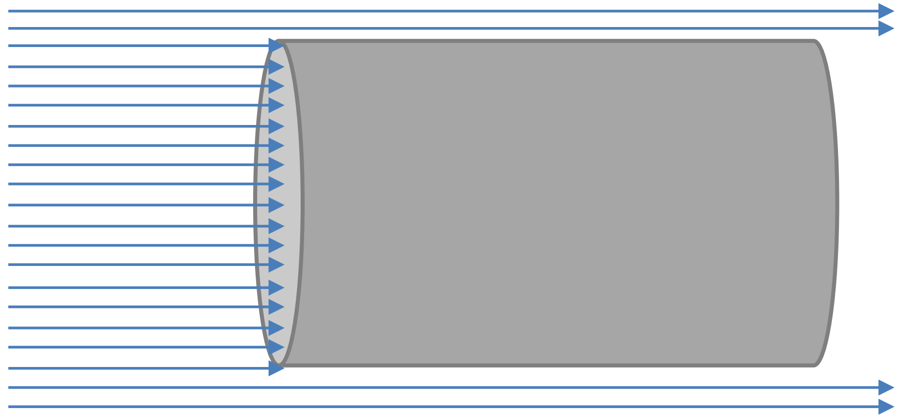
Mean motion, n, determines where the satellite will be along its orbit at any given time (in track motion)

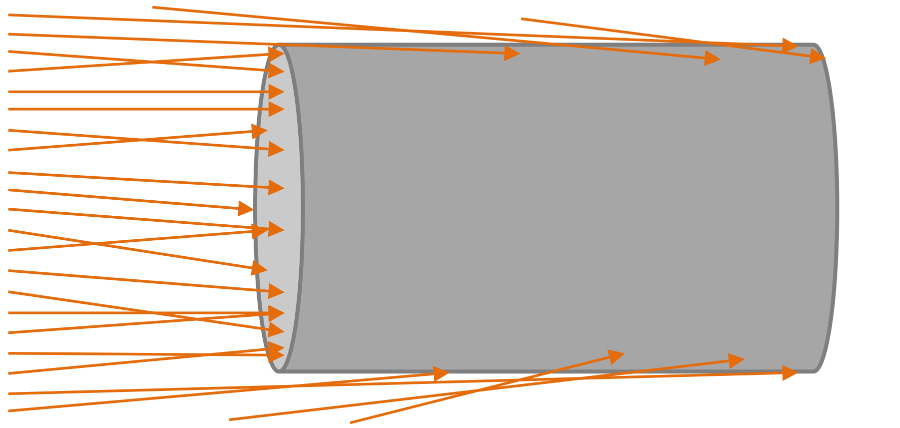
Thermospheric Influence on Satellite Orbits



Free-Stream Properties







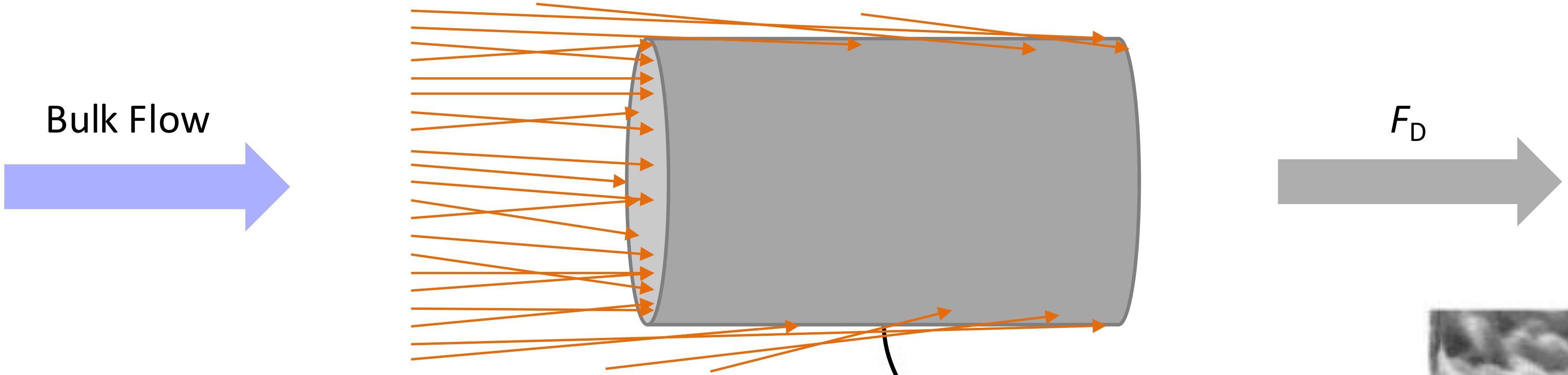
$$c_{mp,j} = \sqrt{2\frac{k}{m_j}T}\,,$$ Most probable thermal velocity

$$S_j = \frac{v_r}{c_{mp,j}}$$ Speed ratio

Doornbos, 2010

Speed ratio and shape/orientation drive the ratio of low-incidence to high-incidence interactions

Aerodynamic Forces



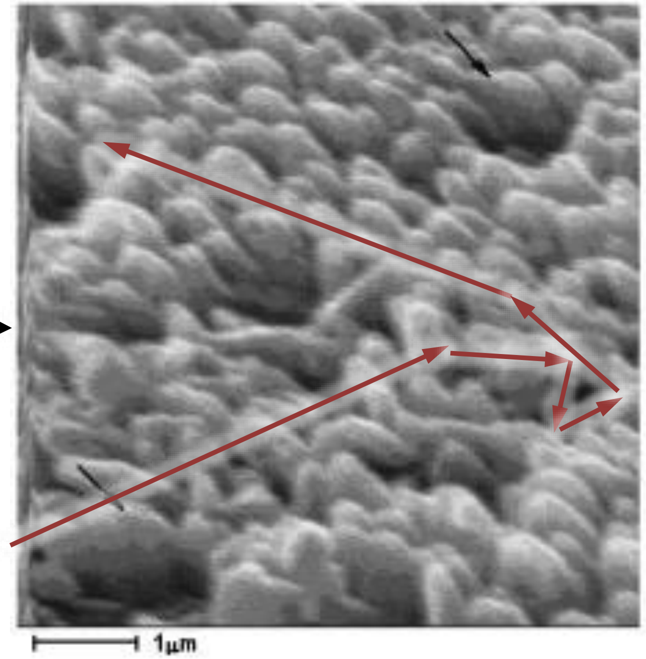
$$F_D = \frac{\Delta p}{\Delta t}$$

$$F_D \sim \{c_1(s) A n_i V_i\} \{c_2(\theta_i E_i \ldots)\, m_i V_i\}$$

$$F_D \sim c_1(s) c_2(\theta_i E_i)\, A\, \rho\, V_i^2$$

$$F_D \sim C_D\, A\, \rho\, V_i^2$$

SEM of solar panel surface (Skurat et al.)



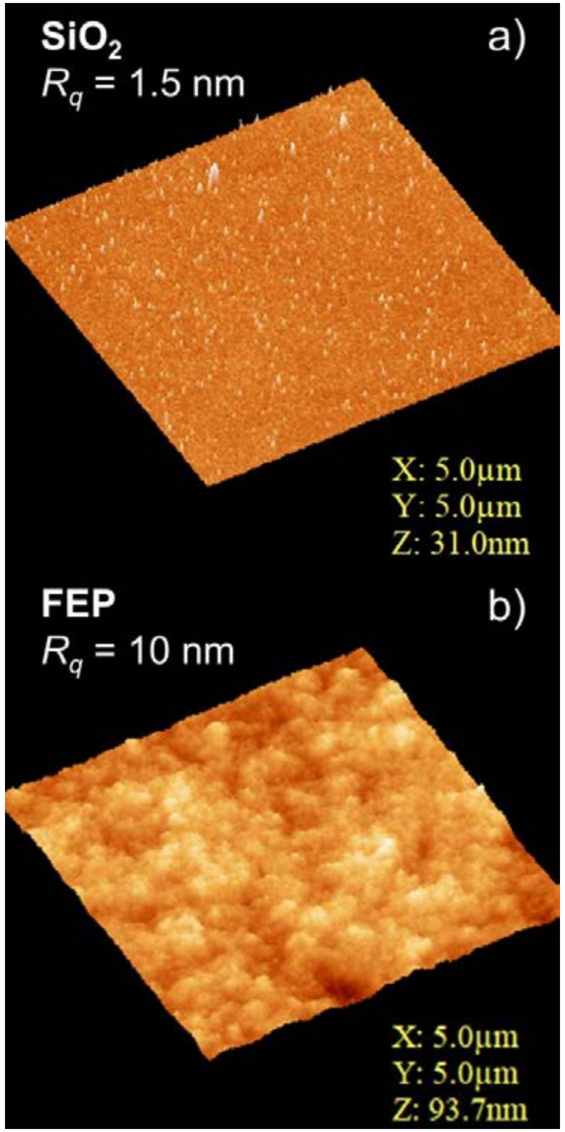
length of N_2 molecule is ~0.0003 µm

Drag Coefficients in LEO: An Emerging Picture

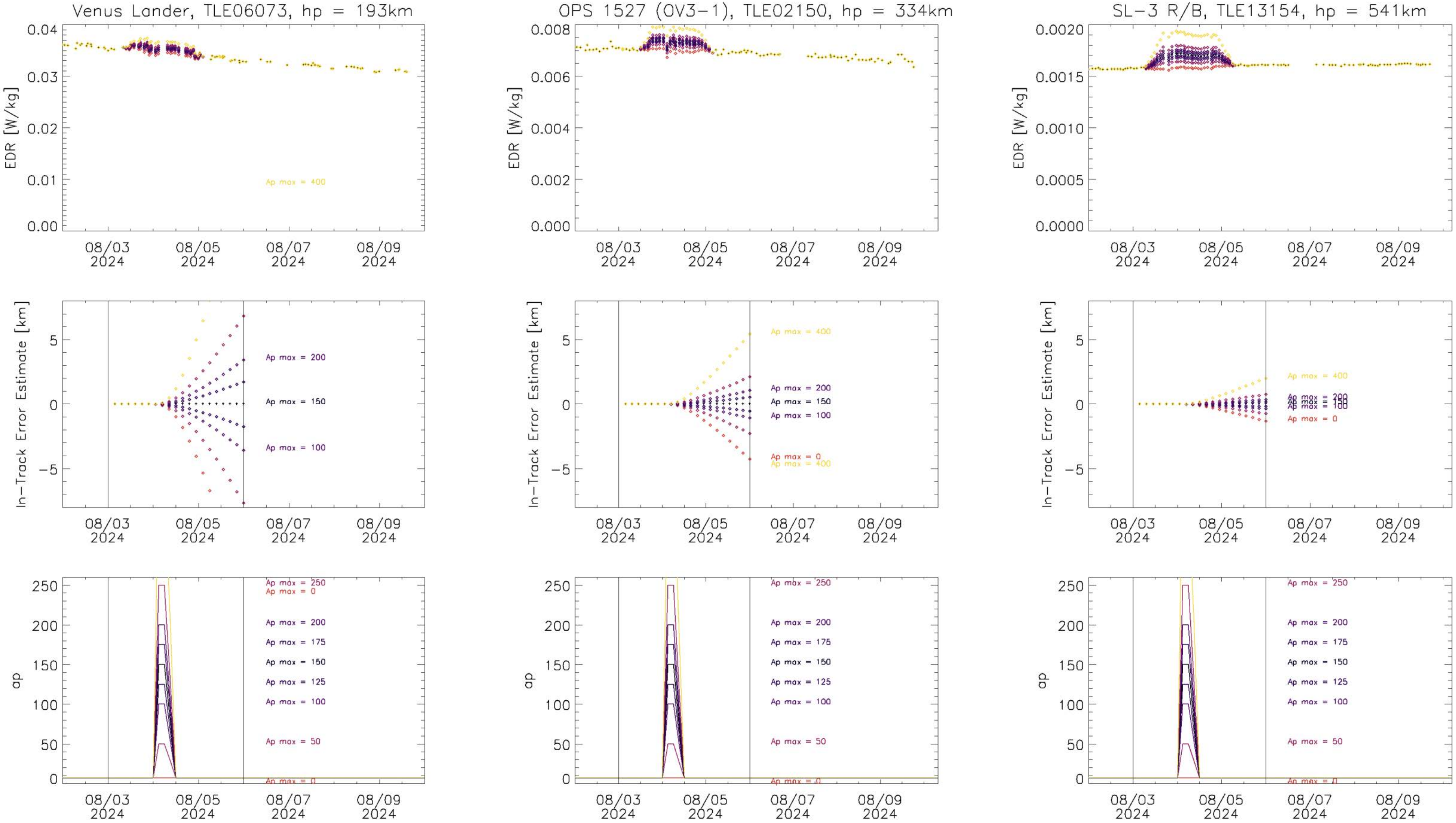
- Scattering from real "engineering" materials can be represented by a broad (backscattering) component and a quasi-specular component with incomplete tangential momentum accommodation

- The more cosine-like component is not necessarily related to thermal desorption (although adsorption/desorption is occurring)

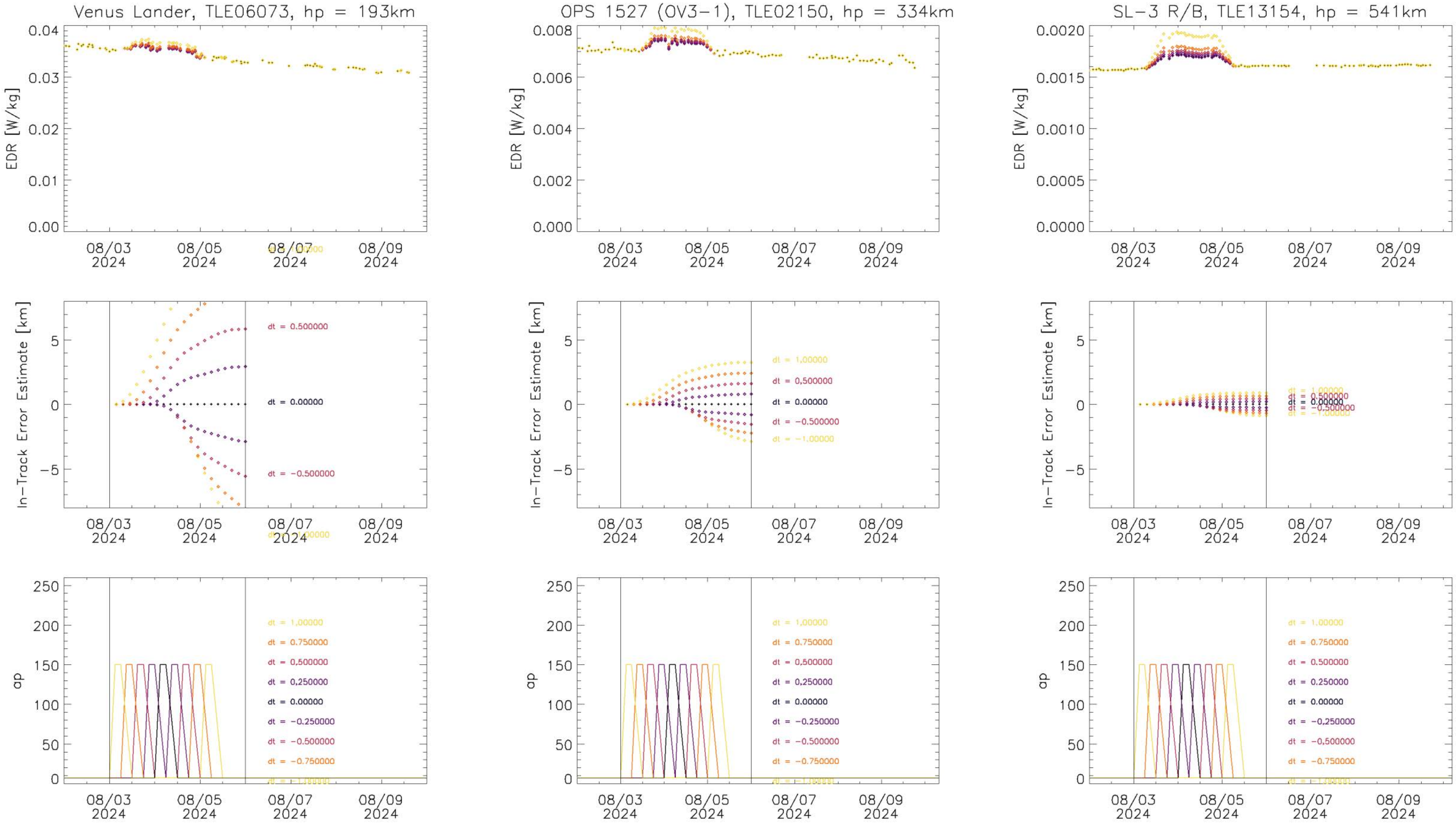
- Tangential momentum accommodation (and normal energy accommodation) appears to be higher for Helium than for AO



Thermospheric Space Weather and Orbit Prediction



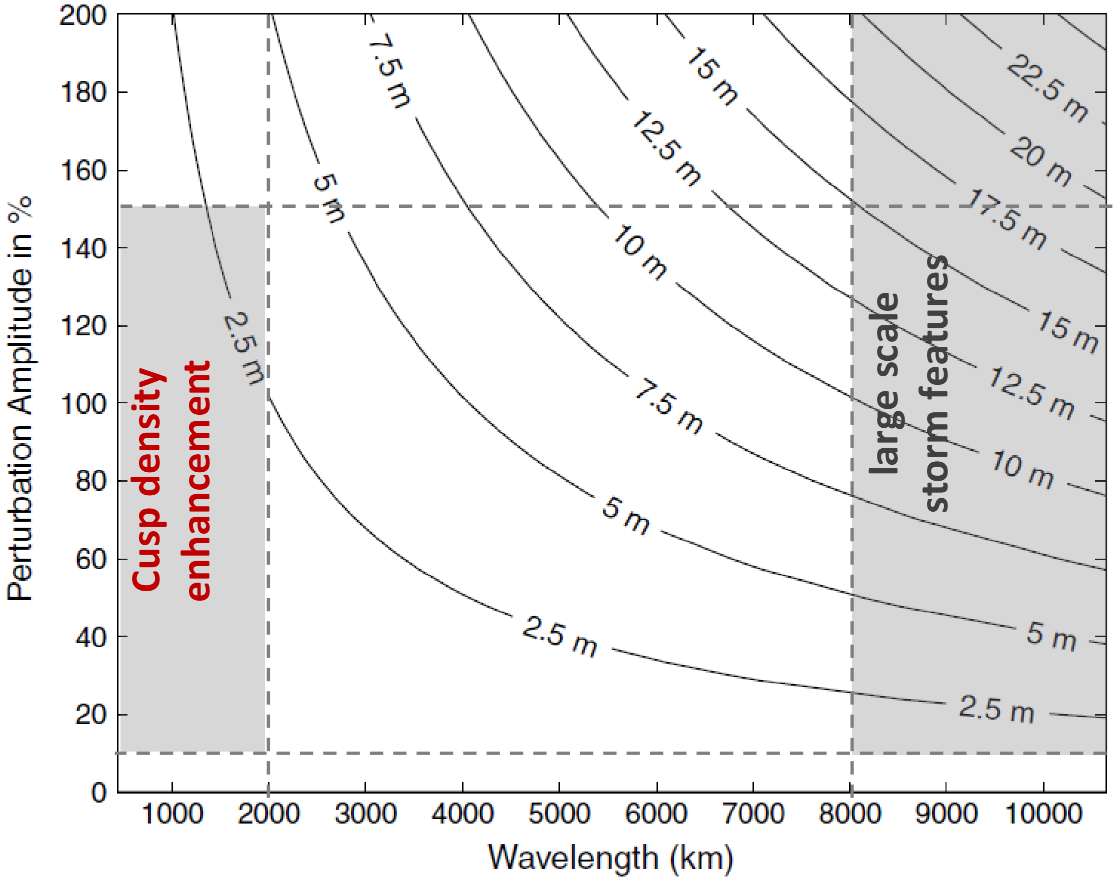
Thermospheric Space Weather and Orbit Prediction



Orbit Sensitivity to Density Perturbations

- Multiple-scales can affect the satellite trajectory in different ways
- However, that doesn't mean some scales are not impactful to satellite drag (due to multi-scale processes indirectly driving behavior across the spectrum)
- Whether an effect is impactful or not depends on the specific user
  - Satellite Geodesy: mm-cm
  - Relative Positioning or station keeping: meters
  - Ground antenna pointing: kilometers

24 Hour Orbital In-Track Error at 400km
Circular Orbit, CHAMP cross sectional area and mass



Values scale with satellite A/m; CubeSat effects might be 10x higher

Anderson et al., 2009 (JSR), DOI: 10.2514/1.42138

Satellite Drag Record and Aeronomy

Phenomena discovered or studied using satellite drag

- Semiannual variation
- Helium bulge
- Geomagnetic storm response
- Long-term thermospheric cooling
- …

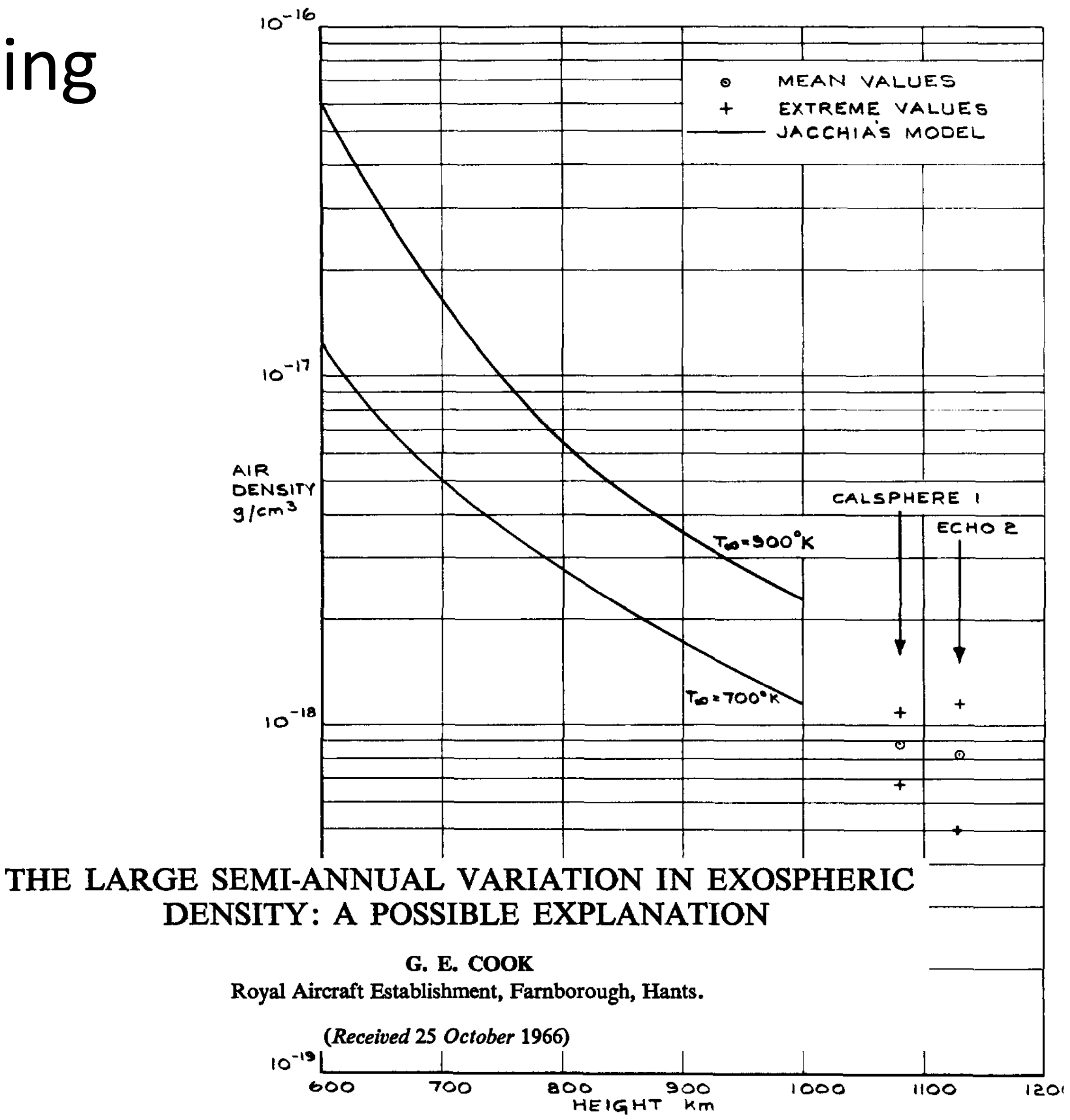
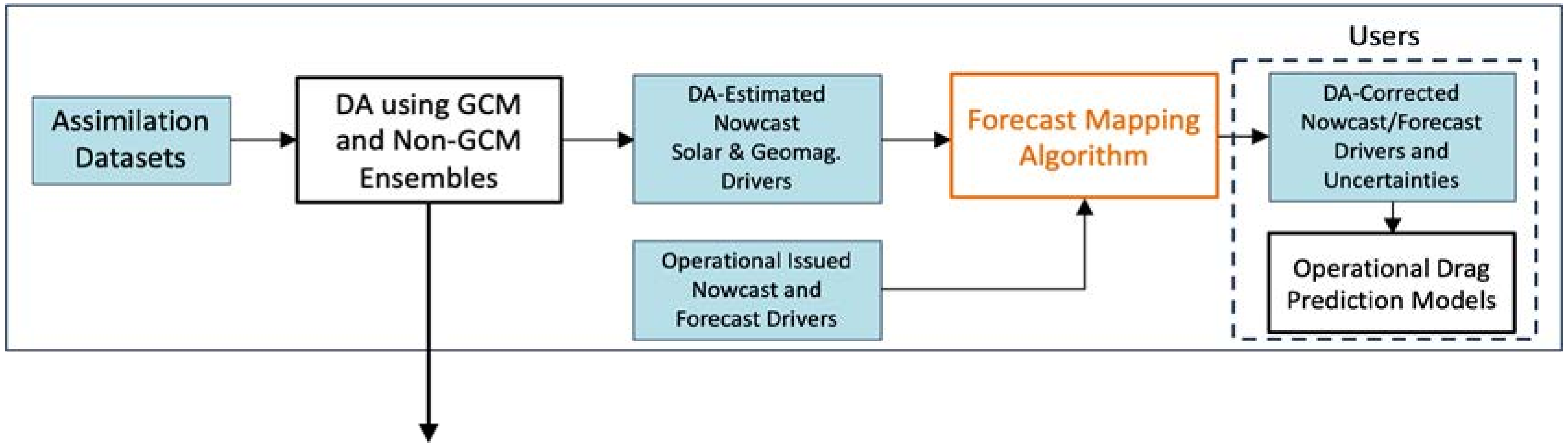


FIG. 2. VALUES OF AIR DENSITY IN 1965.

