### Turning Science to Operations for the Satellite Industry

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# The New (Commercial) Space Economy

- The new space economy delivers space-based products and services driven by government, commercial and retail customers
  - space-based global internet services
  - near real-time surface imagery
- The number of operational objects in low Earth orbit (LEO) in expected to grow 10x over the next few years (proliferation).
  - Already near 10,000 satellites in orbit across regimes
  - Transition from High LEO to LEO and VLEO
- The (expected) rise is so steep that the US congress has made the Department of Commerce responsible for Space Traffic Management/Coordination (STM/C)
  - The US Space Command will limit its purview to DOD requirements
  - Space Policy Directive-3 of the National STM Policy aims to minimize false positives for actionable collision avoidance







## **Satellite Drag**

- Satellite drag is a major uncertainty in LEO and impacts
  - Mission design and planning; e.g. lifetime, orbits, etc.
  - Object tracking and identification, data/track association and custody
  - Orbit determination and prediction, conjunction assessment and collision avoidance
  - Informing debris generation and mitigation; e.g. forensic analysis
  - Policy and guidelines
- Thermosphere density is the primary contributor of uncertainty
  - The upper atmosphere is a dynamic environment and system with three sources of uncertainty:
    - > driver forecast,
    - > (density) model,
    - initial (density) state or nowcast
- The secondary contributor of uncertainty is the drag or ballistic coefficient
- These uncertain parameters are commonly modeled as random processes in operations which affects covariance realism for decision-making



$$\vec{a}_{drag} = -\frac{1}{2} \rho \frac{C_D A}{m} v_{rel}^2 \frac{\vec{v}_{rel}}{|\vec{v}_{rel}|}$$

## **Current Operations**

#### **HASDM and Commercial Satellite Operations**



- High Accuracy Satellite Drag Model (HASDM)
  - It is not actually a model but a framework
  - Empirical JB2008 as the background model; forecast with JB2008
  - Dynamically calibrated using calibration objects, mostly spheres
  - TLE catalogue for active and debris objects generated within the framework
  - Limitations: Not available; low order with limited fidelity (climatological); No Robust Uncertainty Quantification



## **Scientific Advances**

- CHAMP/GRACE/Swarm/GOCE and others provide high-fidelity localized density measurements
- TIMED, GOLD, GDC, DYNAMIC, etc.
- Experimental Investigations
- GEOSPACE coupling

We have touted physics-based models as the next-big thing for satellite operations for over 2 decades.

- Empirical Models
  - MSIS series, Jacchia series, Jacchia Bowman series, DTM series, etc.
  - Limited fidelity/climatological
- Physics-based Models
  - WAM-IPE, TIE-GCM, GITM, WACCM-X, etc.
  - High fidelity but very difficult to accurately parameterize
  - Computationally expensive and can require significant user training



# AI/ML for operationalizing physics-based ITM models (R2O)

- Emulator based on half a solar cycle of Thermosphere Ionosphere Electrodynamics-General Circulation Model (TIE-GCM) Simulation Data
  - Dimensionality reduction followed by dynamic modeling in reduced state space
  - Uncertainty quantification with ensemble approach
- Application to Thermosphere for neutral mass density
  - PCA+LSSM ROM Mehta et al. 2018
  - PCA+RNN ROPE Licata et al., 2023

PCA = Principal Component Analysis LSSM = Linear State Space Model RNN = Recurrent Neutral Network ROM = Reduced Order Model ROPE = Reduced Order Probabilistic Emulator



	Dimensionality Reduction	Dynamic Model
Linear	Principal Component Analysis (PCA)	Linear State-space Model (LSSM)
Nonlinear	Autoencoders (AE)	Recurrent Neural Networks (RNN)



amazon project kuiper

LEOLABS

5

## **TIE-GCM ROPE**

 Emulator based on half a solar cycle of TIE-GCM Simulation Data

- Dimensionality reduction followed by dynamic modeling in reduced state space
- Uncertainty quantification with ensemble approach