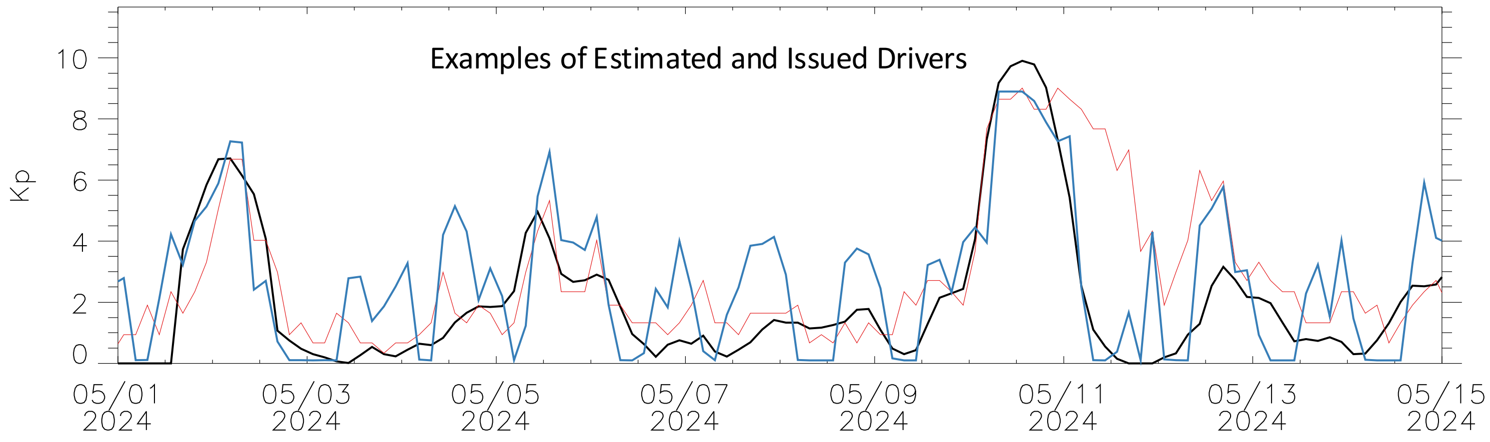
Evaluating Nowcast and Forecast Driver Mapping



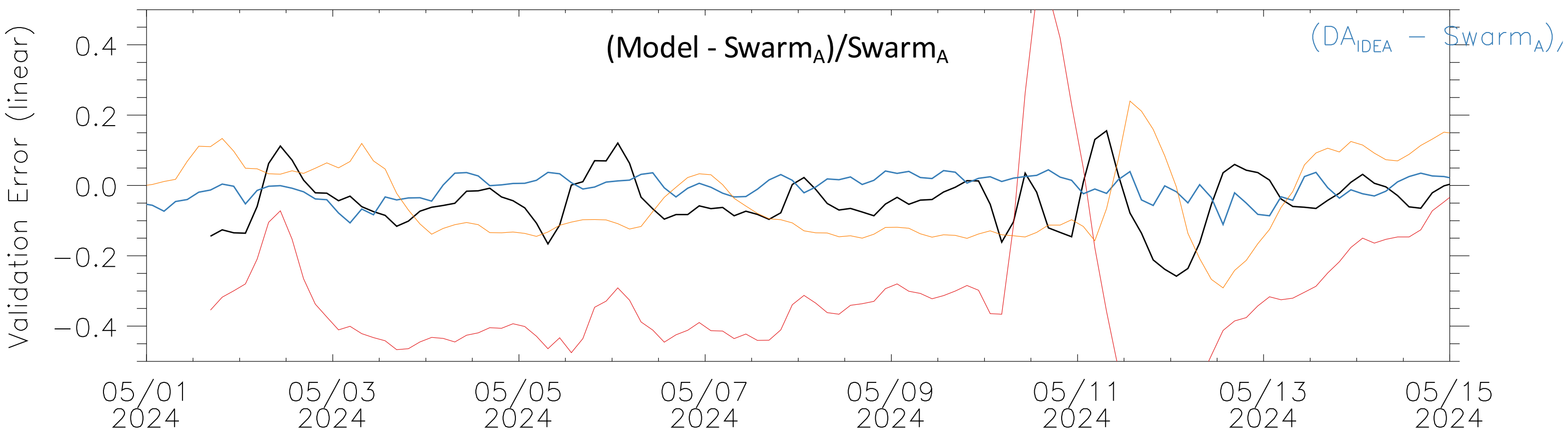
	GCM	Non-GCM
DA Technique	IDEA (TIE-GCM Ensemble)	CAFE (MSIS 2.1 Ensemble)
Assimilated Dataset	GRACE-FO Accelerometers	Orbit-Avg. Drag from ground observations of ~70 calibration objects
Validation	Swarm POD	Swarm POD

Evaluating Nowcast and Forecast Driver Mapping

Data Assimilation (DA) Nowcast Driver Database and Validation

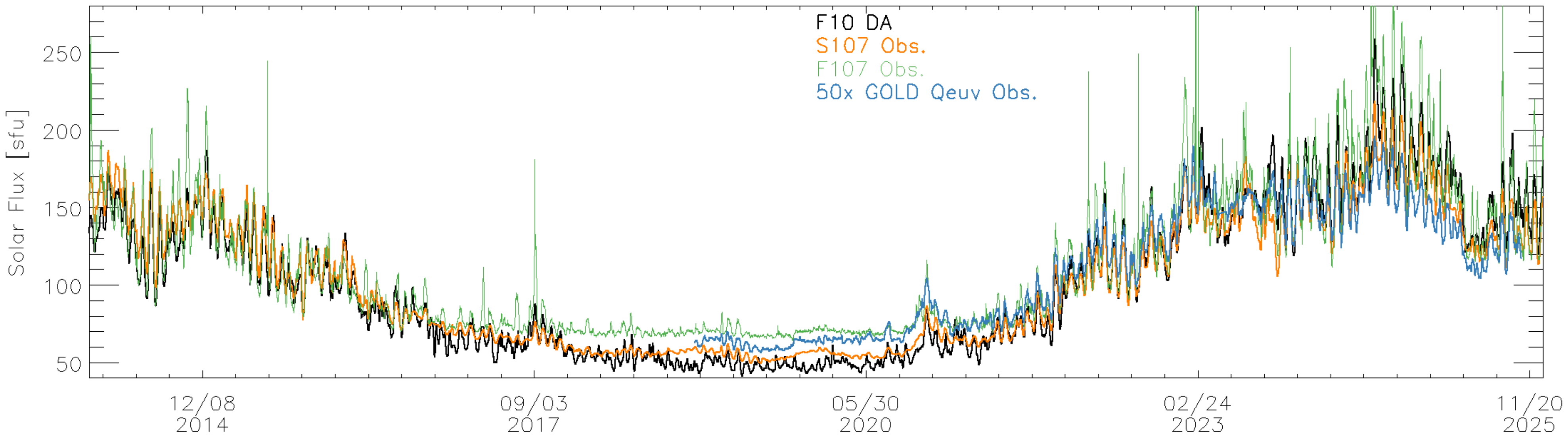


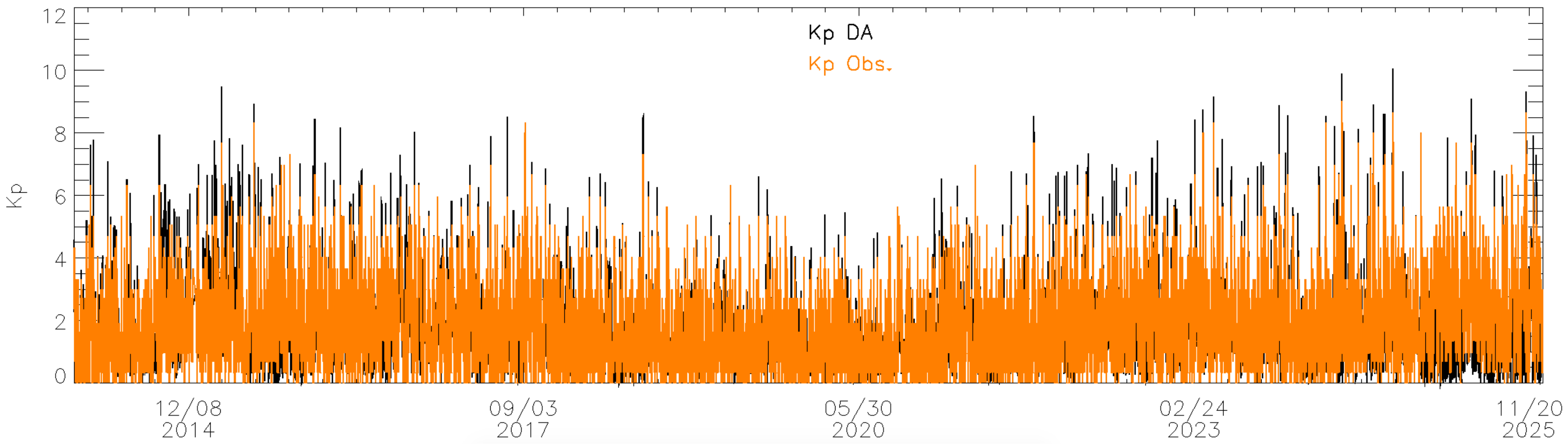
CAFE (MSIS-DA)
IDEA (TIEGCM-DA)
Issued Kp



CAFE (MSIS-DA)
IDEA (TIEGCM-DA)
$TIEGCM_{GPI}$
NRLMSISE-2.1

Evaluating Nowcast and Forecast Driver Mapping





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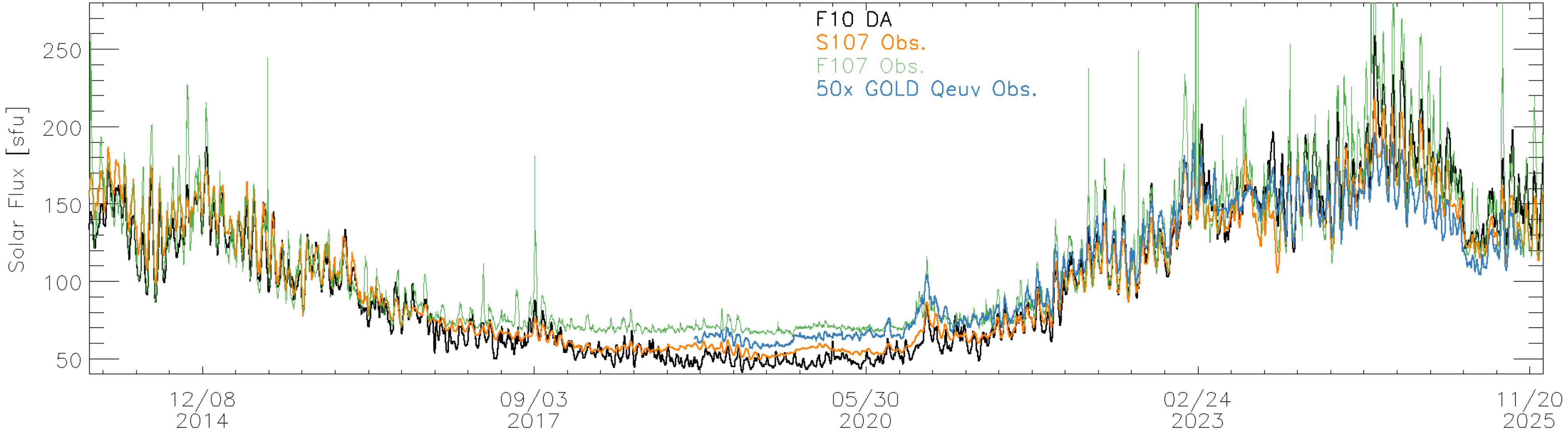
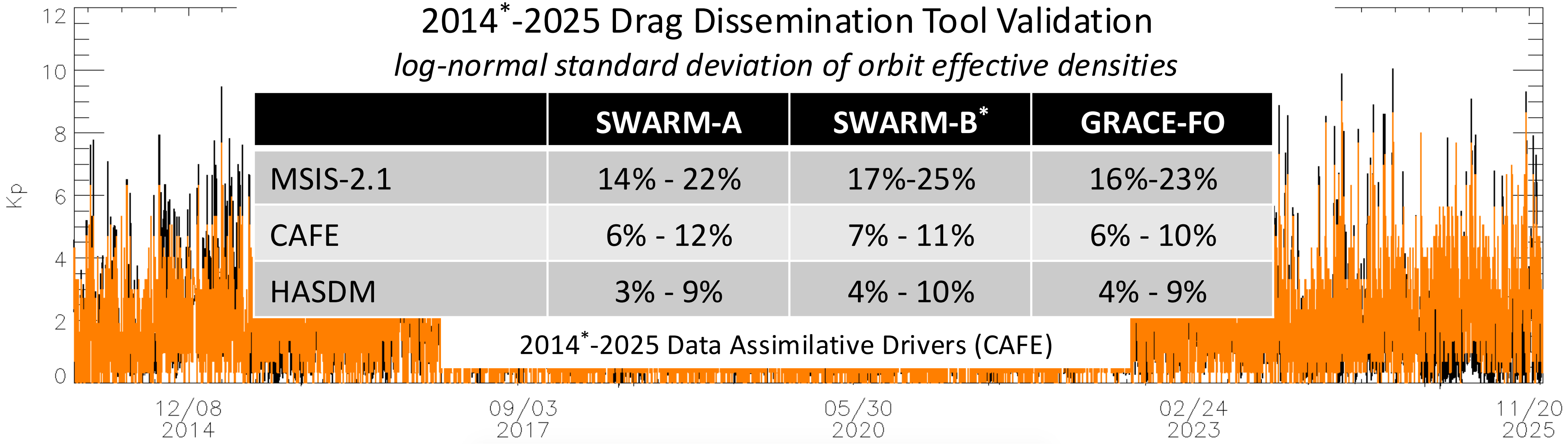


2014*-2025 Drag Dissemination Tool Validation

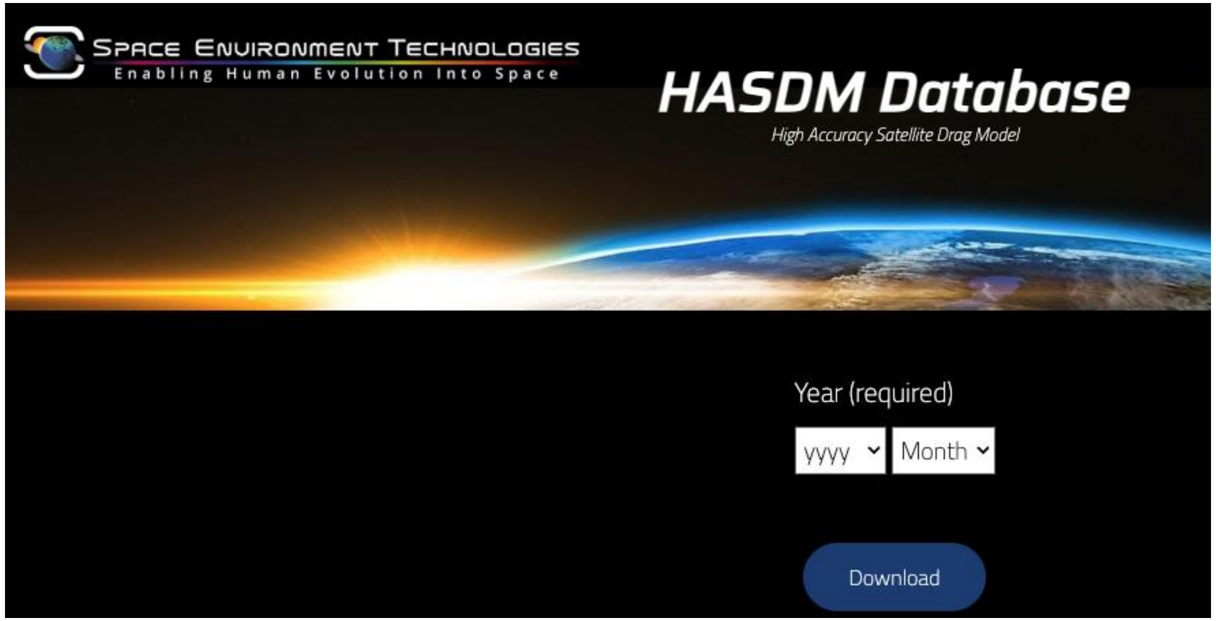
log-normal standard deviation of orbit effective densities

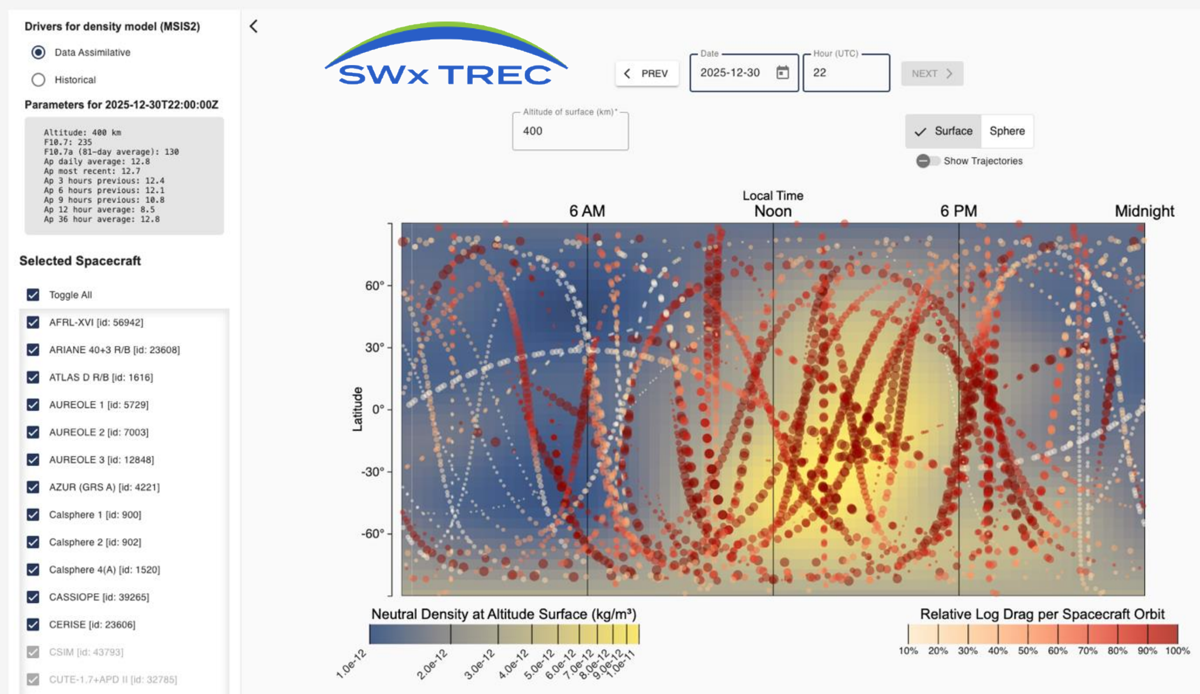
	SWARM-A	SWARM-B*	GRACE-FO
MSIS-2.1	14% - 22%	17%-25%	16%-23%
CAFE	6% - 12%	7% - 11%	6% - 10%
HASDM	3% - 9%	4% - 10%	4% - 9%

2014*-2025 Data Assimilative Drivers (CAFE)



HASDM, Another Aside

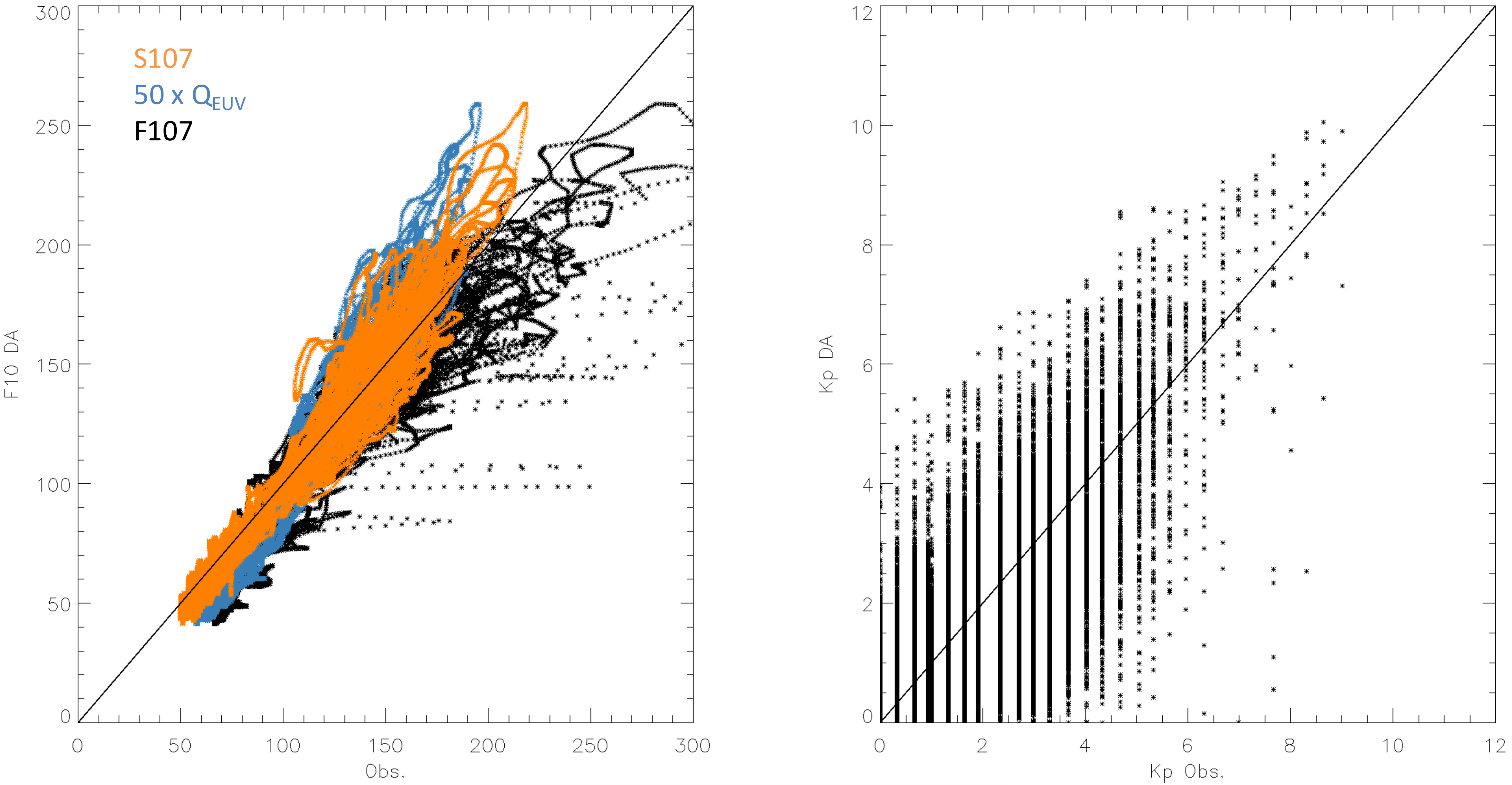




Data can be accessed at:

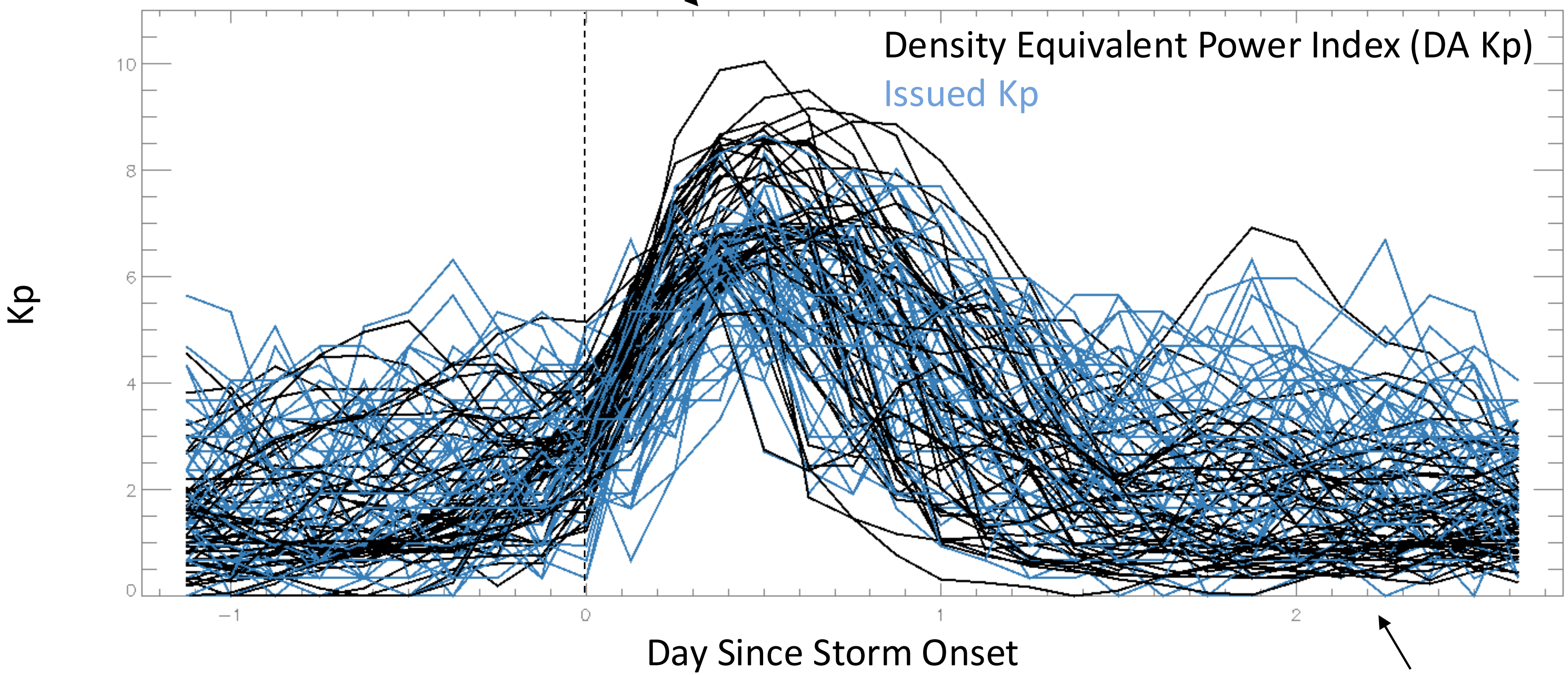
- **HASDM** https://sol.spacenvironment.net/Hasdm_database/
- **MSIS-DA and Drag Visualization** https://swx-trec.com/cafe/

Evaluating Nowcast and Forecast Driver Mapping



Issued and Observed Drag

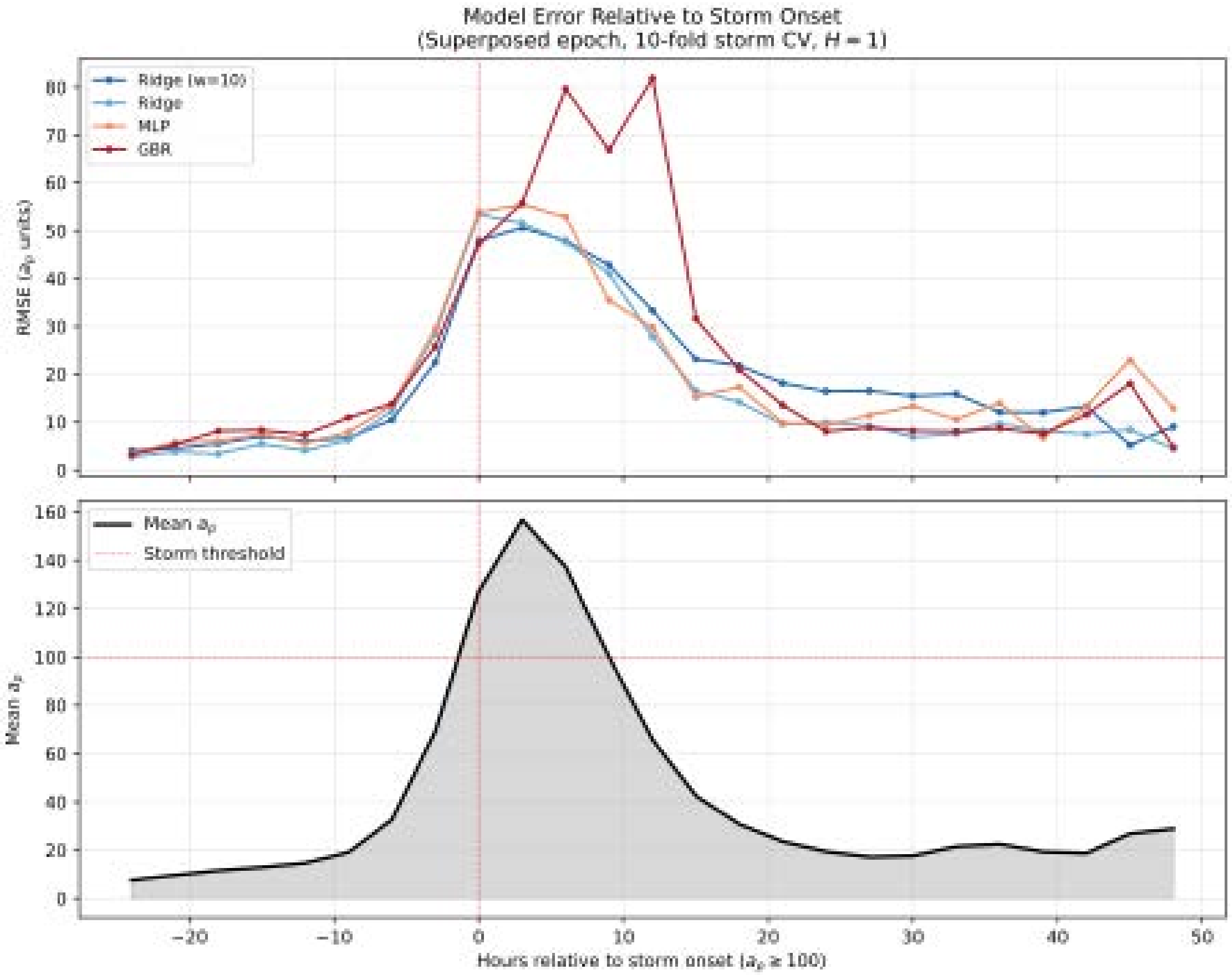
Power at storm peaks underspecified



Power after recovery overspecified

- Improve model physics (post storm cooling)
- Implement NO cooling index/observations

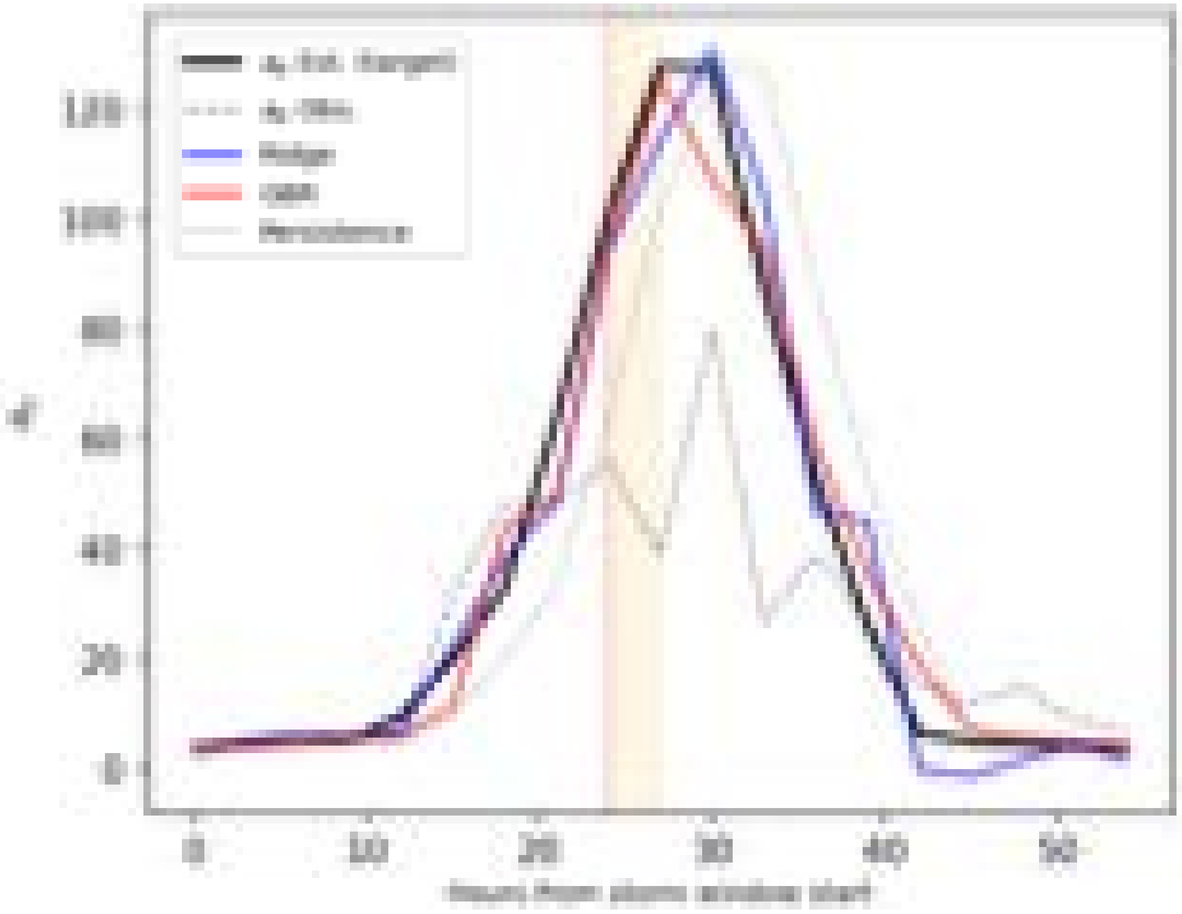
Machine Learning and Forecast Mapping

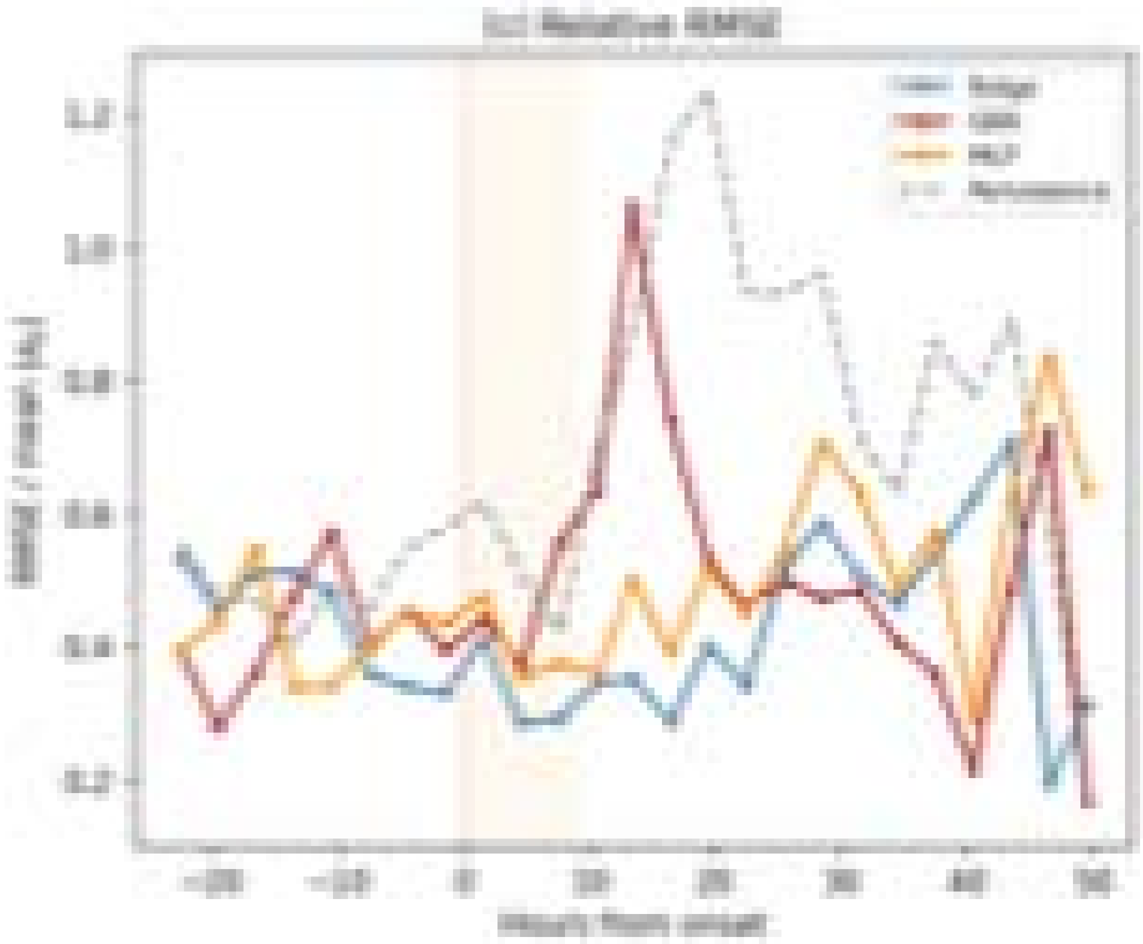


Andong Hu, SWxTREC

$$\mathbf{x}_i = \Big[\underbrace{a_{p,\mathrm{est}}^{\mathrm{past}}}_{24},\ \underbrace{K_{p,\mathrm{est}}^{\mathrm{past}}}_{24},\ \underbrace{a_{p,\mathrm{obs}}^{\mathrm{past}}}_{24},\ \underbrace{\mathrm{Dst}_{\mathrm{obs}}^{\mathrm{past}}}_{24},\ \underbrace{\text{6 daily solar indices (past)}}_{18},\ \underbrace{\sin/\cos(\mathrm{UT},\mathrm{DOY})}_{4}\Big]$$

Machine Learning and Forecast Mapping





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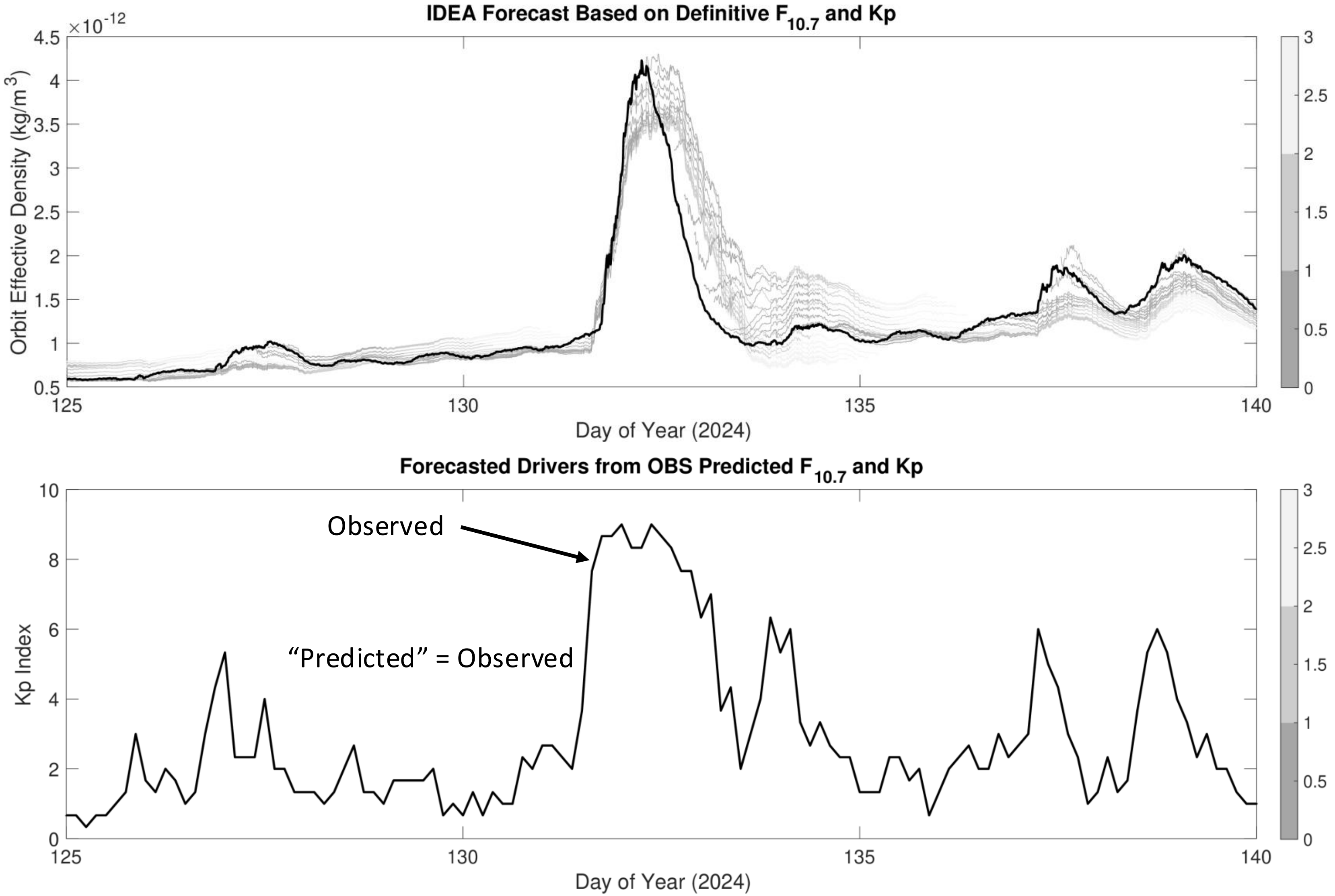
IDEA (TIE-GCM) Forecast Experiments: Definitive Drivers

72-Hour "Forecast" using Definitive Drivers:

EDDYDIF: Fixed
NO Beta2: Fixed

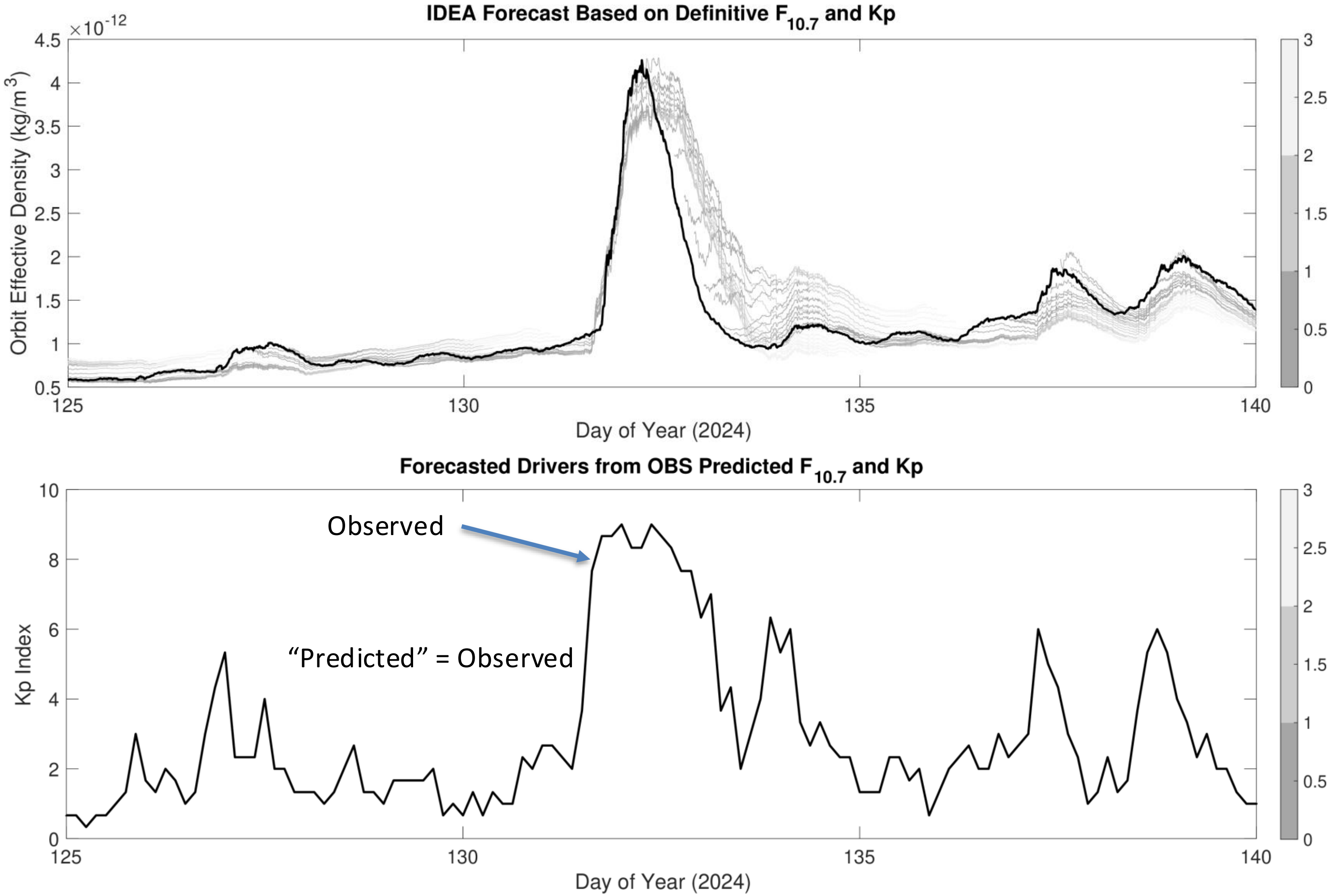
Eric Sutton, SWxTREC



IDEA (TIE-GCM) Forecast Experiments: Definitive Drivers

72-Hour "Forecast" using Definitive Drivers:

EDDYDIF: Variable
NO Beta2: Fixed

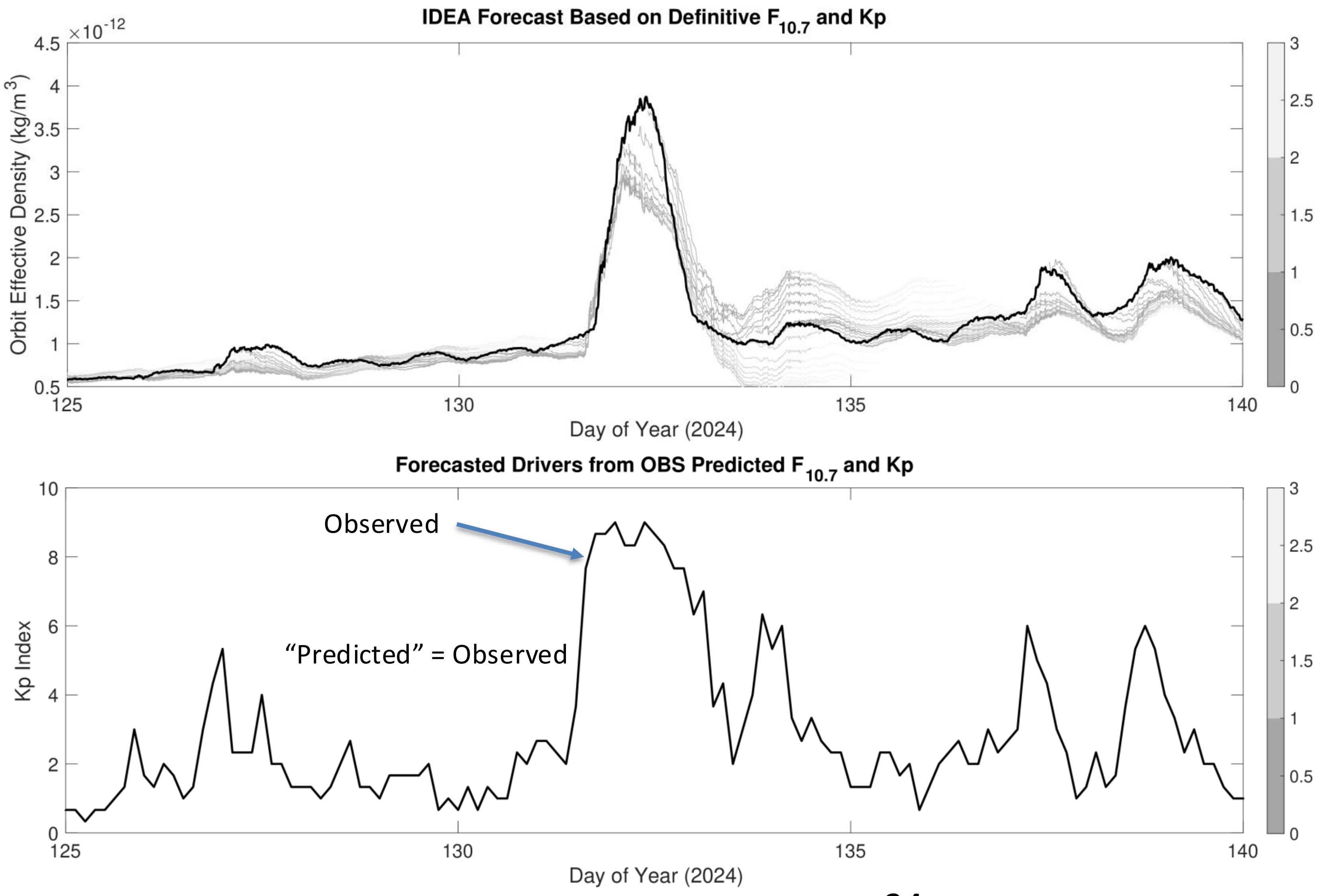


Eric Sutton, SWxTREC

IDEA (TIE-GCM) Forecast Experiments: Definitive Drivers

72-Hour "Forecast" using Definitive Drivers:

EDDYDIF: Variable
NO Beta2: Temperature Dependent



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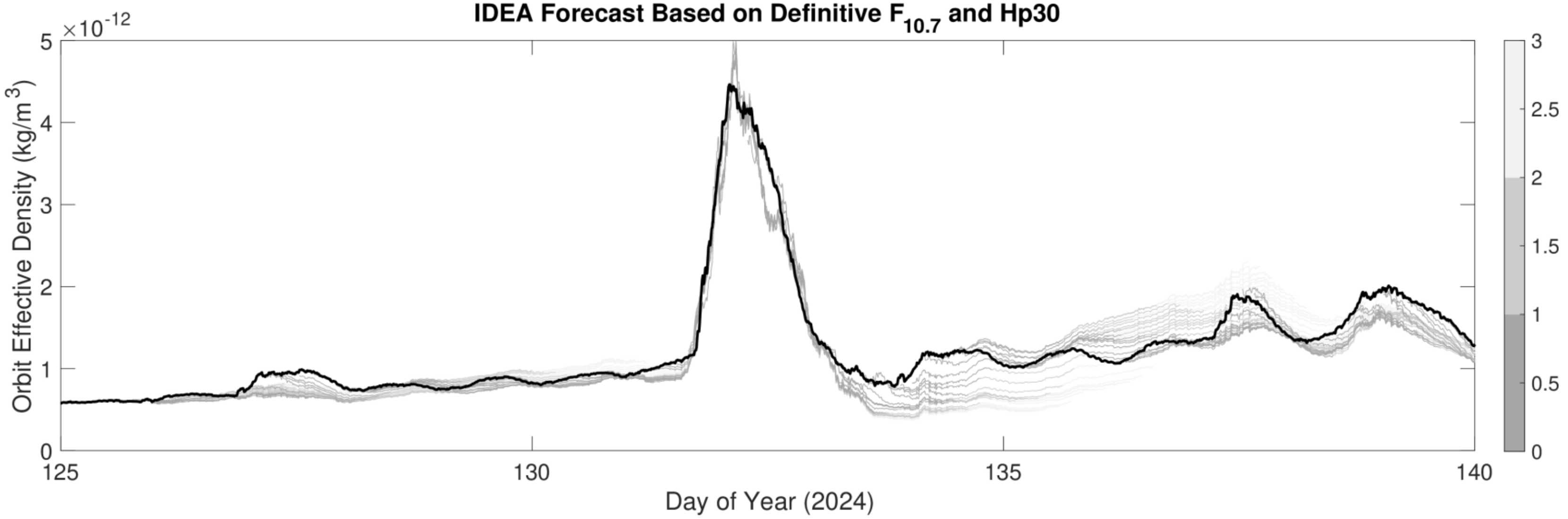
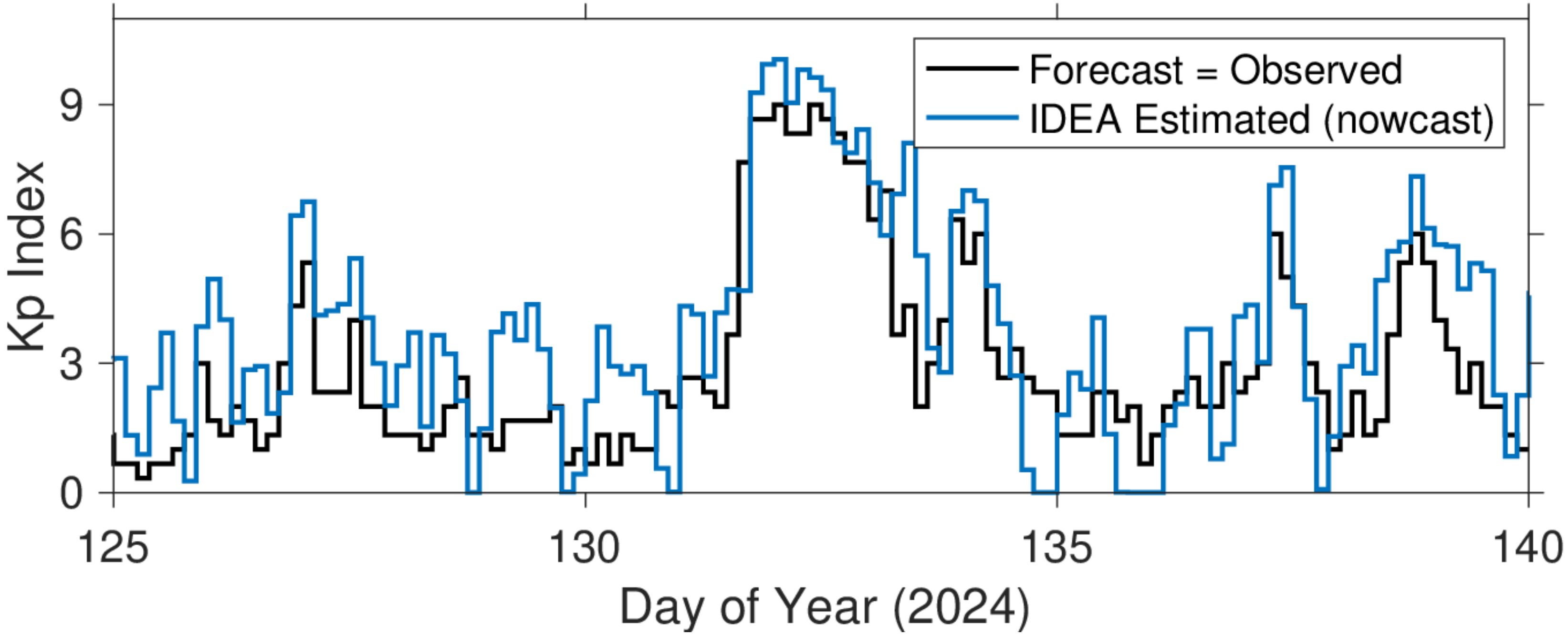
IDEA (TIE-GCM) Forecast Experiments: Definitive Drivers

72-Hour "Forecast" using Definitive Drivers:

EDDYDIF:	Variable
NO Beta2:	Temperature Dependent
Kp Bounds:	Expanded
Geomag F'cst:	Hp30





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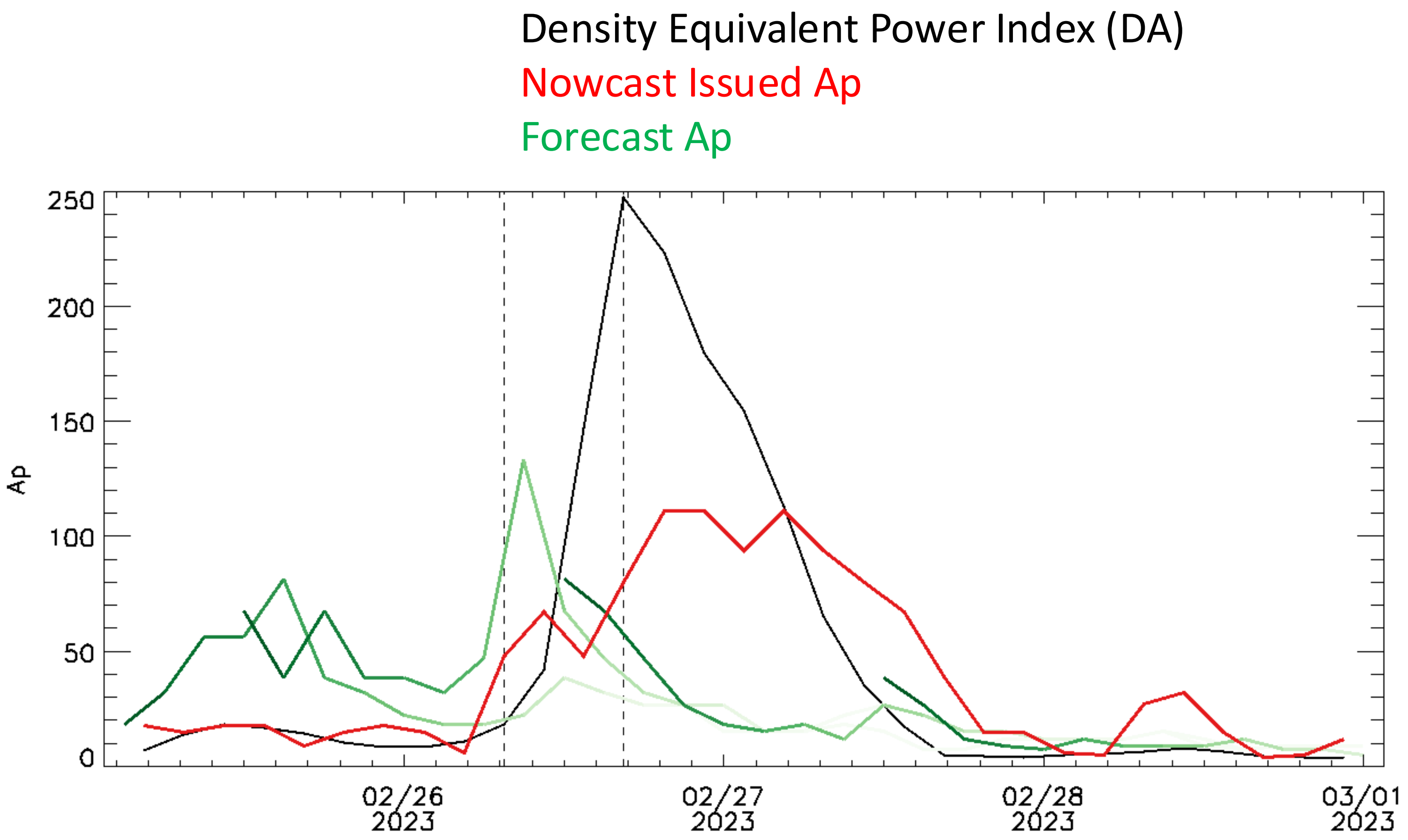
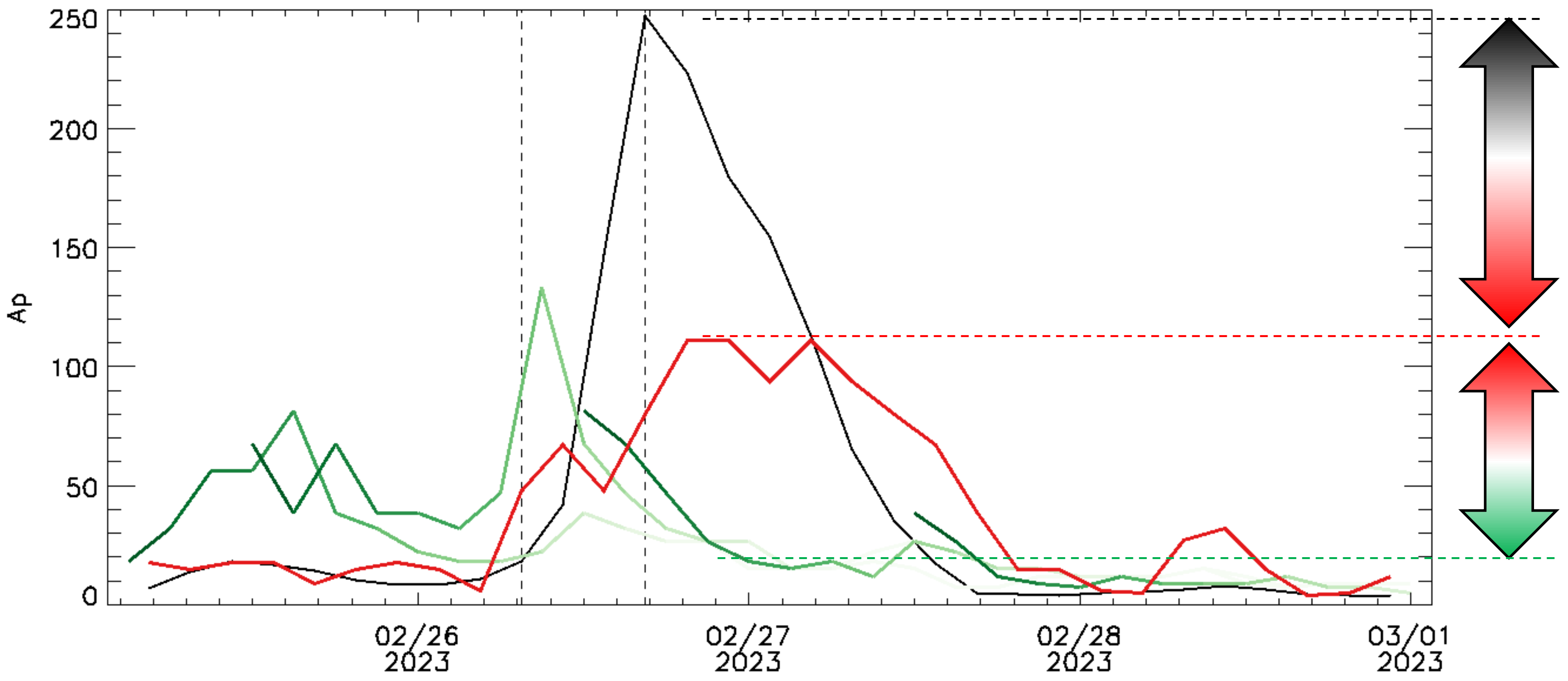
Real-World Forecast Example



Real-World Forecast Example

Density Equivalent Power Index (DA)
Nowcast Issued Ap
Forecast Ap



Energy input (output) specification

- Interface physics/coupling
- Energetics
- Parametrizations
- Model physics

Energy input forecasting

- Solar wind plasma propagation
- Solar and solar-wind observations / properties
- Event detection

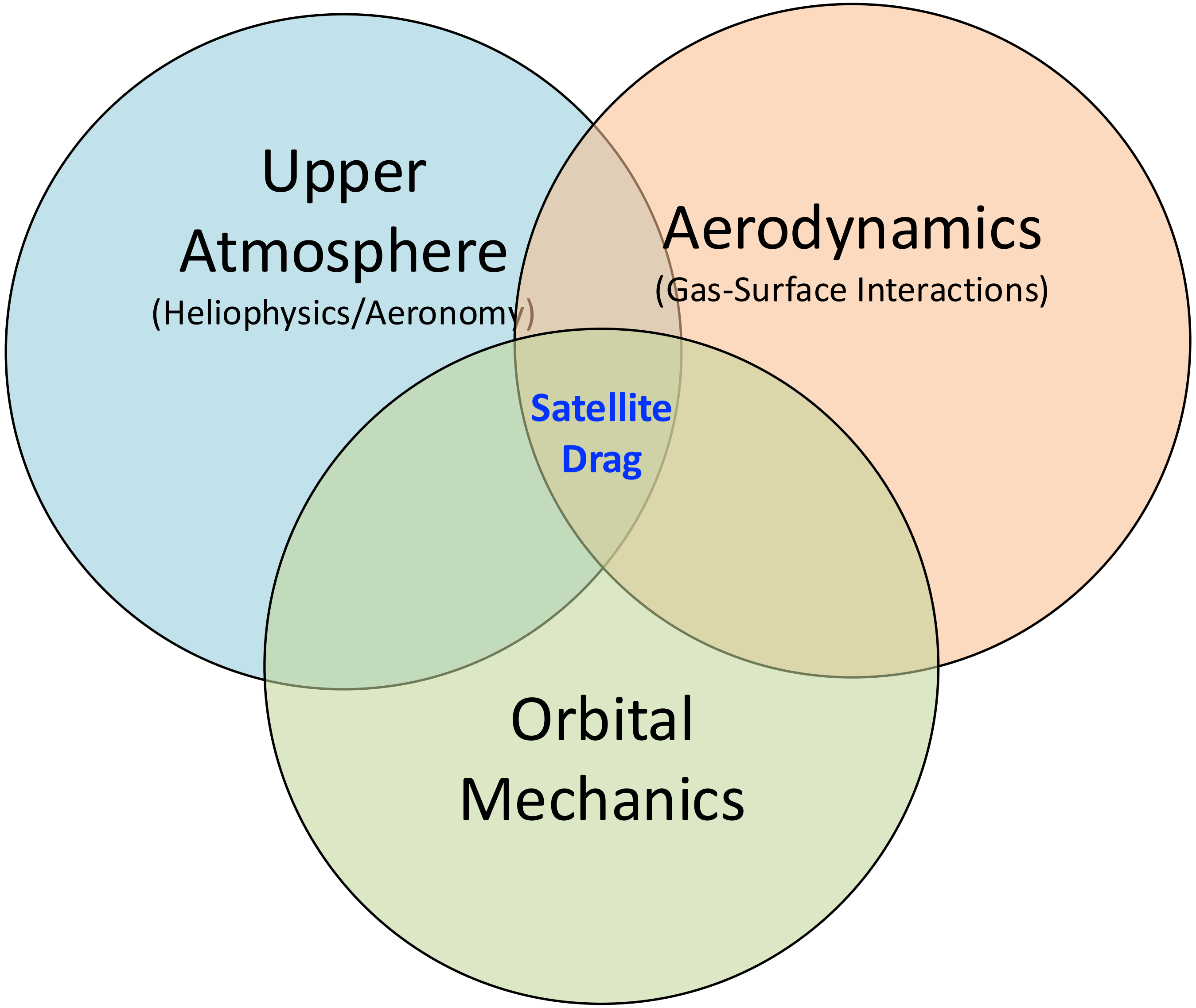
- Thermospheric weather has a significant impact on satellite orbits in LEO
- A multidisciplinary problem, the community has a lot of work to do!
- Some ongoing efforts include
  - Publicly/Commercially available assimilation schemes for thermospheric ND
  - Better utilization of existing on-orbit data like POD
  - Improvement in atmospheric model-physics and coupling
  - Improvements in drag coefficient physics
  - Solar wind forecast improvements using ML and other techniques
  - Characterization of impacts to on-orbit assets

SET

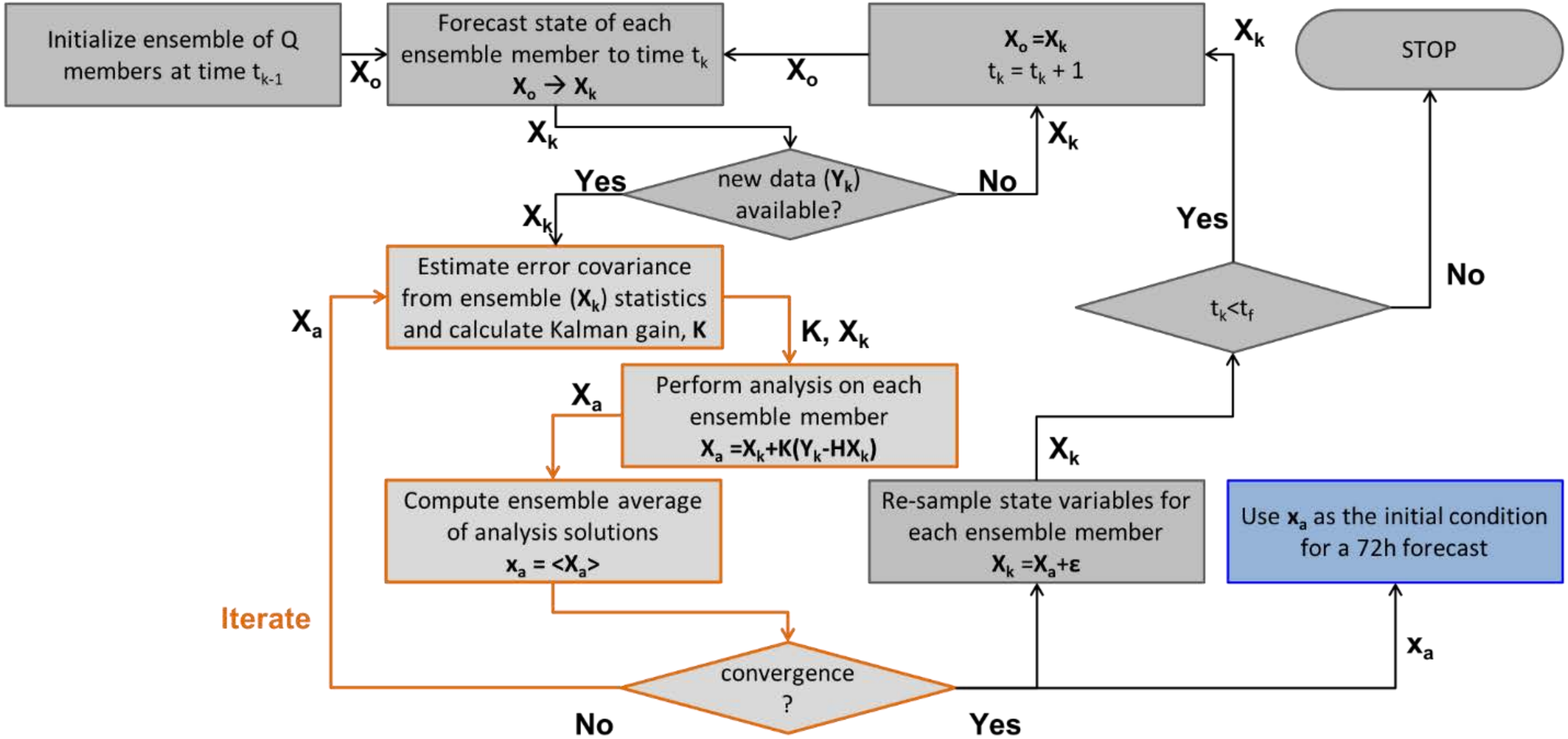
SWx TREC

mpilinski@spacewx.com

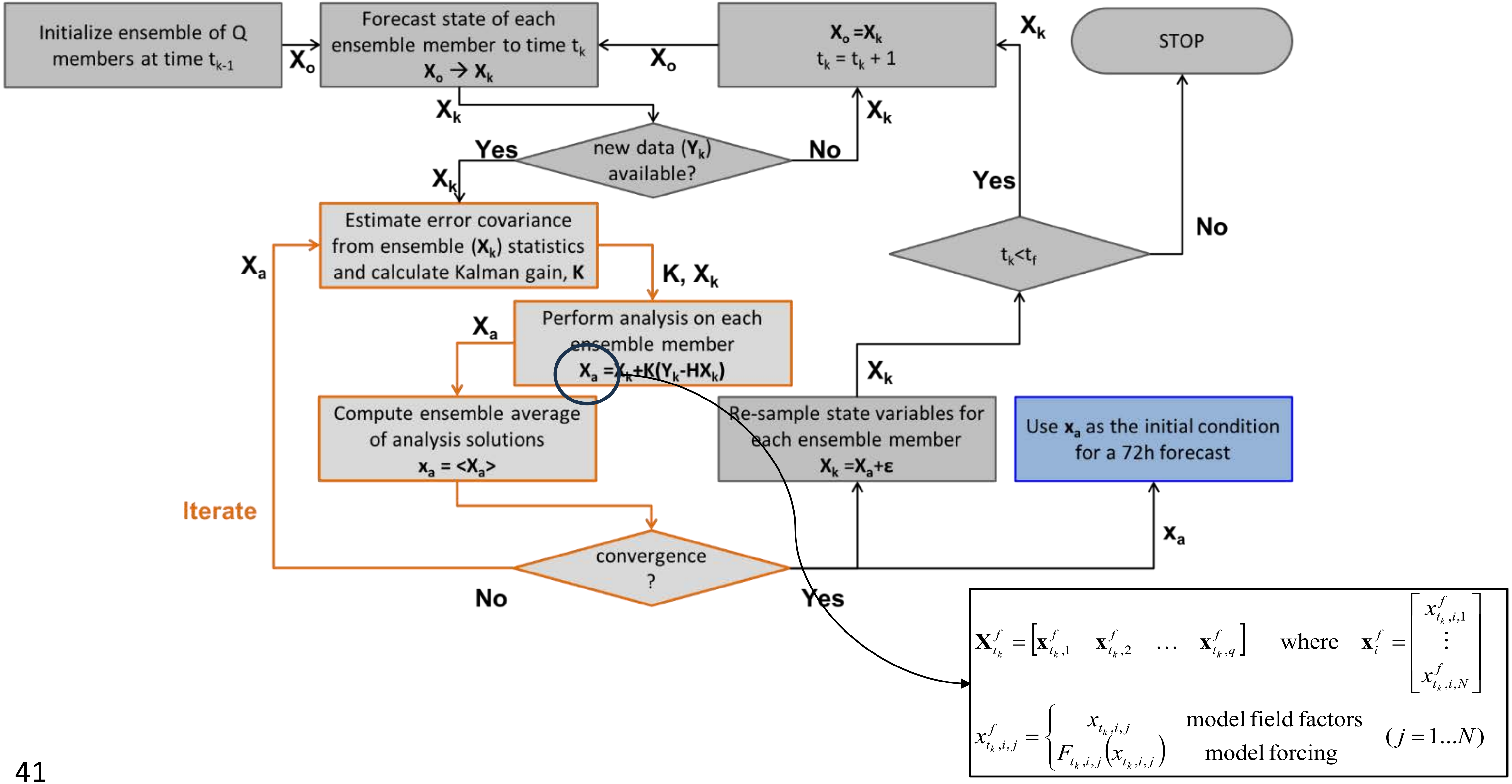
Satellite Atmospheric Drag



CAFÉ DA Process



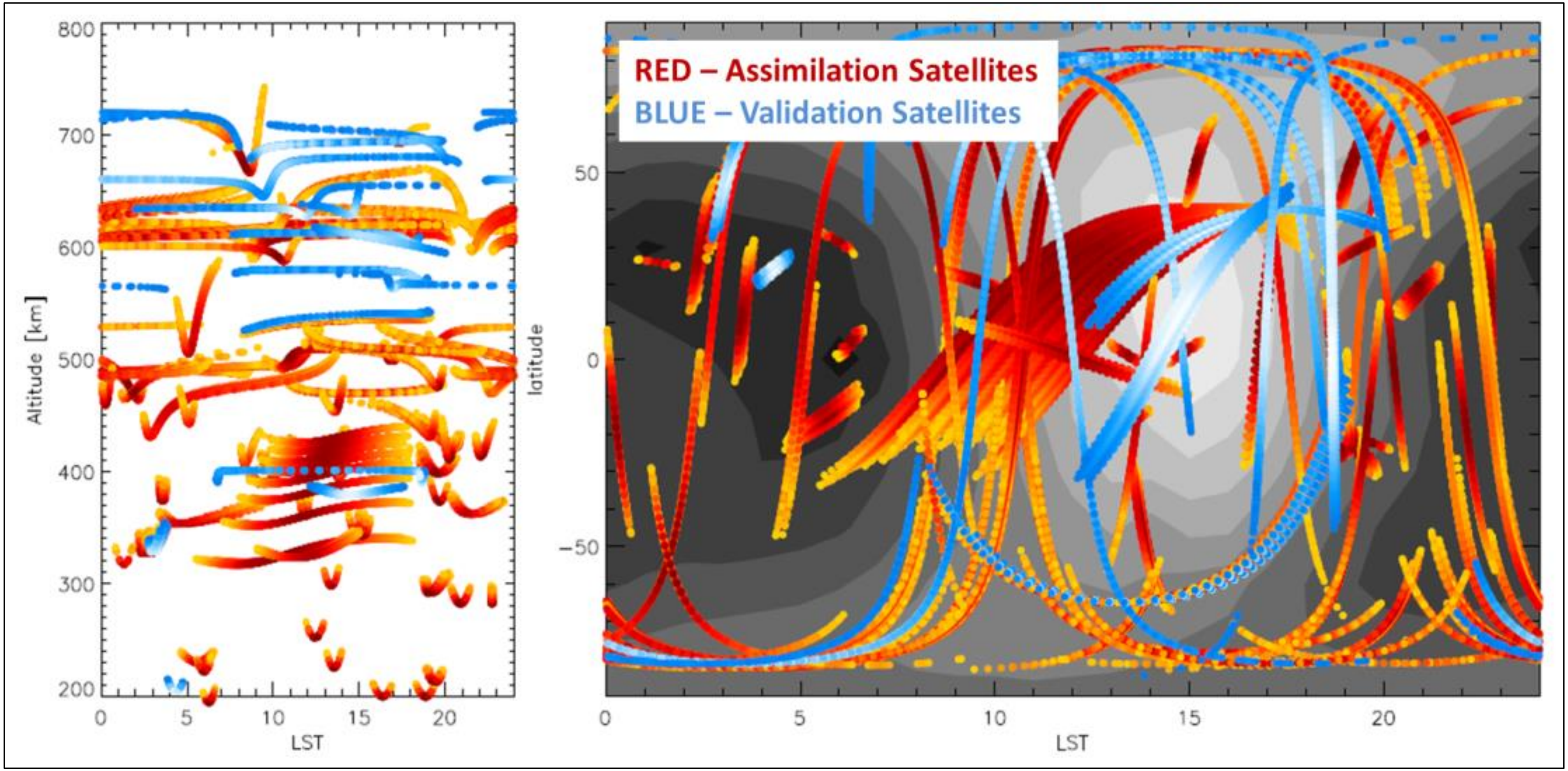
CAFE DA Process



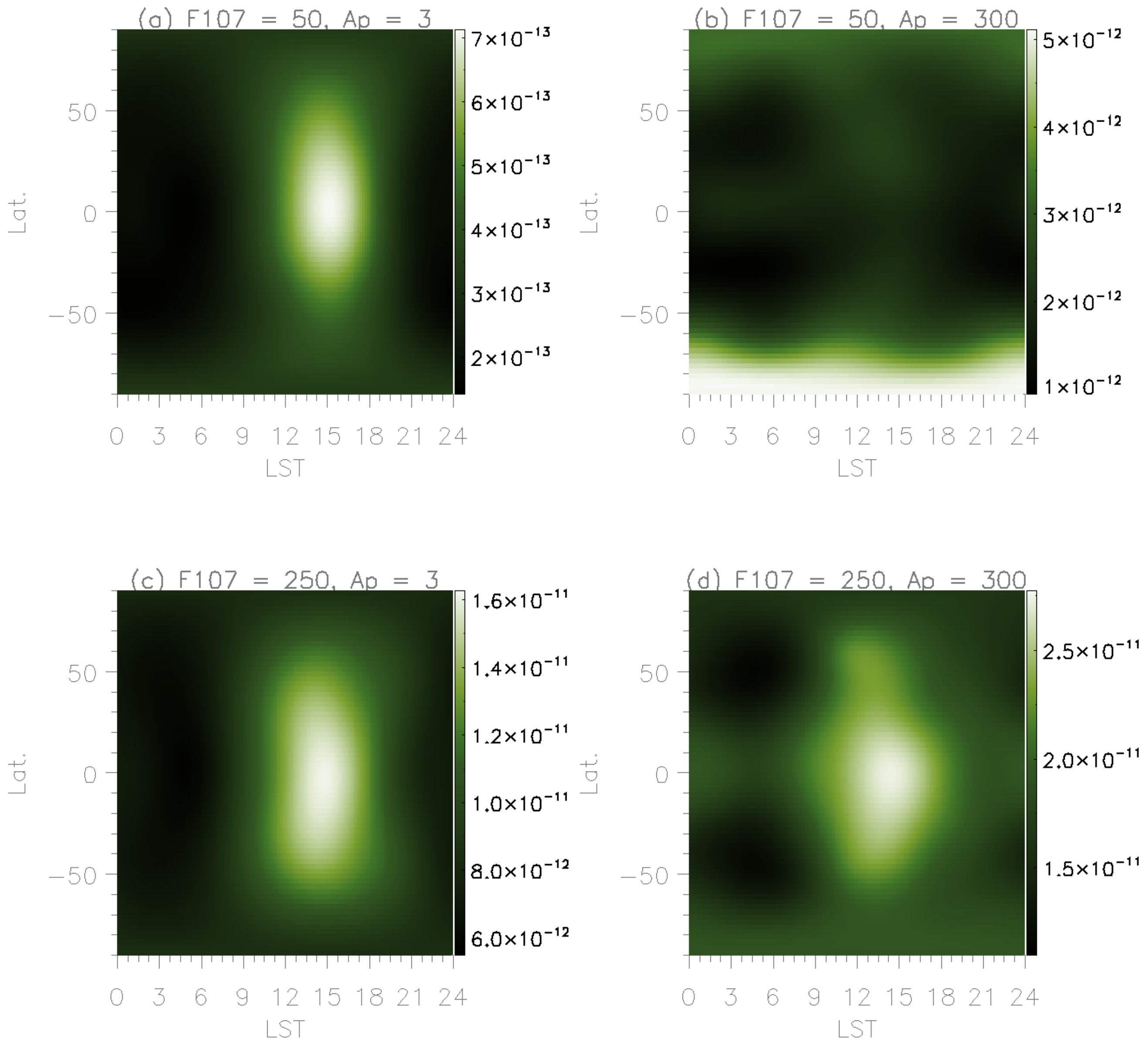
$$\mathbf{X}_{t_k}^f = \left[\mathbf{x}_{t_k,1}^f \quad \mathbf{x}_{t_k,2}^f \quad \ldots \quad \mathbf{x}_{t_k,q}^f\right] \quad \text{where} \quad \mathbf{x}_i^f = \begin{bmatrix} x_{t_k,i,1}^f \\ \vdots \\ x_{t_k,i,N}^f \end{bmatrix}$$

$$x_{t_k,i,j}^f = \begin{cases} x_{t_k,i,j} & \text{model field factors} \\ F_{t_k,i,j}\left(x_{t_k,i,j}\right) & \text{model forcing} \end{cases} \quad (j = 1 \ldots N)$$

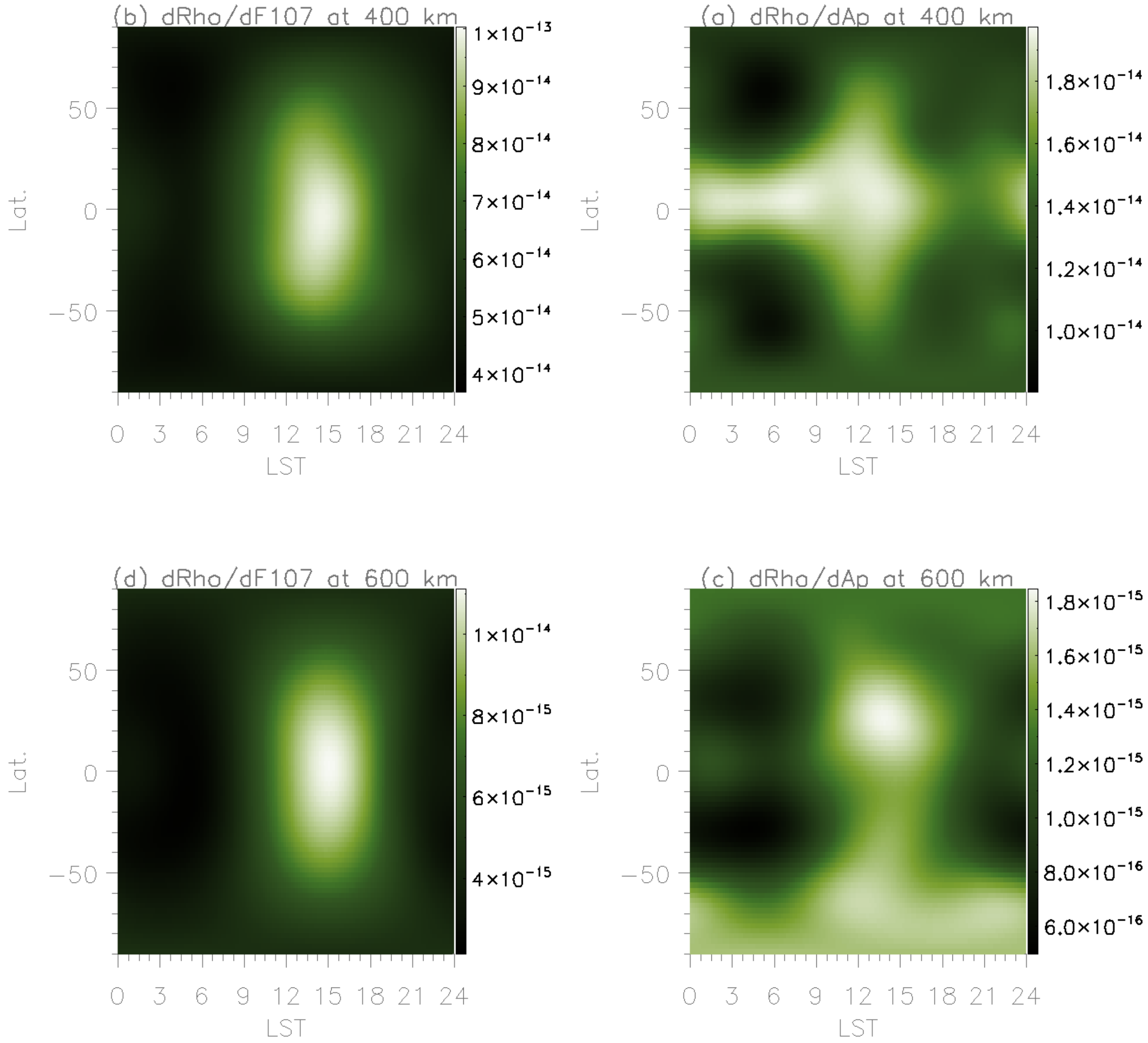
Assimilated Data Spatial Information



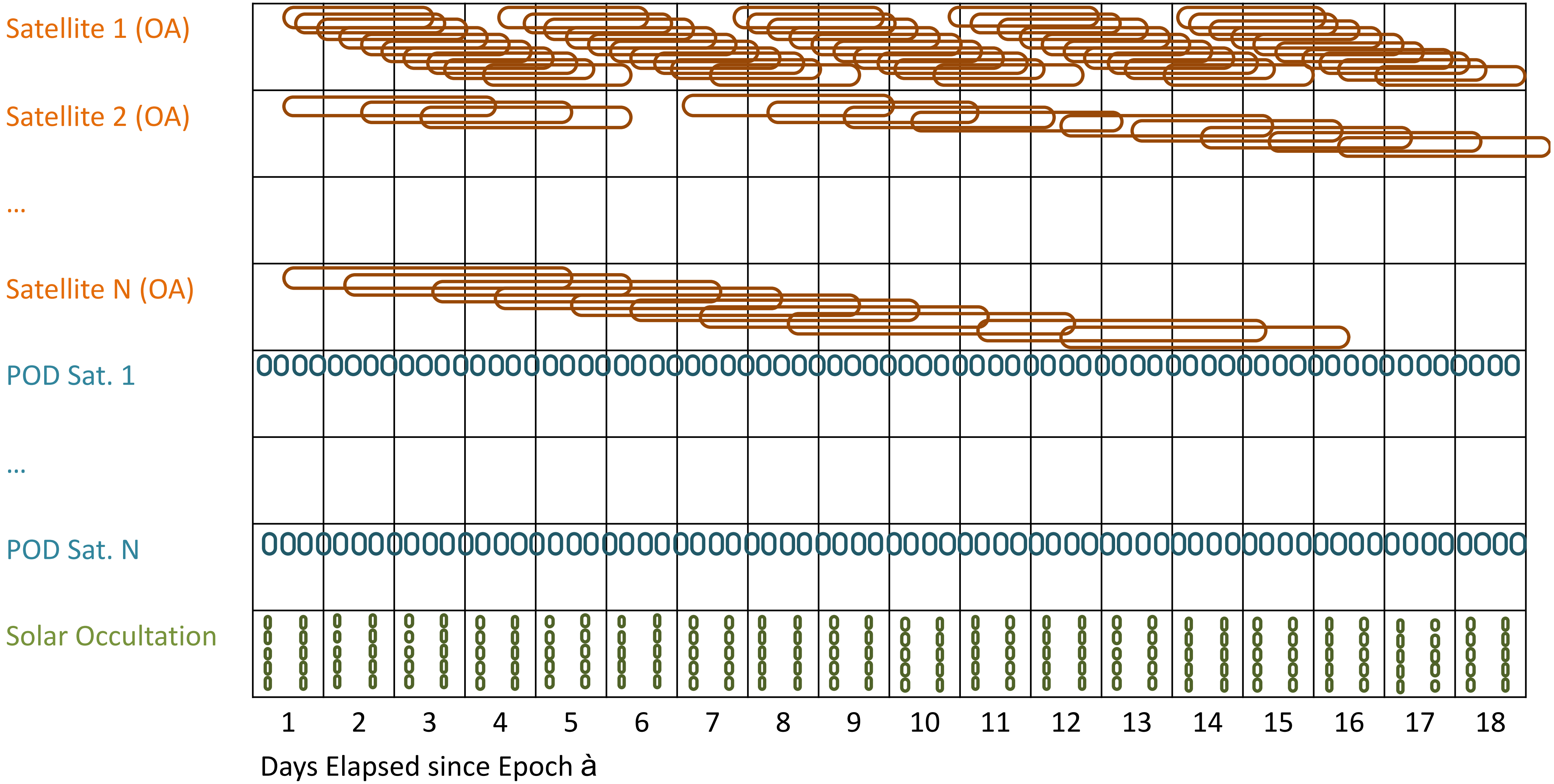
Observability of Driver Estimates



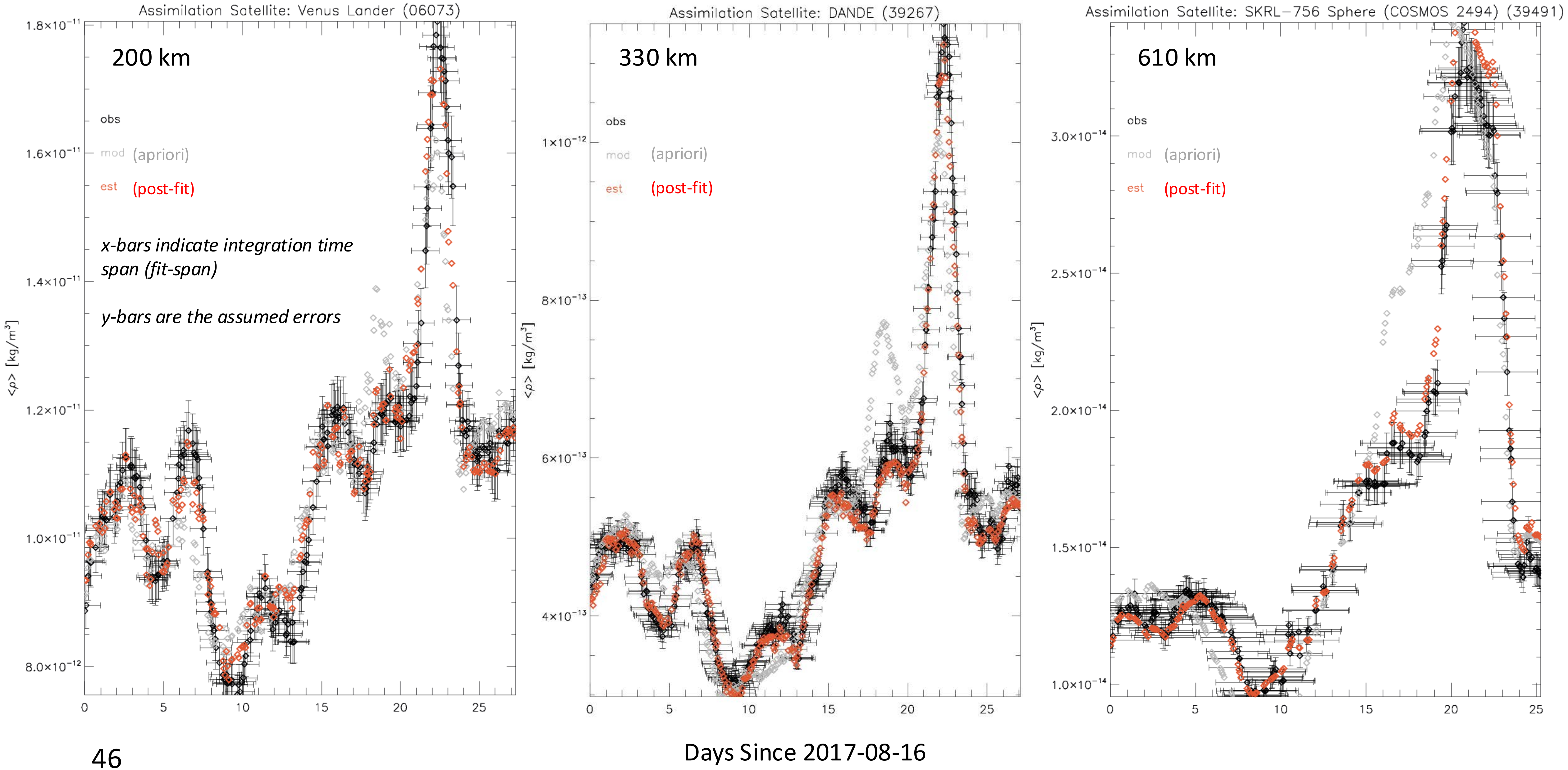
Observability of Driver Estimates



Assimilated Data Temporal Information



Assimilation Data, Examples

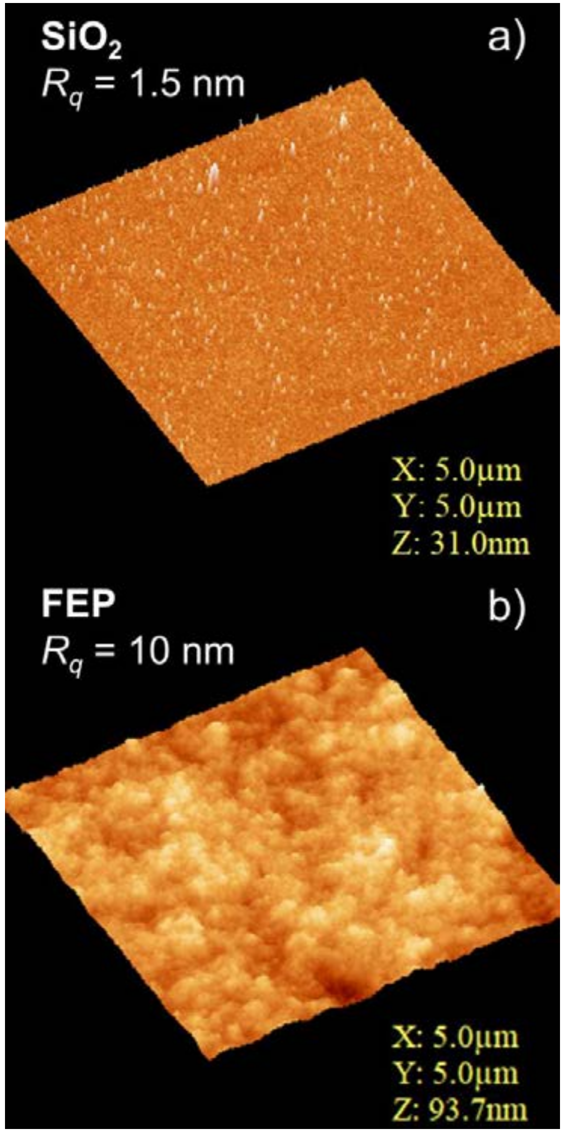


Drag Coefficients in LEO: An Emerging Picture

- Scattering from real "engineering" materials can be represented by a broad (backscattering) component and a quasi-specular component with incomplete tangential momentum accommodation

- The more cosine-like component is not necessarily related to thermal desorption (although adsorption/desorption is occurring)

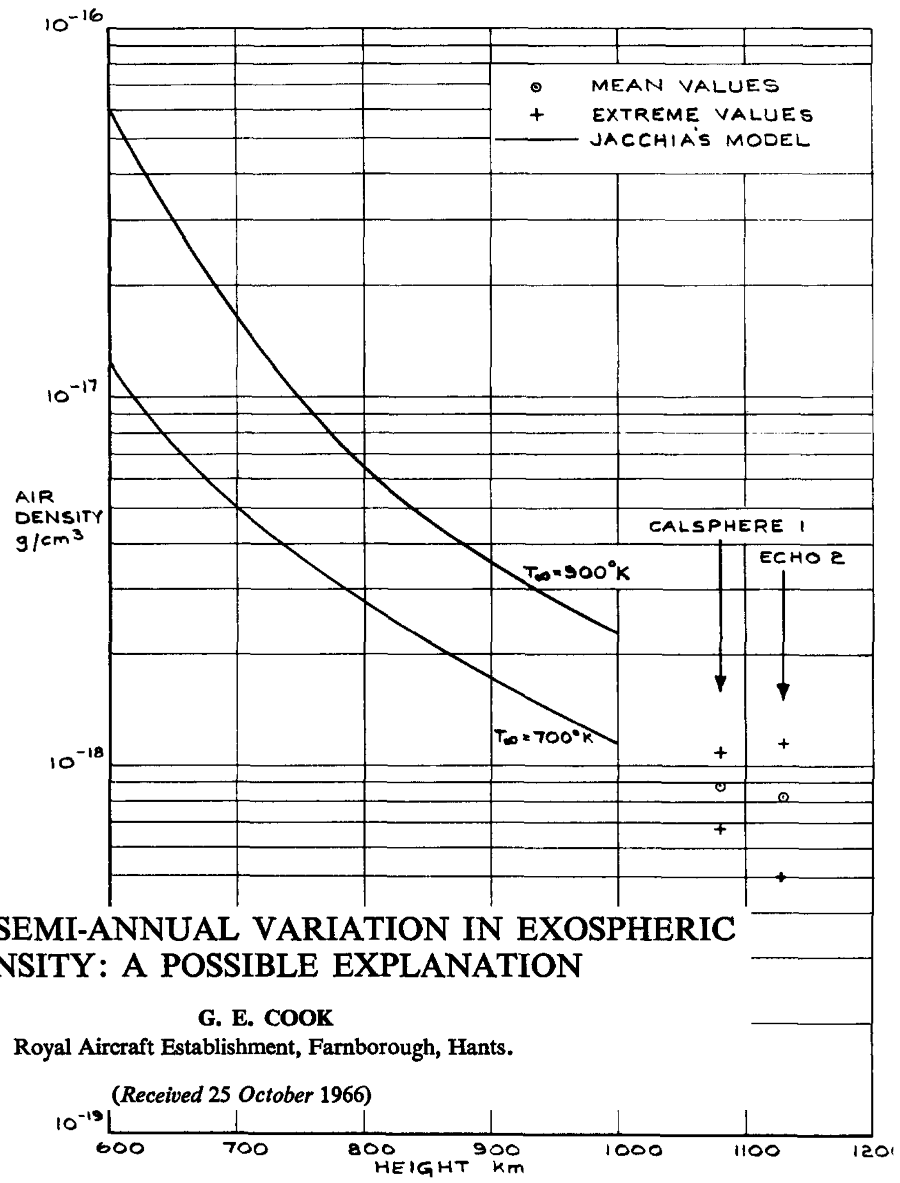
- Tangential momentum accommodation (and normal energy accommodation) appears to be higher for Helium than for AO



Satellite Drag Record and Aeronomy

Phenomena discovered or studied using satellite drag

- Semiannual variation
- Helium bulge
- Geomagnetic storm response
- ETA
- Thermospheric Winds
- Long-term thermospheric cooling
- …



THE LARGE SEMI-ANNUAL VARIATION IN EXOSPHERIC DENSITY: A POSSIBLE EXPLANATION

G. E. COOK
Royal Aircraft Establishment, Farnborough, Hants.

(*Received 25 October 1966*)

FIG. 2. VALUES OF AIR DENSITY IN 1965.

Importance of Satellite Drag

Examples

Model Construction

- Orbit-Average Drag
  - Jacchia and Jacchia-Bowman
- Orbit-Average and Accelerometers
  - NRLMSIS
  - DTM

Model Validation and Tuning

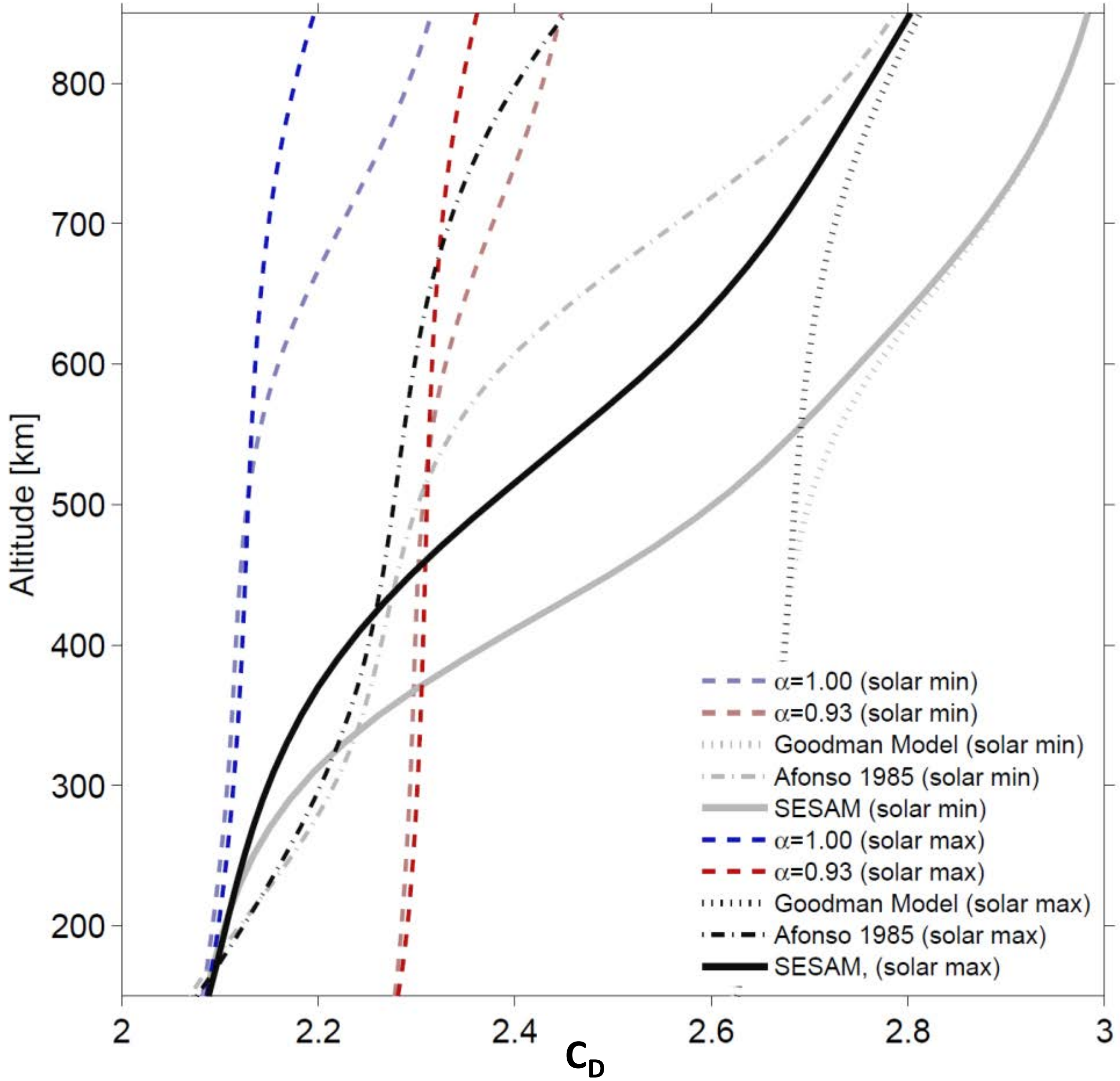
- TIE-GCM
- GITM
- CTIPe
- WAM-IPE

Assimilation

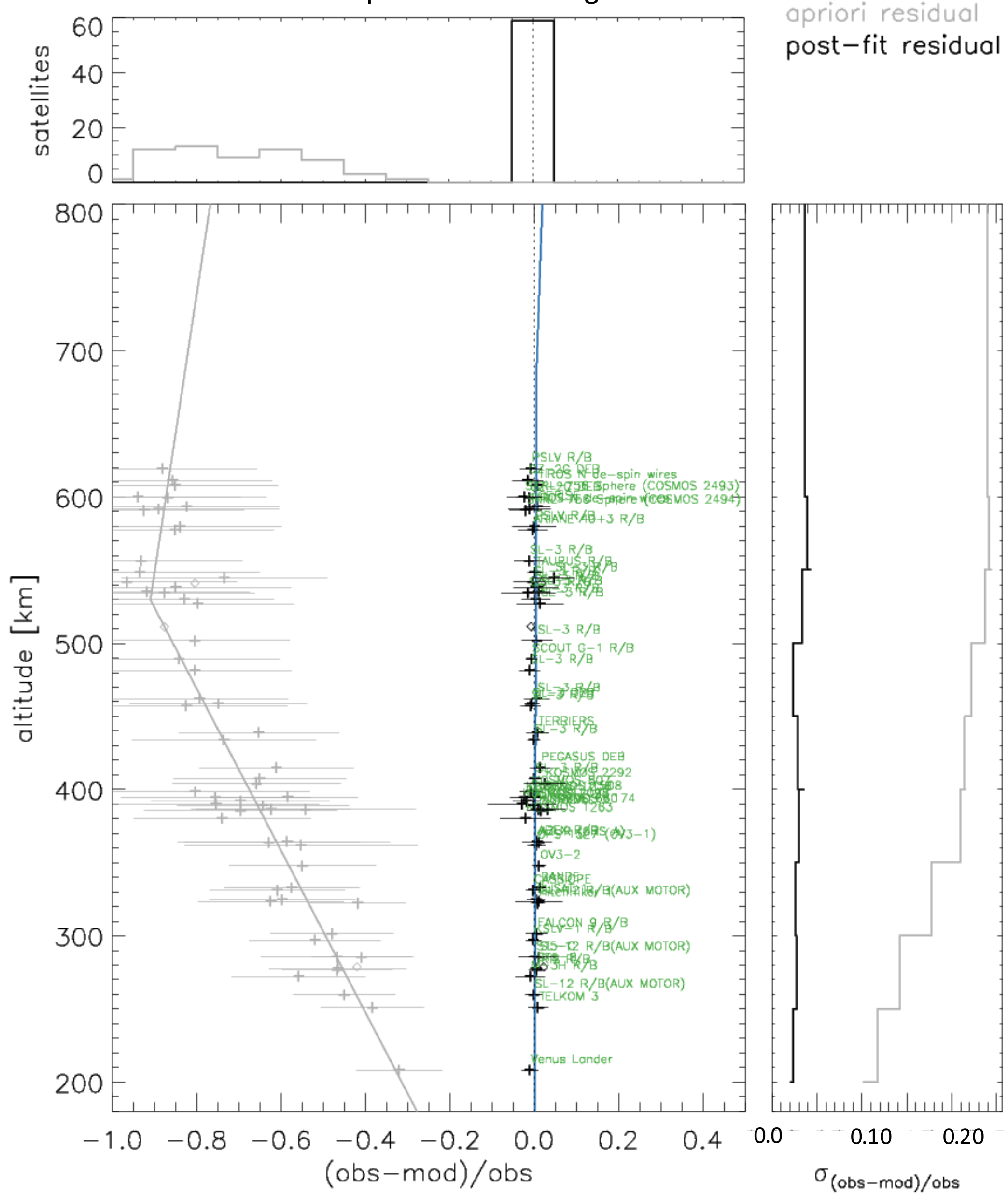
- HASDM
- IDEA
- *…other*

Drag Environment and Data Assimilation

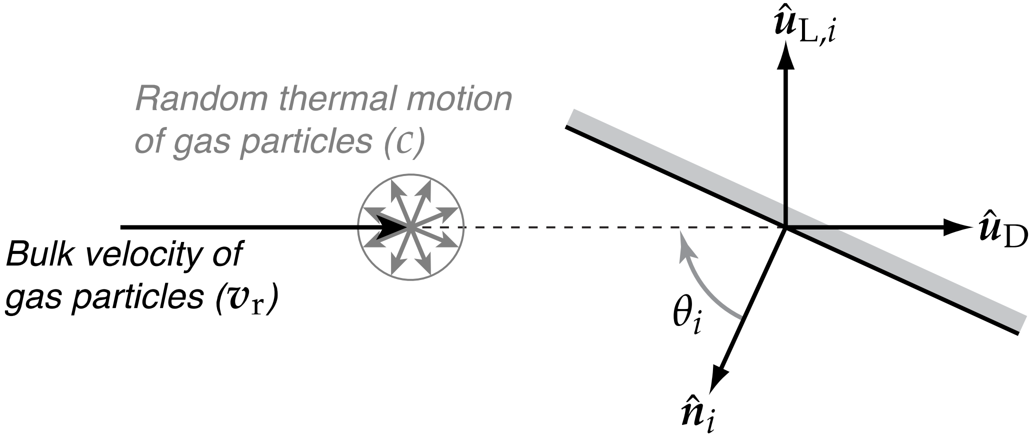
Subset of Analytical Drag Coefficient Models Evaluated for Spheres



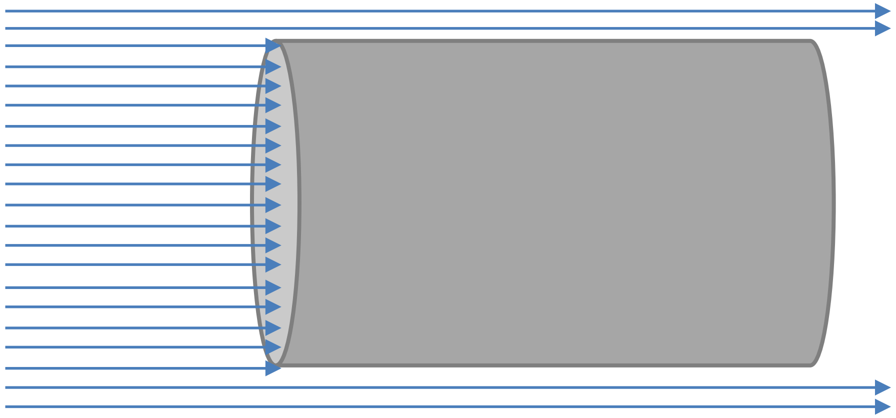
Calibration Atmosphere with Forcing Estimates



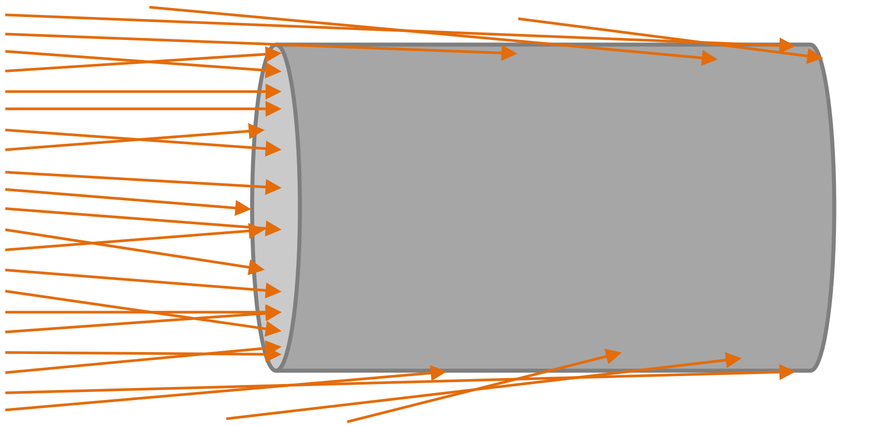
Free-Stream Properties



low atmospheric temperature T_a



high atmospheric temperature T_a



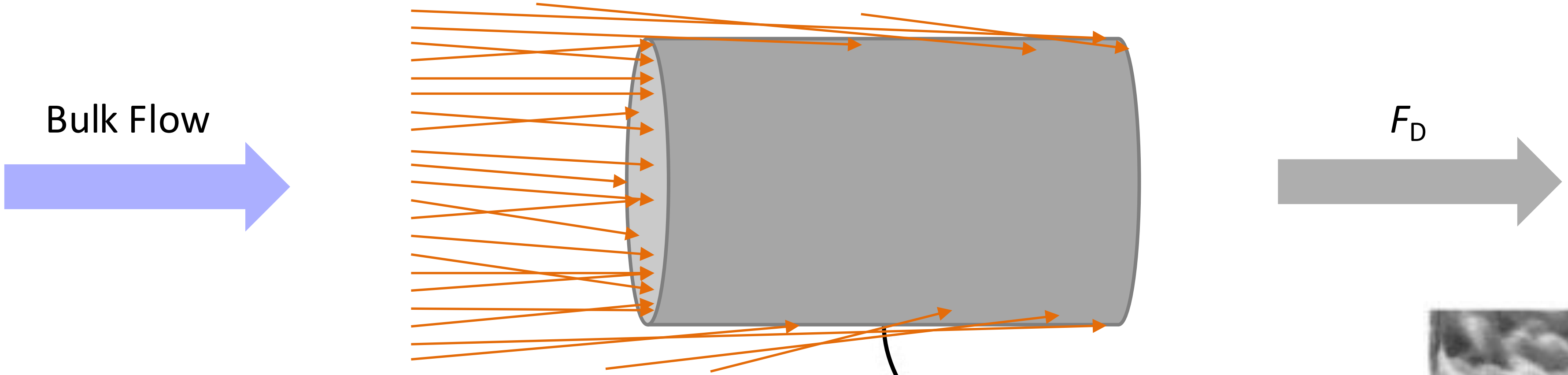
$$c_{mp,j} = \sqrt{2 \frac{k}{m_j} T} \, ,$$ Most probable thermal velocity

$$S_j = \frac{v_r}{c_{mp,j}}$$ Speed ratio

Doornbos, 2010

Speed ratio and shape/orientation drive the ratio of low-incidence to high-incidence interactions

Aerodynamic Forces



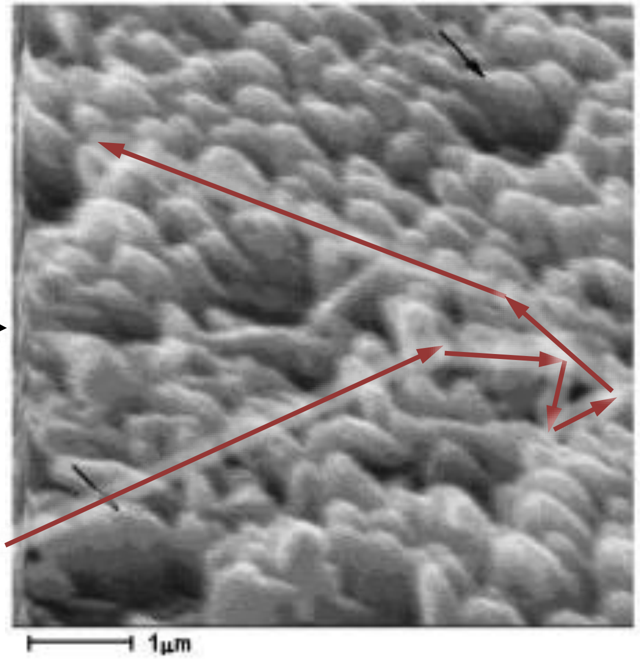
$$F_D = \frac{\Delta p}{\Delta t}$$

$$F_D \sim \{c_1(s) A n_i V_i\} \{c_2(\theta_i E_i \dots)\, m_i V_i\}$$

$$F_D \sim c_1(s) c_2(\theta_i E_i)\, A\, \rho\, V_i^2$$

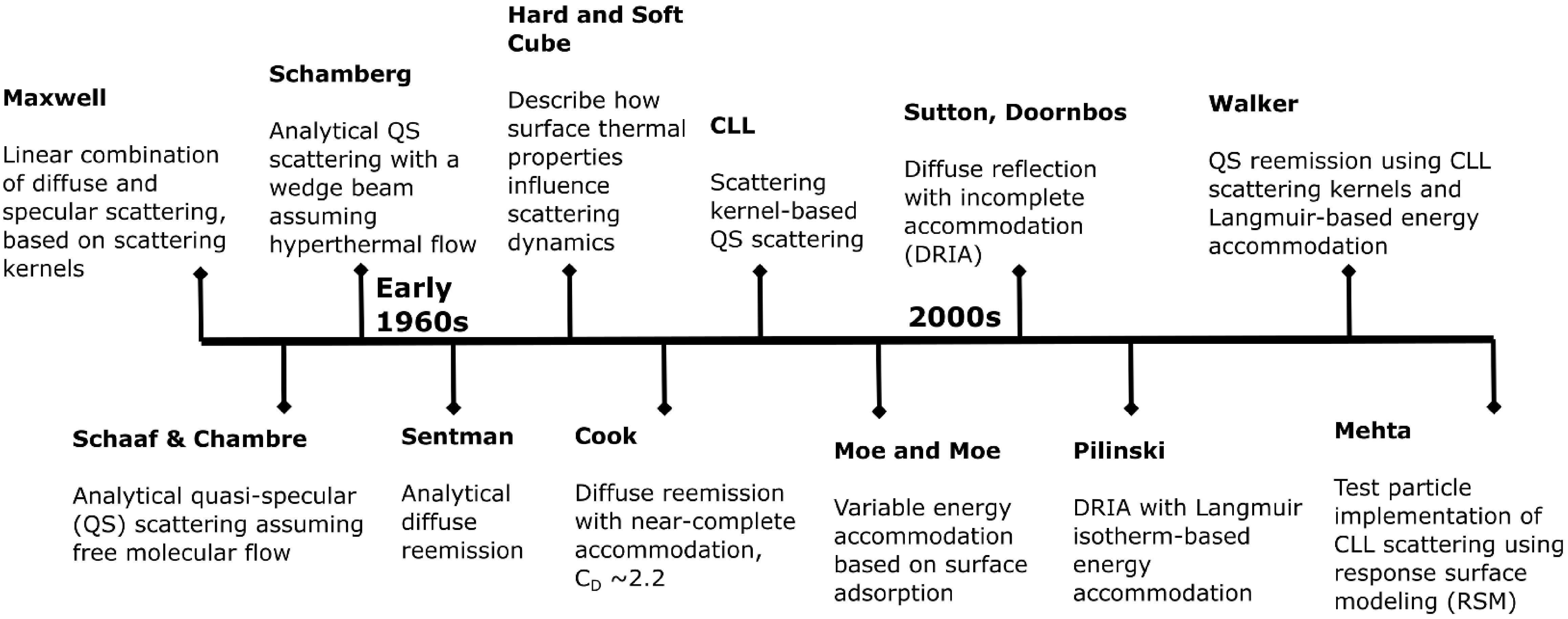
$$F_D \sim C_D\, A\, \rho\, V_i^2$$

SEM of solar panel surface (Skurat et al.)



length of N_2 molecule is ~0.0003 µm

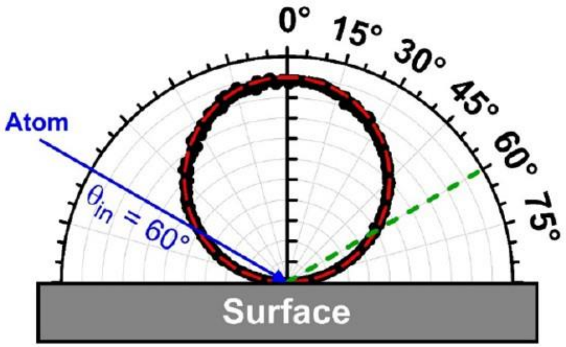
Historical Overview



Diffuse and quasi-specular scattering → Effect of surface contamination → Diffuse with variable energy accommodation → Quasi-specular with variable energy and momentum accommodation

GSI Currently in Use for Published Density Datasets (Mostly)

Diffuse (Cosine) Reflection with Incomplete Accommodation (DRIA)



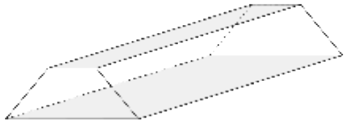
+ $$\alpha = \frac{E_i - E_r}{E_i - E_s} \leq 1$$ =

$$C_{D,\text{sphere}} = \frac{2s^2+1}{\sqrt{\pi}s^3}\exp(-s^2) + \frac{4s^4+4s^2+1}{2s^4}\text{erf}(s) + \frac{2\sqrt{\pi}}{3s}\sqrt{T_{\text{out}}/T_a}$$

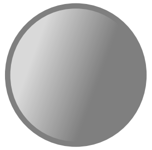
- Static energy accommodation (values between 0.8 – 1.0)
- Semi-empirical model of energy accommodation (SESAM)
- Similar approach can be taken with CLL scattering model but there are now two GSI parameters

Density Ratio Altitude Corrections

$$\Delta R = \left(\frac{\rho^{obs}}{\rho^{mod}}\right)_{GRACE} - \left(\frac{\rho^{obs}}{\rho^{mod}}\right)_{sphere}$$



GRACE



sphere

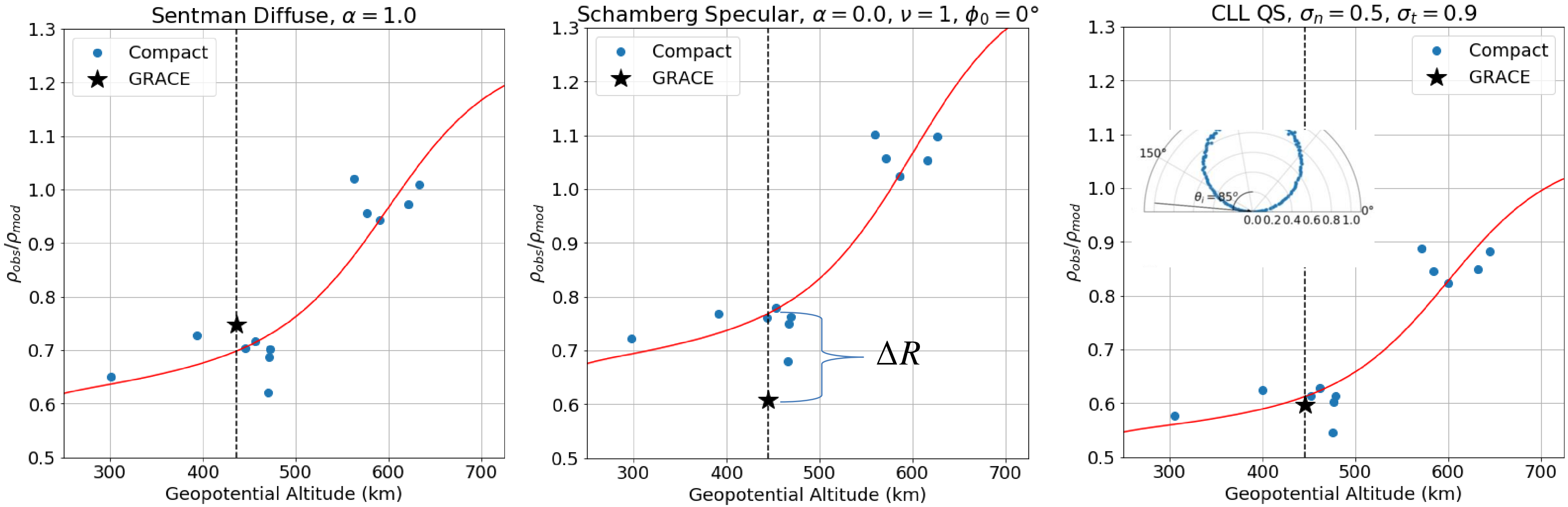


Figure: Avg. altitude profiles of observed-to-modeled density ratios during solar minimum conditions. Observations from spherical satellites (blue circles) are based on TLE analysis, while GRACE density (black star) is accelerometer-derived. The atmospheric model used in NRLMSISE-00

(Bernstein & Pilinski, SWJ, 2022)

GSI consistent with GRACE-sphere comparisons (work by Valerie Bernstein)

$$\Delta R = \left(\frac{\rho^{obs}}{\rho^{mod}}\right)_{GRACE} - \left(\frac{\rho^{obs}}{\rho^{mod}}\right)_{sphere}$$

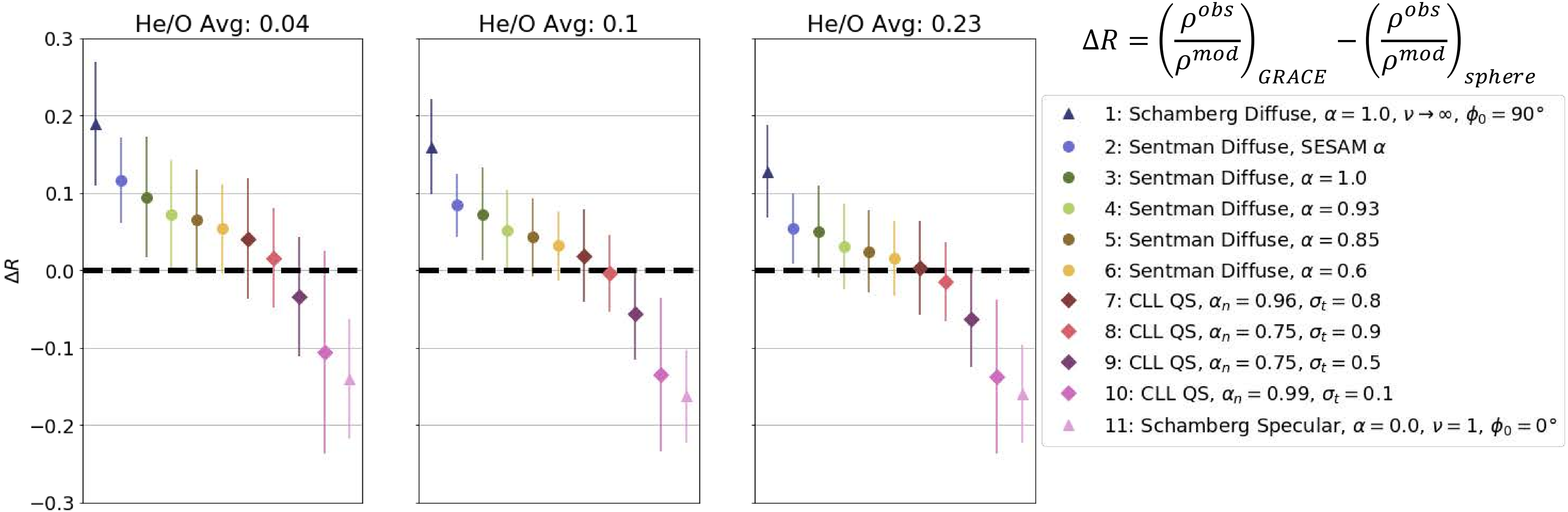


Figure: Average derived density ratio differences between GRACE and compact satellites in three different atmospheric He/O conditions. Different colors and markers represent different C_D models, and vertical error bars represent compact satellite density uncertainty

GSI consistent with GRACE-sphere comparisons (work by Valerie Bernstein)

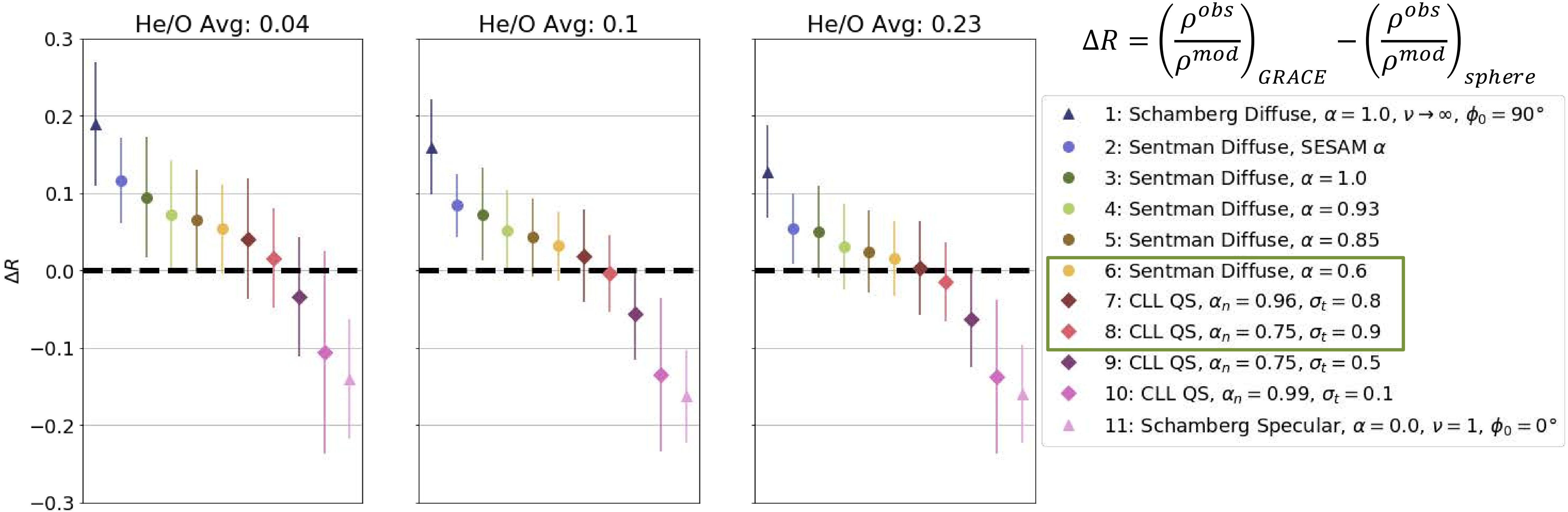
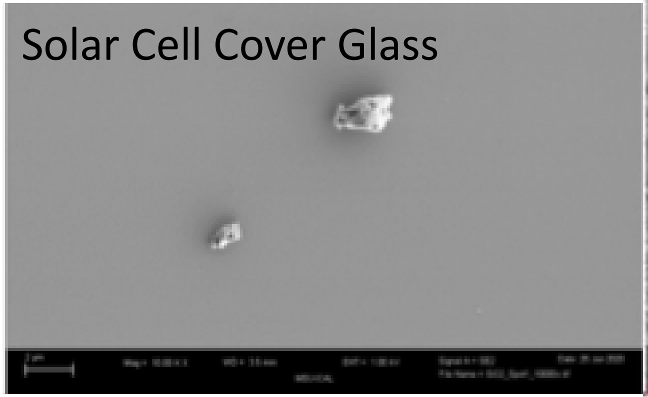
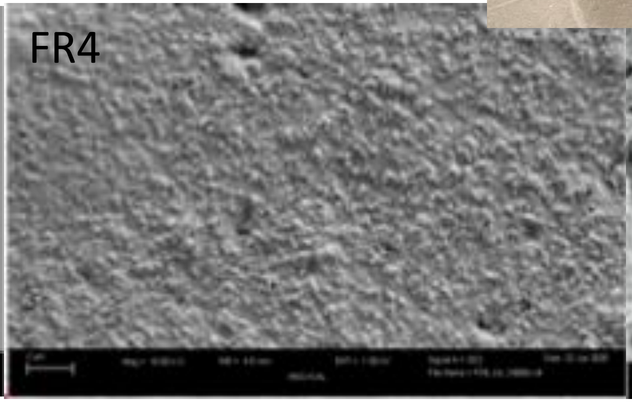


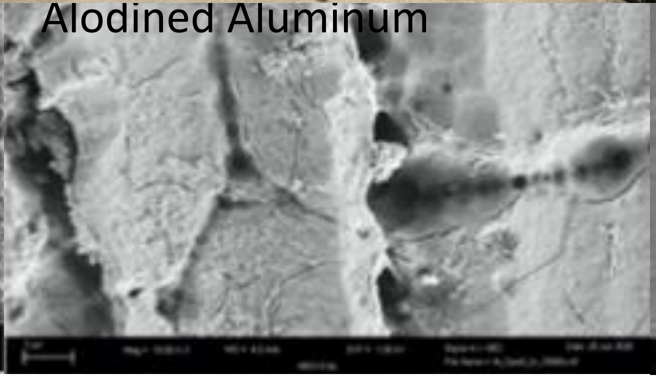
Figure: Average derived density ratio differences between GRACE and compact satellites in three different atmospheric He/O conditions. Different colors and markers represent different C_D models, and vertical error bars represent compact satellite density uncertainty

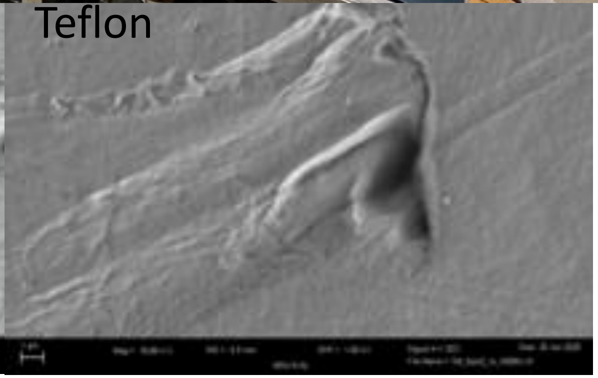
Laboratory Investigation

- Laboratory investigation of GSI (Tim Minton, CU Aerospace Engineering)
  - Examine both AO scattering from common s/c materials
  - Fit model parameters to laboratory results



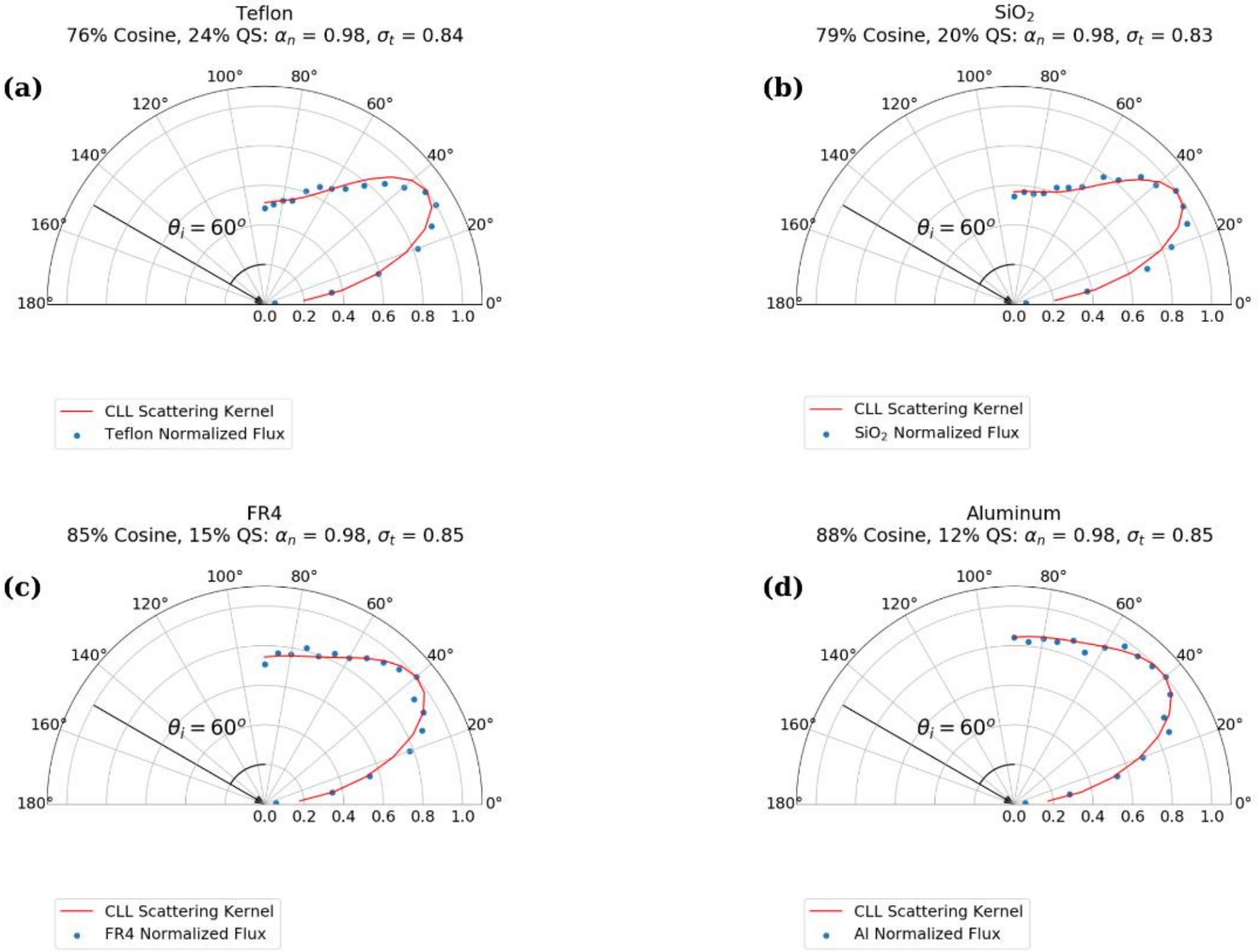






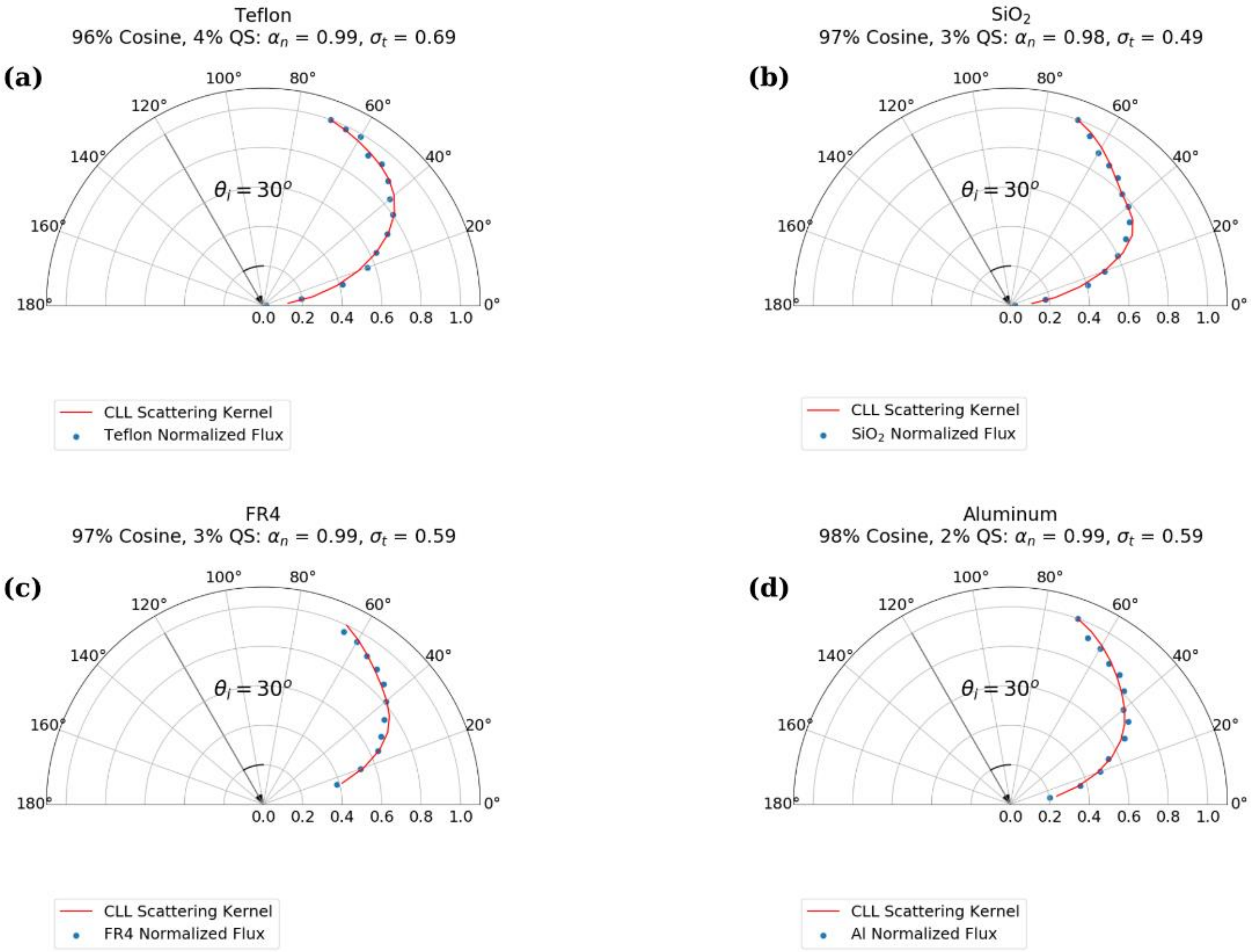
Laboratory Results, High Incidence Angles

- Laboratory scattering exhibits broad distributions that are well-represented by combining cosine and quasi-specular (CLL) scattering
- For the quasi-specular component, tangential momentum is incomplete
- Very little thermal desorption



Laboratory Results, Lower Incidence Angles

- Laboratory scattering exhibits broad distributions that are well-represented by combining cosine and quasi-specular (CLL) scattering
- For the quasi-specular component, tangential momentum is incomplete
- As incident angle decreases, the cosine portion increases



Main findings – Gas-surface energy transfer

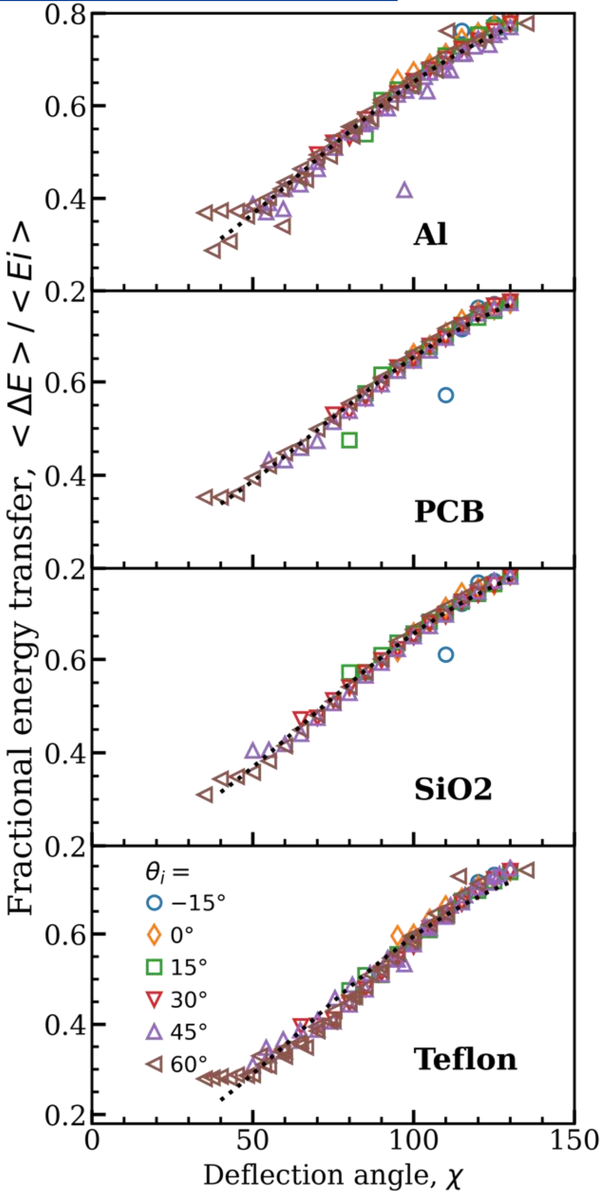
Energy transfer to the surface is very well fitted by the soft spheres model.

$$\frac{\Delta E}{E_i} = \frac{2\mu}{(\mu+1)^2}\left[1 + \mu\sin^2\chi + \frac{E_{int}}{E_i}\left(\frac{\mu+1}{2\mu}\right) - \cos\chi\sqrt{1 - \mu^2\sin^2\chi - \frac{E_{int}}{E_i}(\mu+1)}\right].$$

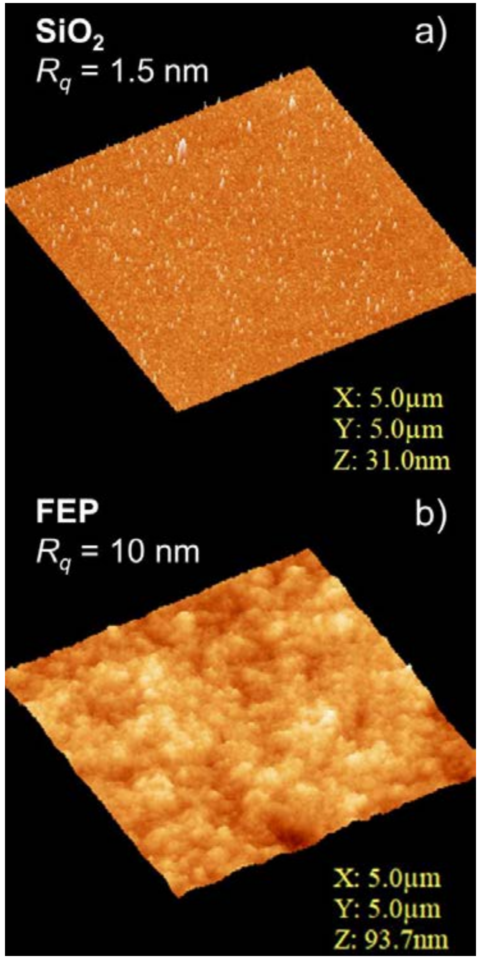
The deflection angle is what matters, it fits well every incident angle and both **in-plane and out-of-plane (OOP) data**.

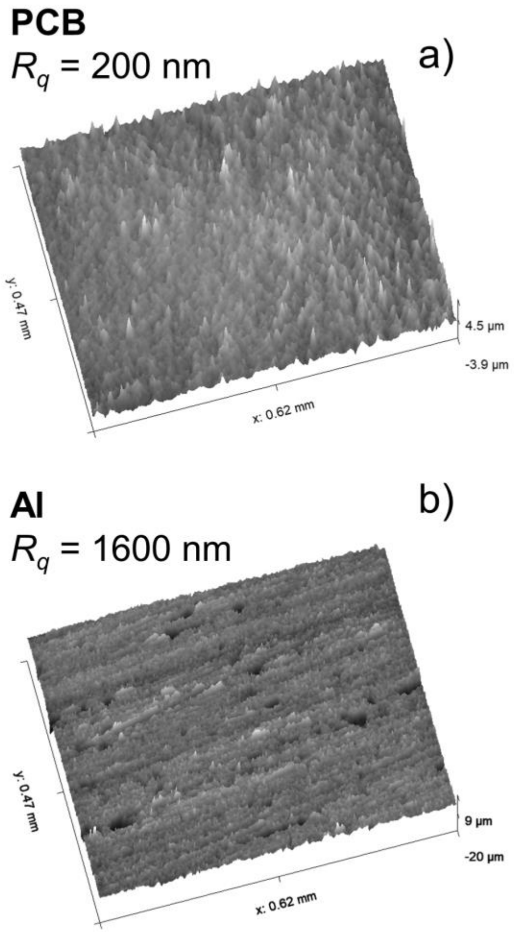
Surface morphology does not dictate energy transfer behavior. SiO2 is the smoothest surface and shows similar energy transfer as the Al and PCB samples.

From Pedro Jorge and Tim Minton



Main findings - Fraction of thermal particles

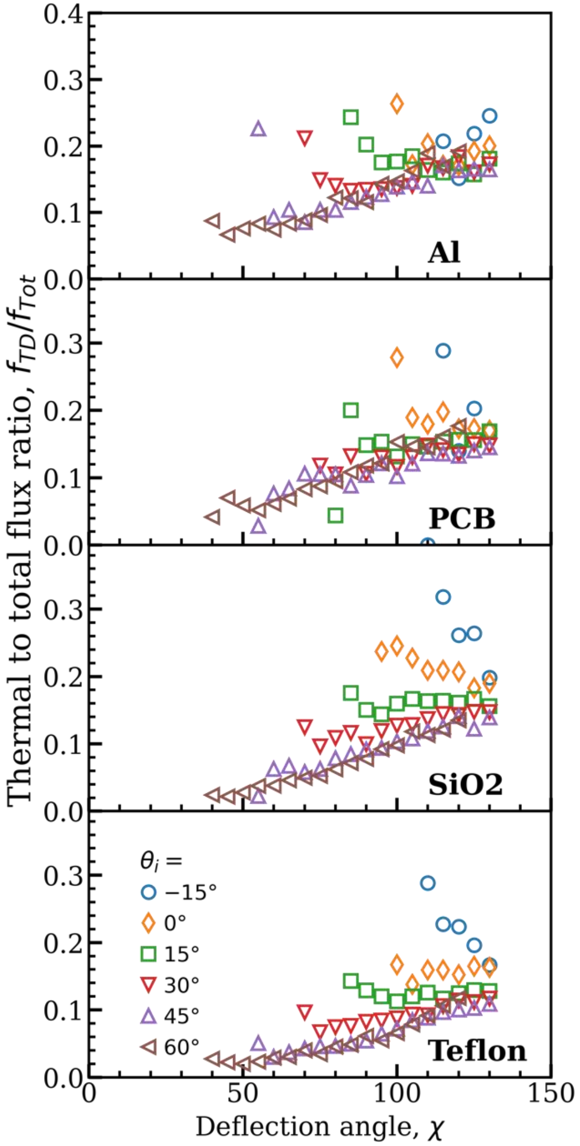




Surface roughness and energy transfer (proportional to deflection angle) correlates well with the fraction of thermal particles.

This also holds for Kapton experiments where roughness was gradually increased.

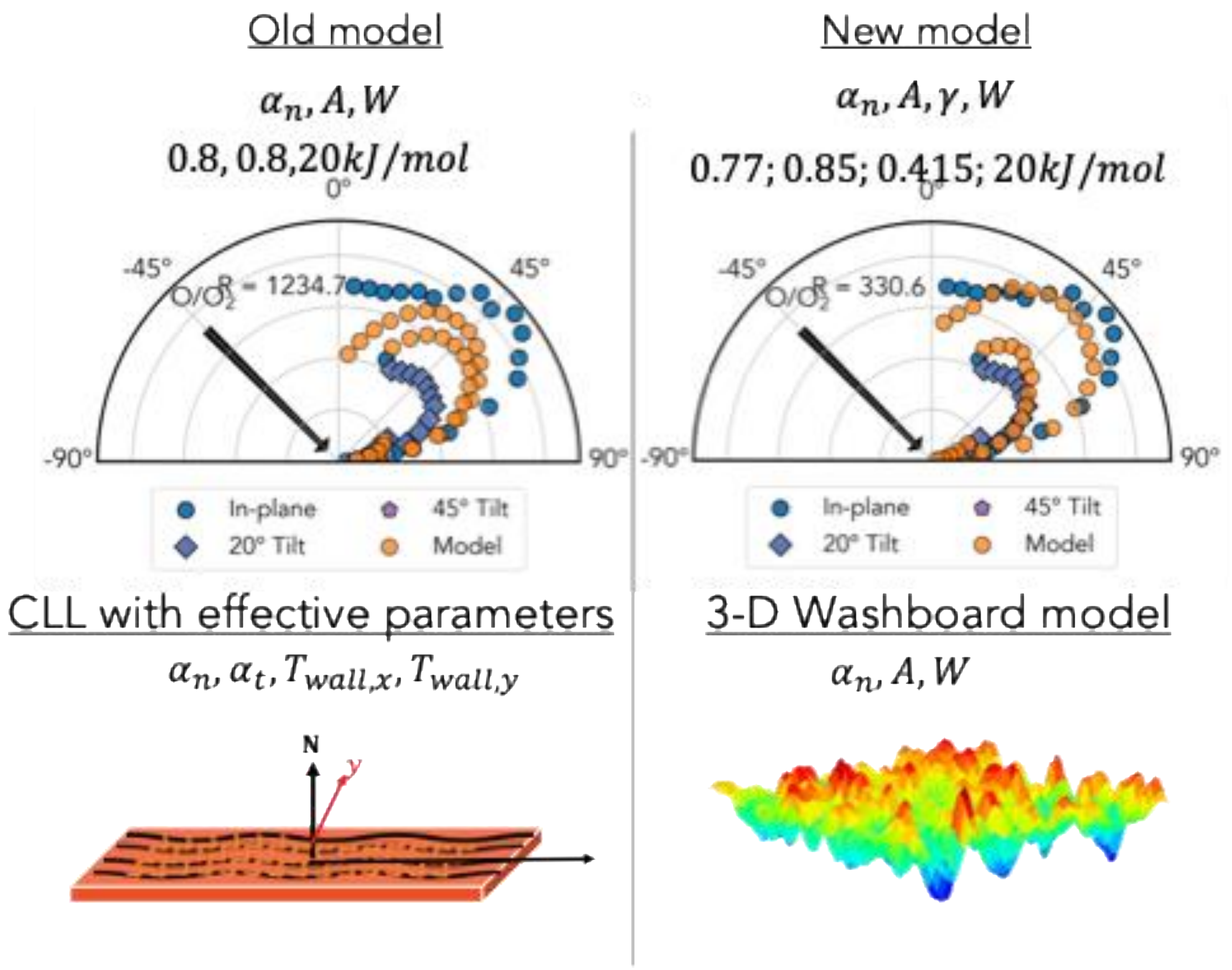
Is there an intrinsic threshold of roughness that most engineering materials achieve?



From Pedro Jorge and Tim Minton

Surface Roughness and Scattering (courtesy of Pedro Jorge)

- Work by Pedro Jorge (visiting graduate student from VKI)
- On the left is a scattering model compared with lab results wherein the model uses the imposition of effective wall temperatures to scale the thermal velocity to yield broader distributions using CLL.
- On the right, the imposition of a corrugation parameter and potential well depth results in closer data-model agreement.
- Independent work by Sabin Anton and Christian Siemes at TU Delft, modeling the scattering from real surfaces semi-analytically also implies significant levels of backscatter.



Surface Roughness and Scattering (Sabin Anton)

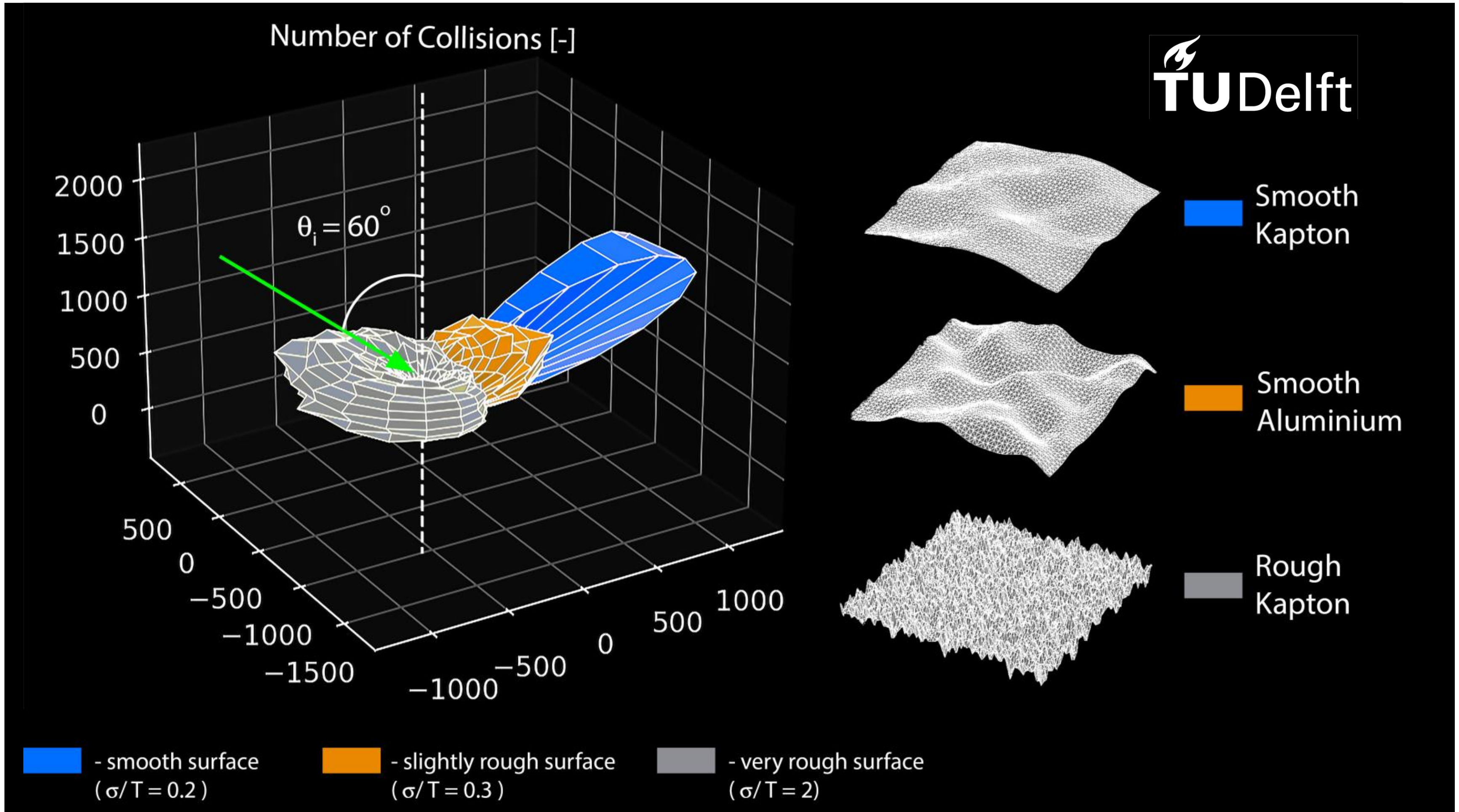
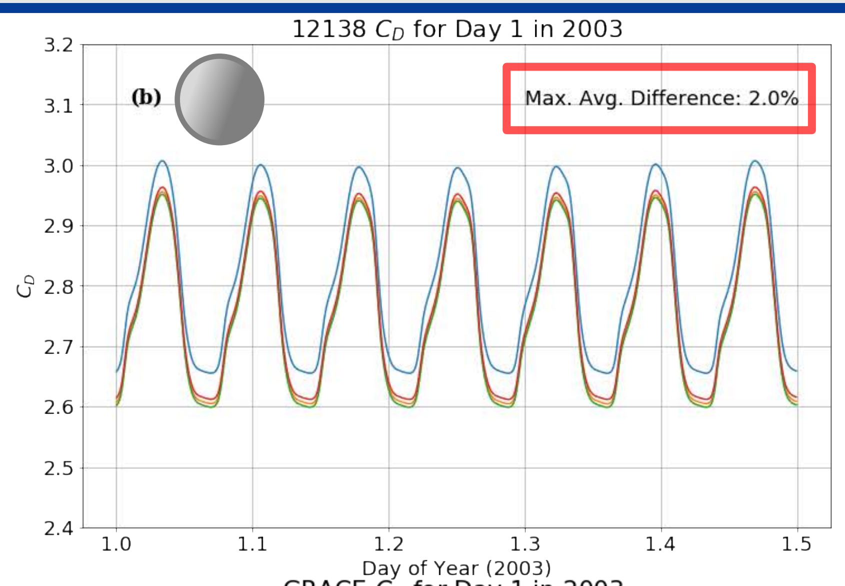
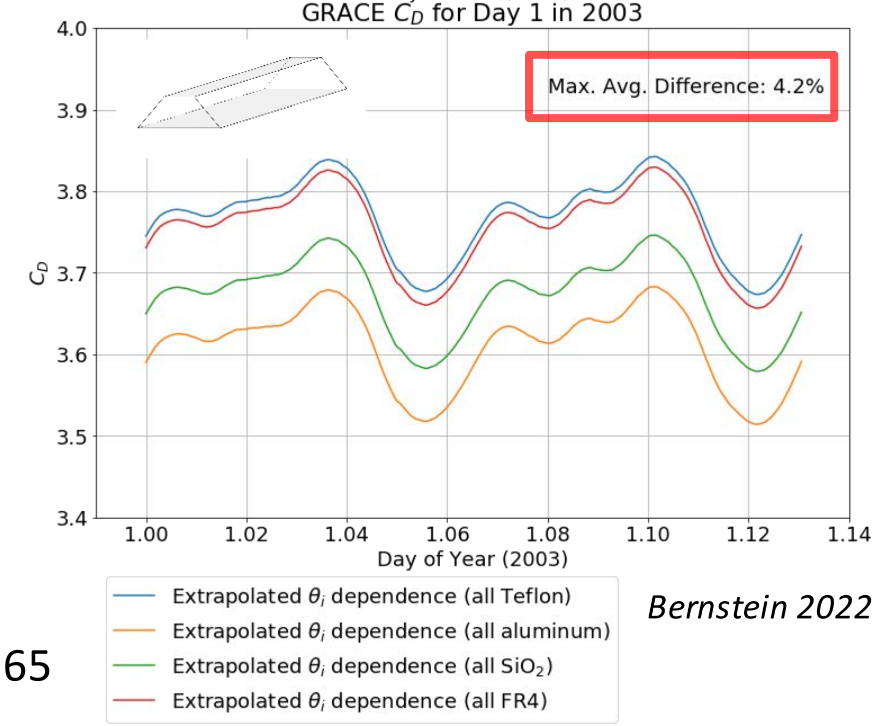


Figure 4: The influence of surface roughness on the 3D scattering indicatrix of Helium, assuming a normal energy accommodation coefficient of $\alpha_N = 0.2$.

Work by Sabin Anton and Christian Siemes

Surface Composition and Drag Coefficient





Bernstein 2022

Satellite	Diameter	Surface	CD	Mean Sig %	Delta CD % (-aluminum)
22991	4"	sand-blasted aluminum	1.99	0.2	-----
22990	4"	polished chrome	1.93	0.2	-3.0
23472	4"	white chemglaze paint	1.96	0.2	-1.5
22995	6"	sand-blasted aluminum	2.01	0.2	-----
22994	6"	polished chrome	1.96	0.2	-2.5
23471	6"	black iridite	1.97	0.2	-2.0

Table 1. Mean and standard deviation C_D values, with differences from a roughened aluminum sphere, for the 4" and 6" ODERACS spheres at an average altitude of about 280 km.

Moe and Bowman, 2005

Effect of different surface materials based on laboratory atomic oxygen flux is < 5% (~2% for spheres), consistent with Moe and Bowman (2005) orbital analysis of spheres and Pilinski et al. (2011) Starshine satellite analysis.

Starlink Drag Analysis (David Fitzpatrick) at 550 km

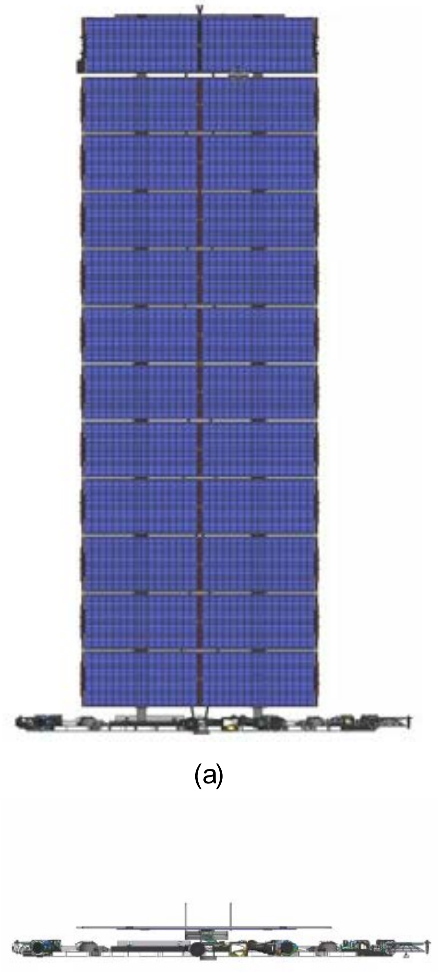
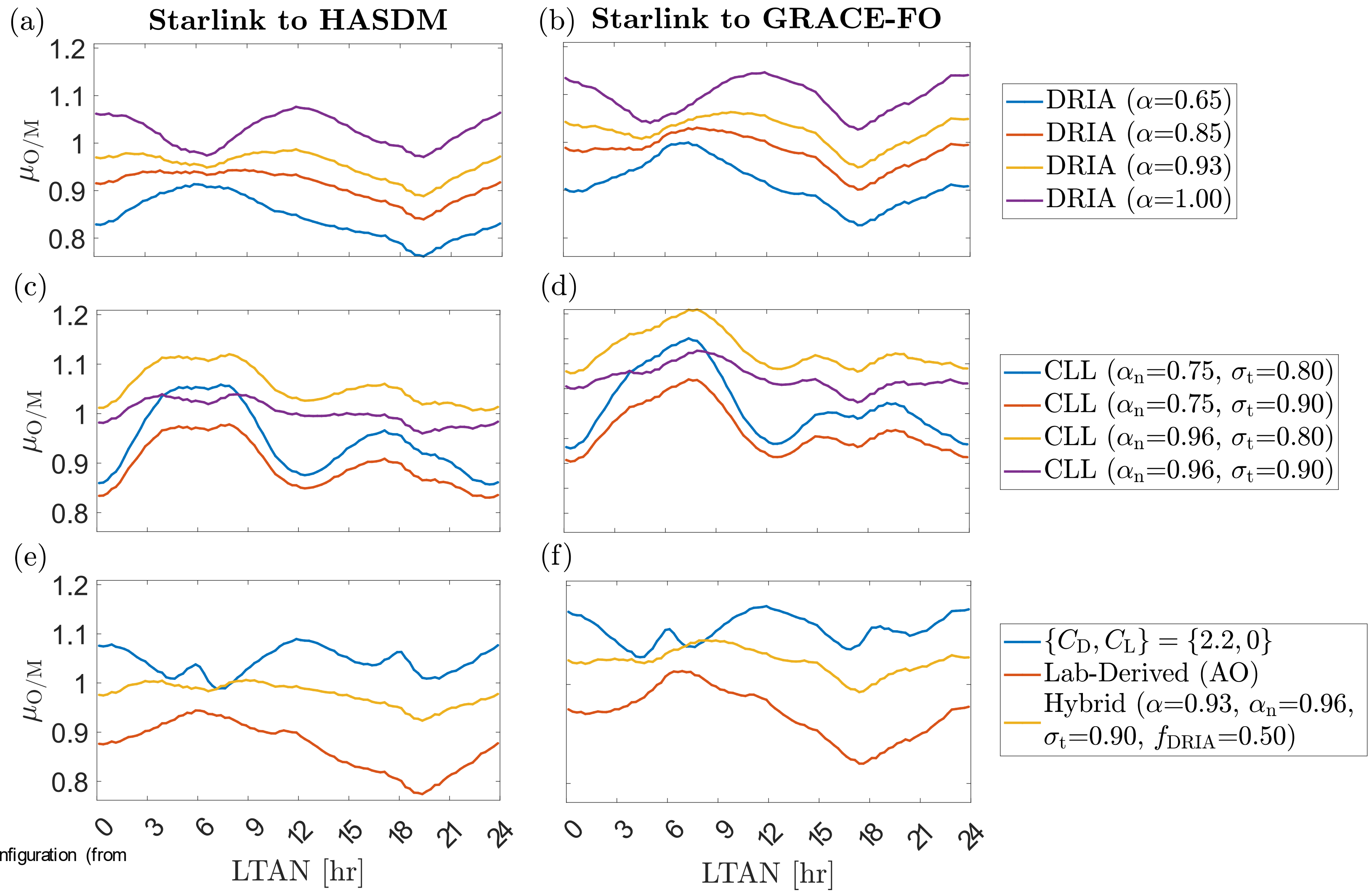


Fig. 1: Rendering of a STARLINK v1.0 satellite in (a) a shark-fin and (b) an open-book configuration (from www.spacex.com/updates [16]).

Observed-Modeled Density Ratio based on Orbit-Average Drag from ~1500 Satellites



Work by David Fitzpatrick and Eric Sutton

Starlink Drag Analysis (David Fitzpatrick) at 550 km

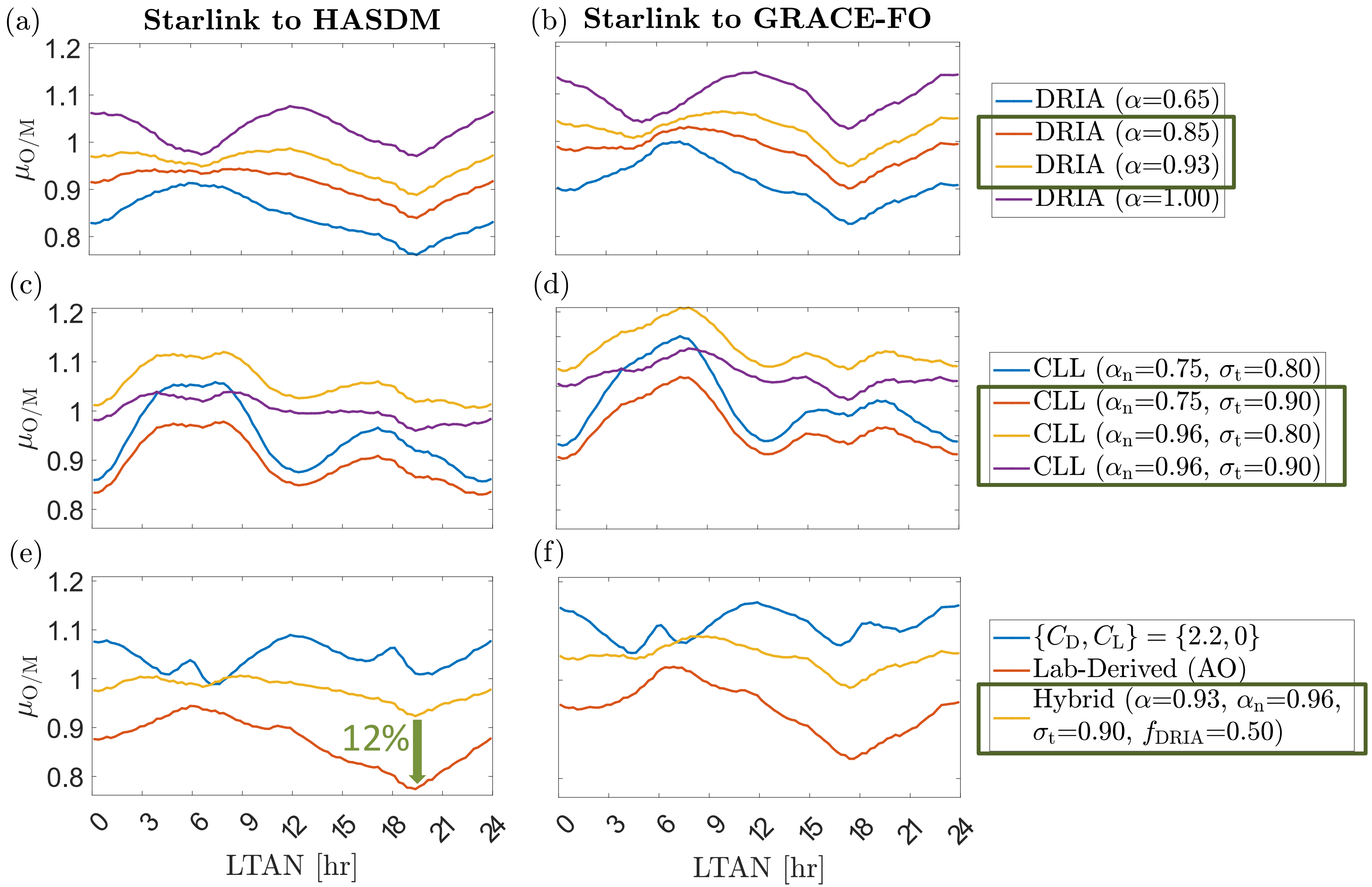
Observed-Modeled Density Ratio based on Orbit-Average Drag from ~1500 Satellites

- Caveat: baseline CD is not controlled for
- DRIA model does not work well with ”flat plate” geometries
- Fits based only on AO scattering also fall short
- Hybrid DRIA+CLL seems to produce the most consistency

CLL, consistent with Bernstein and Pilinski 2022

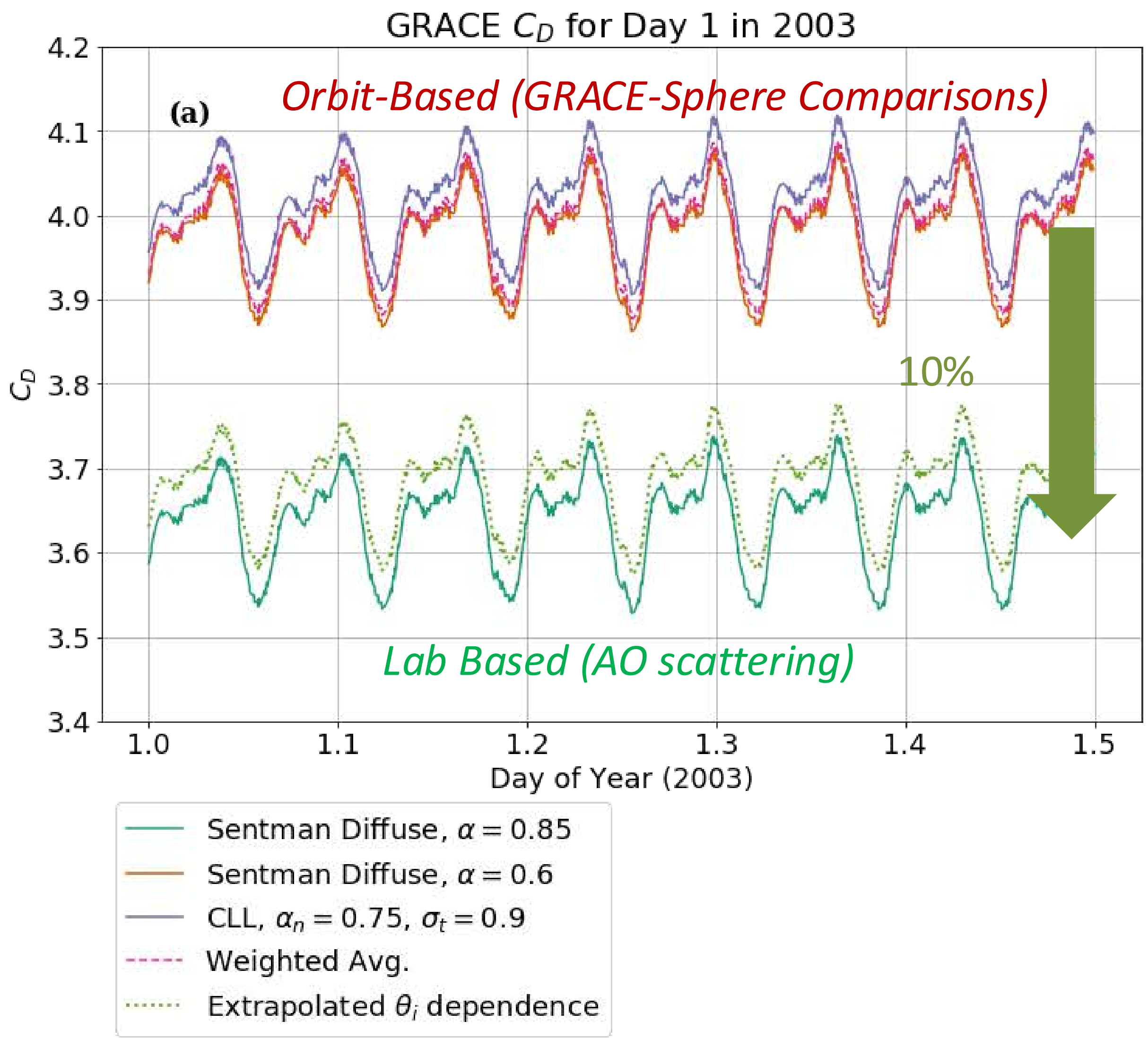
Hybrid-Model (Fitzpatrick)

Based on AO-scattering

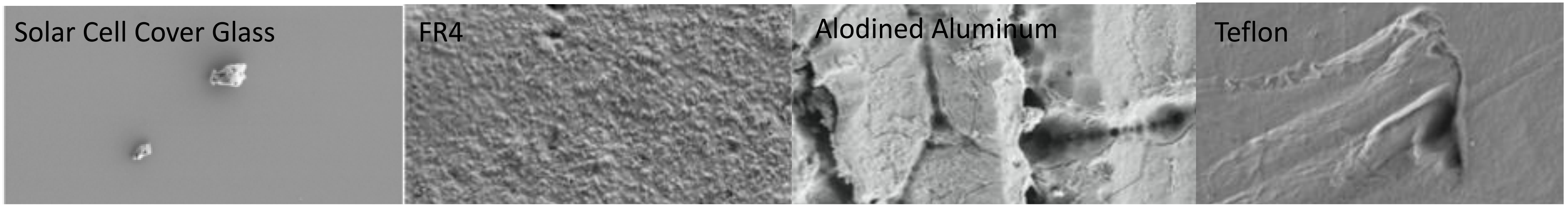


Work by David Fitzpatrick and Eric Sutton

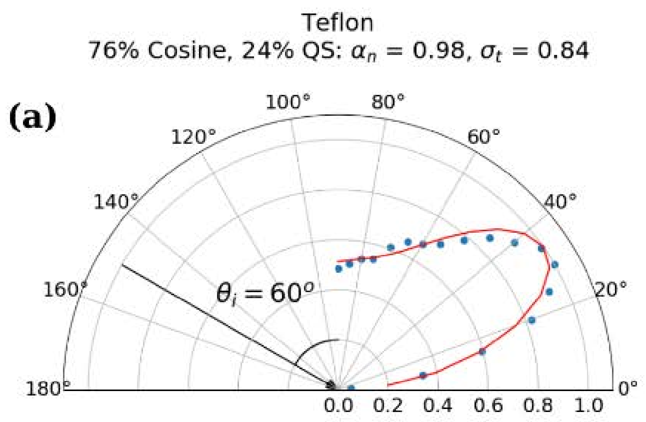
GRACE analysis at 500 km (Valerie Bernstein)

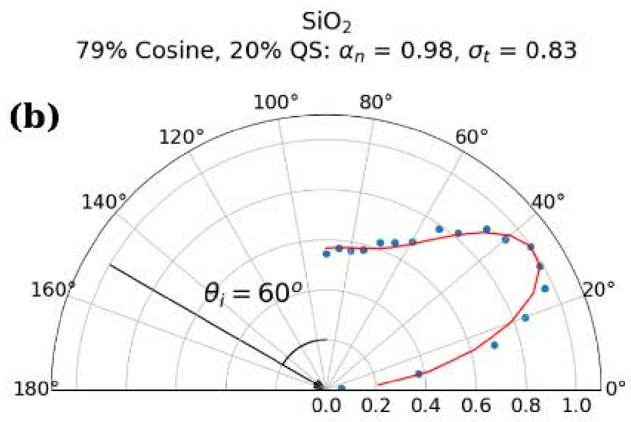


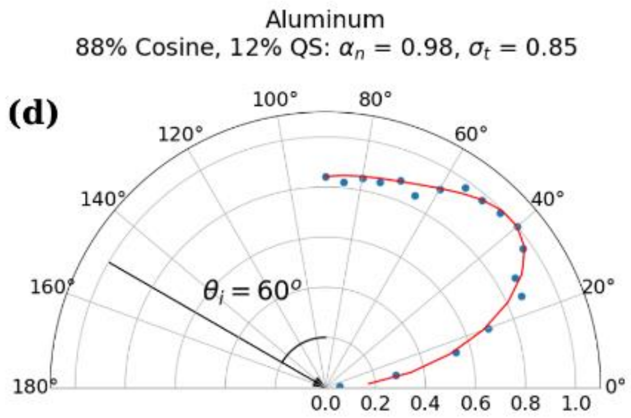
- **Tangential momentum accommodation is incomplete** in both laboratory scattering of AO from engineering surfaces and as implied by comparative aerodynamics above and below the O/He transition in the Earth's thermosphere [Bernstein and Pilinski 2022]
- *Remaining Challenges*: Large uncertainties remain in quantifying the level of tangential momentum accommodation for both AO and (esp.) He in orbit and in the laboratory.
- **Atoms are backscattered with very broad angular distributions**, somewhat like DRIA, but not well represented by CLL. For the quasi-specular component, tangential momentum is incomplete. As the incident angle *decreases*, the near-cosine portion *increases.*
- *Remaining Challenges*: constraints of the current laboratory facility do not allow the detection of in angular positions that are close to the incident beam. Need better models of **out of plane scattering** on engineering surfaces.
- **Tangential momentum accommodation (and normal energy accommodation) appears to be higher for Helium than for AO.** This conclusion is based on comparative drag analysis but is also consistent with early results of Jorges, Anton and Siemes as well as work by Erofeev et al. 2012. This increase in tangential momentum accommodation for Helium could be associated with even larger "backscattered" fluxes in the Helium-dominated upper thermosphere. Implies increase in drag coefficient with increasing altitude for most satellite geometries.
- *Remaining Challenges*: Refining estimates of the tangential momentum accommodation values for Oxygen and Helium.

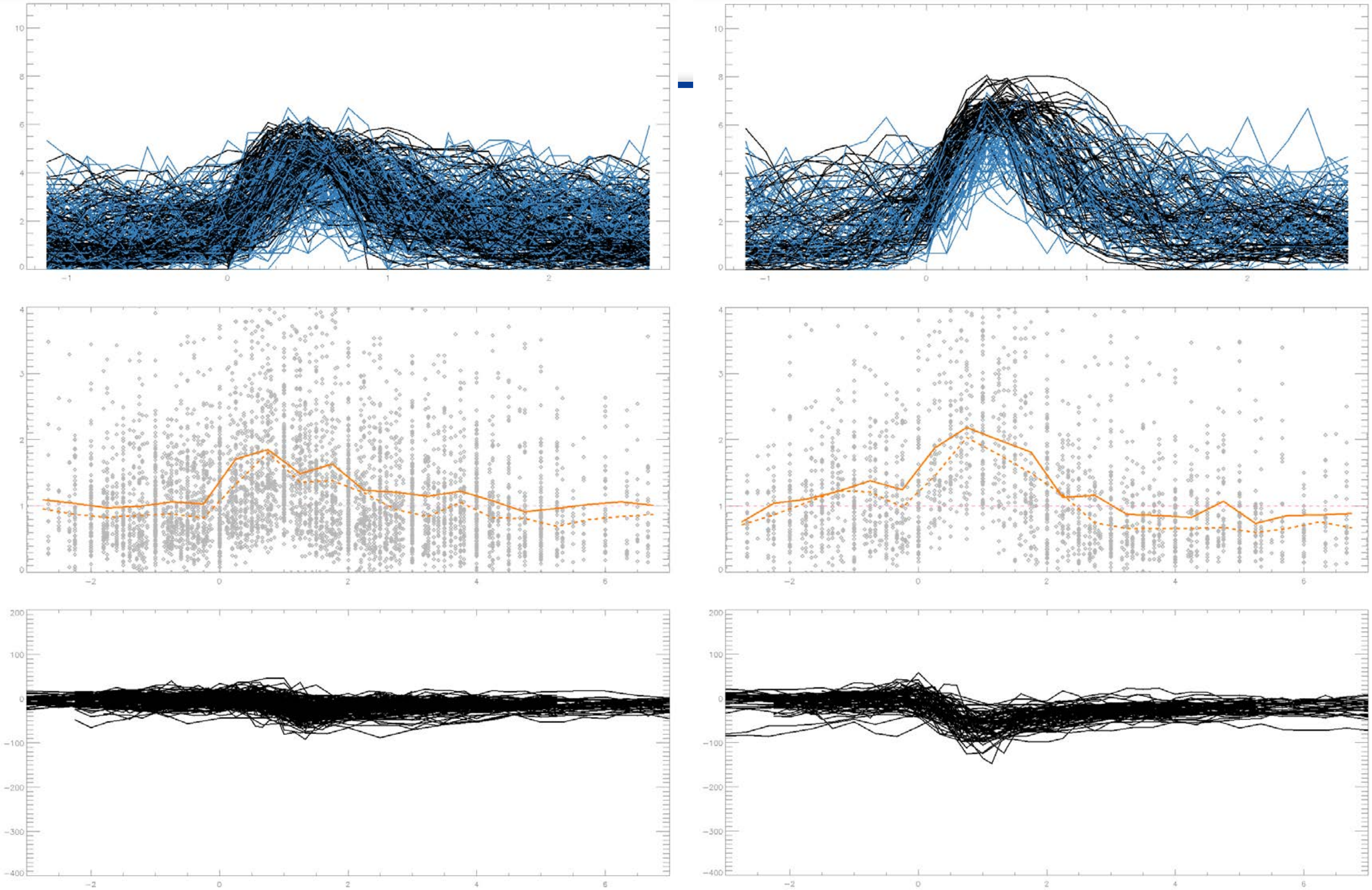


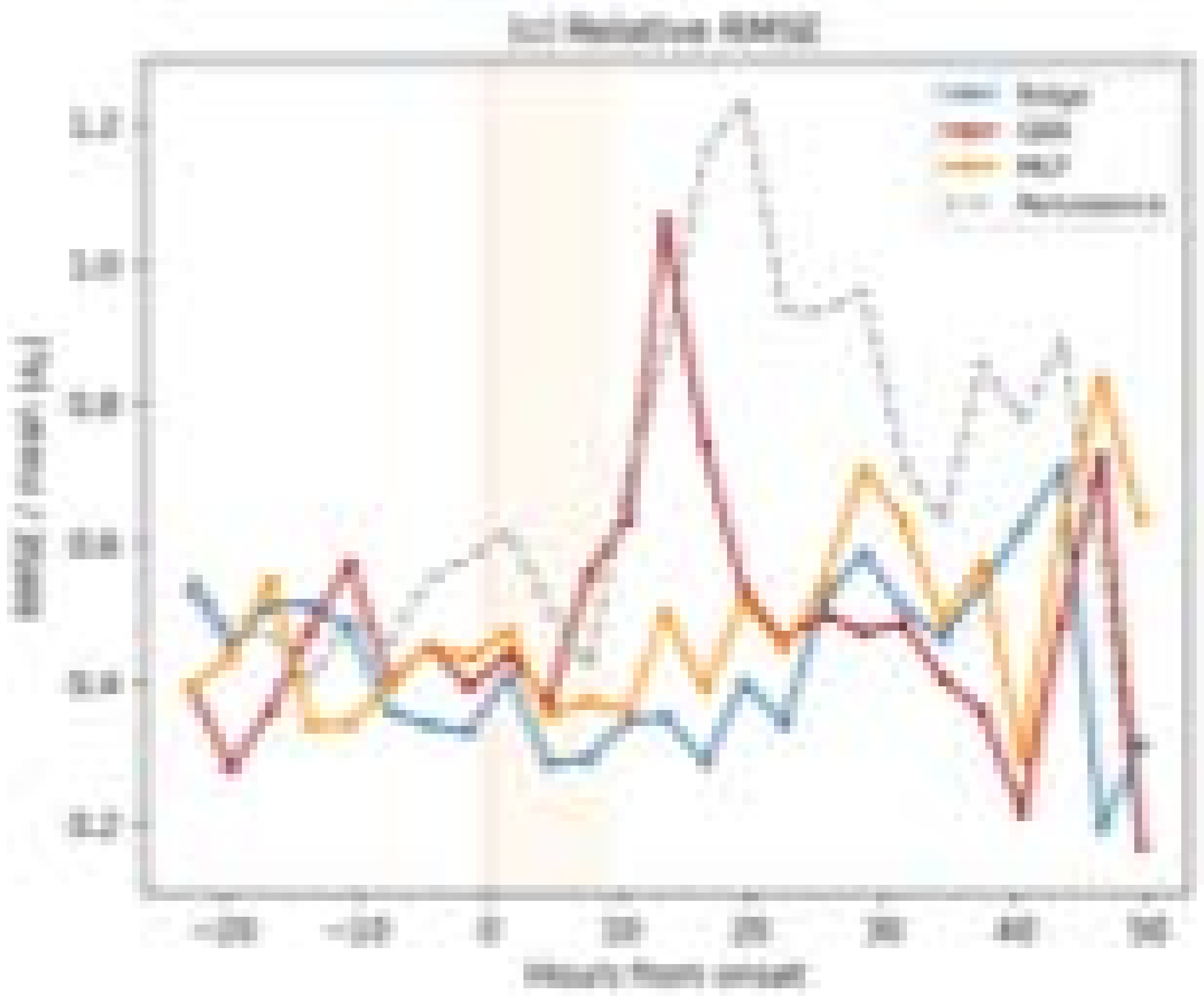
- Laboratory results include a small **thermal-desorption (TD) component ranging from a few percent to 20% of the scattered flux**. This TD component is not sufficient to explain most of the observed broad scattering distributions.
- *Open Questions*: Is thermal desorption and/or the presence of adsorbate playing a role in determining aggregate gas-surface interactions alongside with a change in tangential momentum accommodation from oxygen to helium, and is it strongly dependent on the adsorbate coverage fraction as has been supposed over the last 1-2 decades?
- In the AO rich thermosphere (lower altitudes), surface-composition/roughness differences might be responsible for 2-5% CD variation according to our results
- *Open Questions*: What is limiting the impact of surface composition and roughness (at a variety of spatial scales on the surface)?



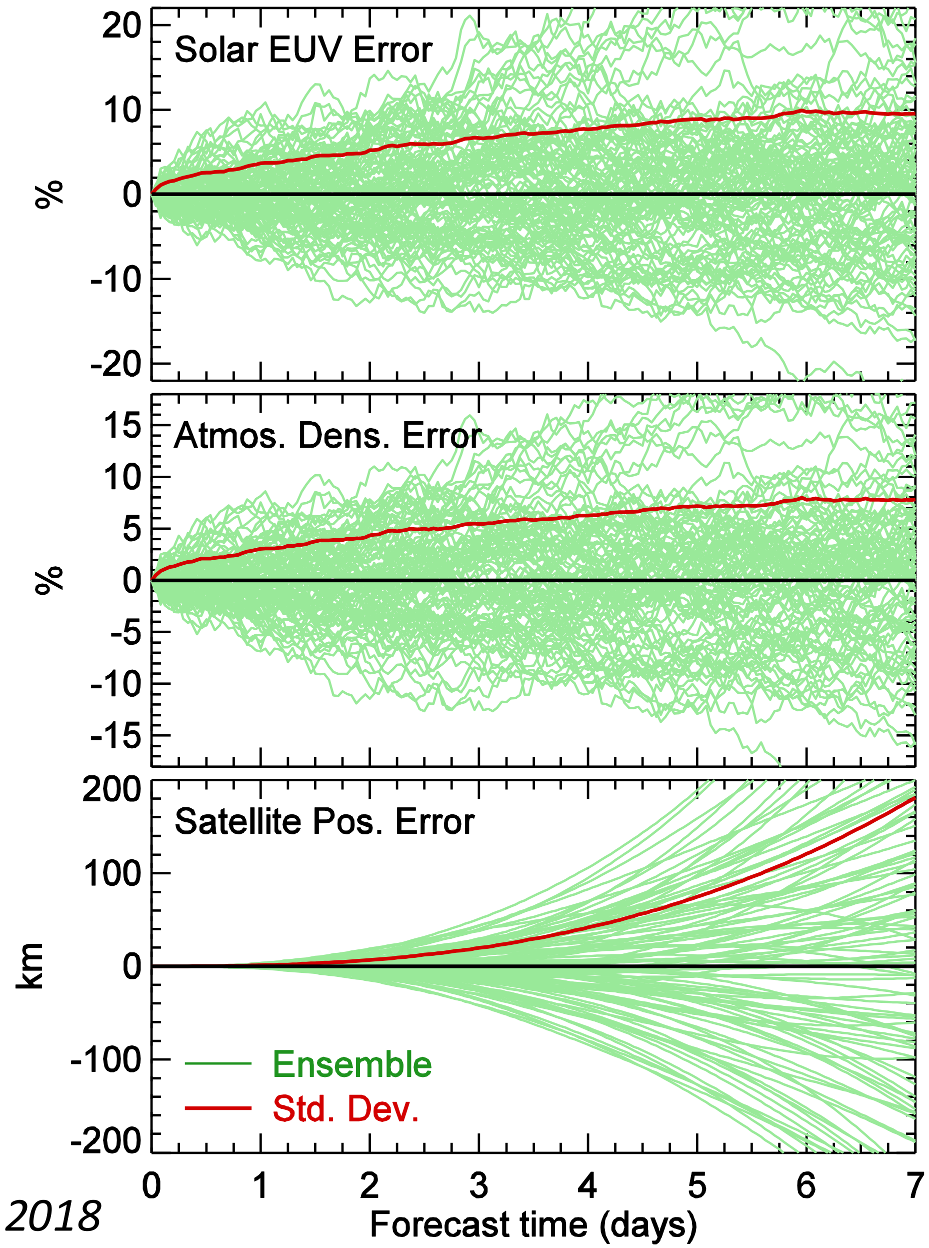








Thermospheric Space Weather and Predicting Orbits



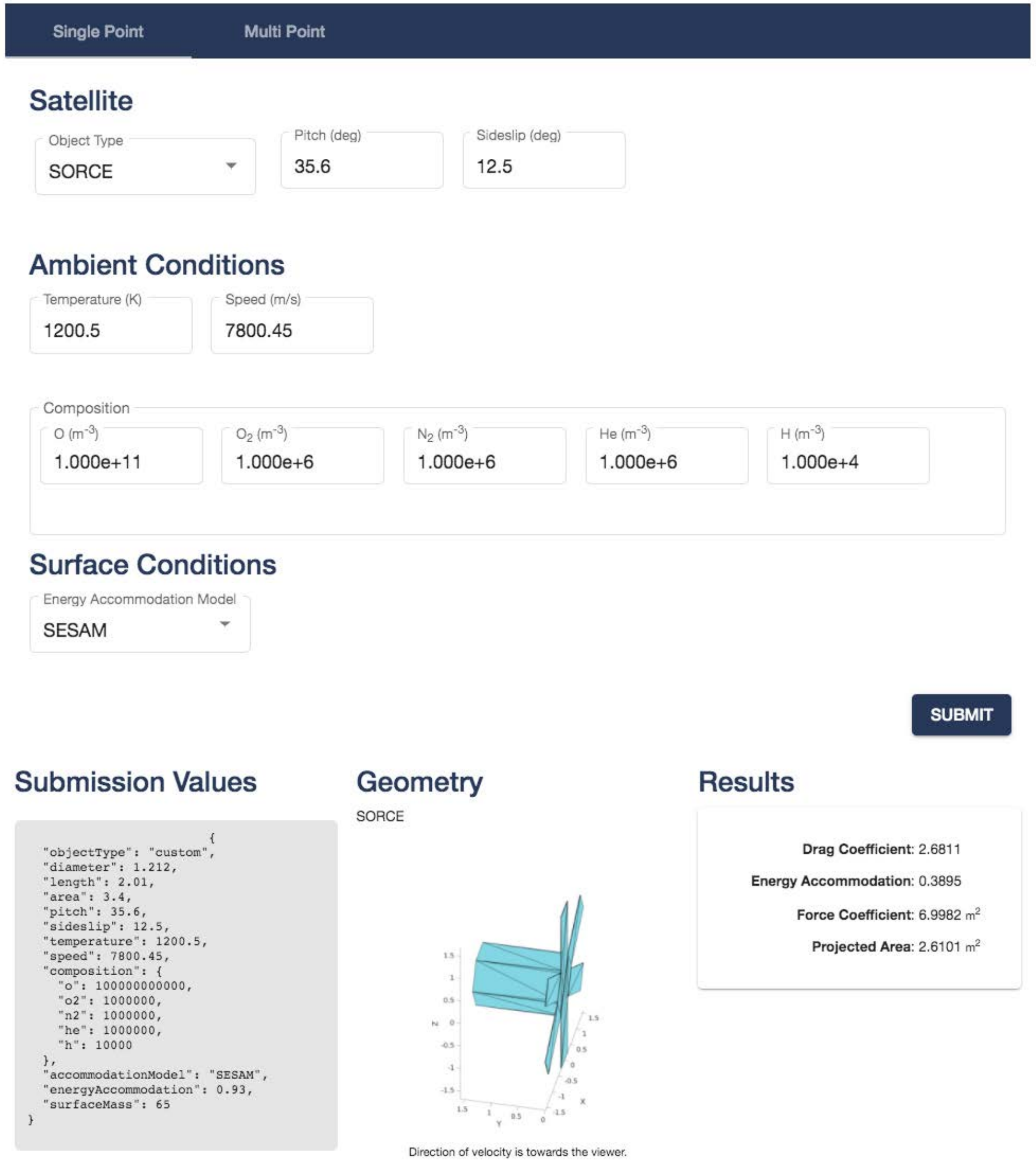
- 400 km altitude
- High ballistic coefficient ($0.1 m^2/kg$)

Emmert et al. 2018

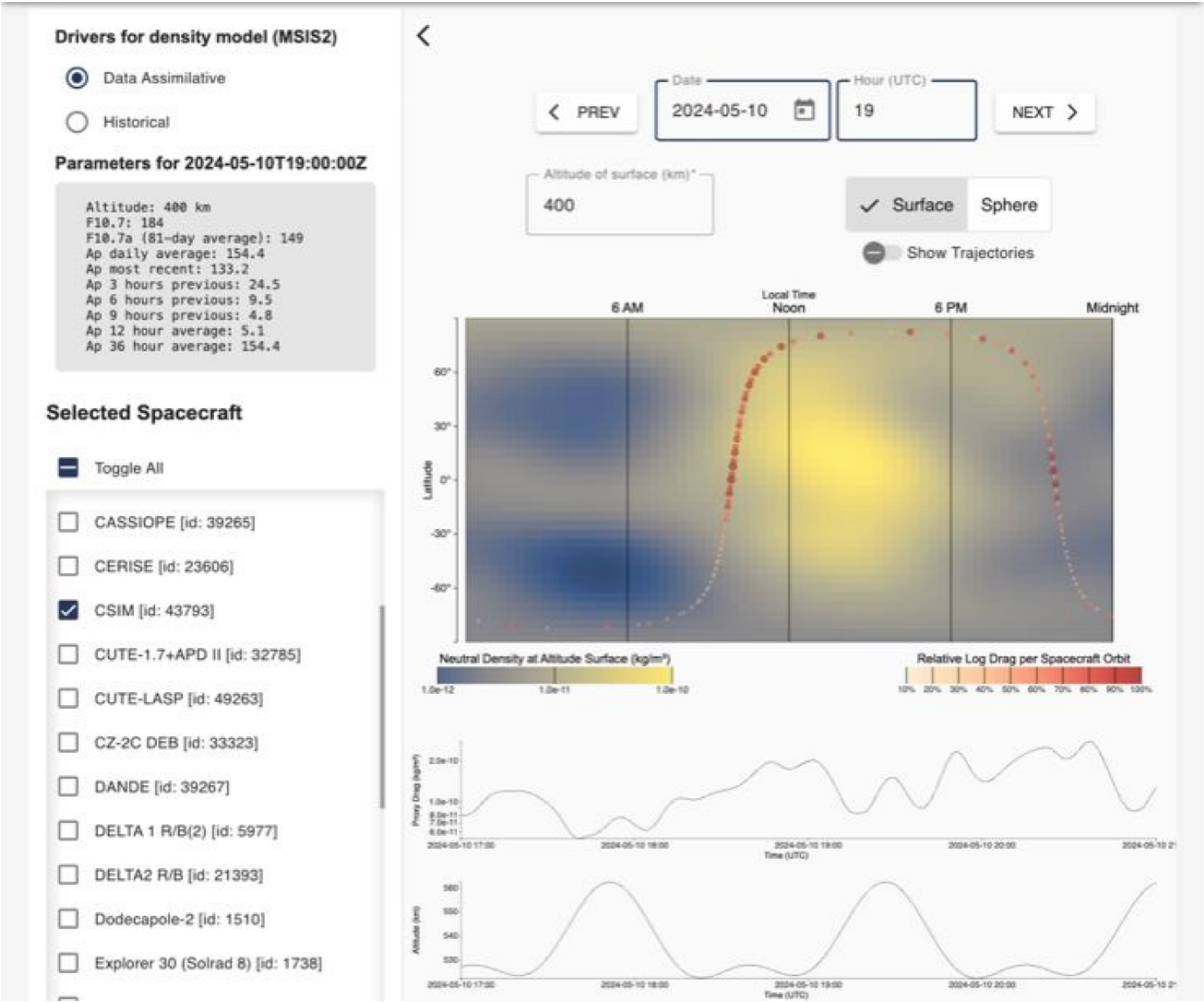
Drag Coefficient Calculator and Software

https://swxtrec.github.io/vector/model

- Compute drag coefficient for basic and complicated shapes
- Still under development… but we welcome your feedback
- MatLab code available on github https://github.com/SWxTREC/vector-code/
- Being updated to include latest results



Vehicle Environment Coupling and TrajectOry Response



- Web-interface for V&V and Satellite Drag Visualization. Flythrough code showing the CSIM CubeSat orbit.
- Compare DA and non-DA results
- Select from a list of satellites
- https://swx-trec.com/cafe/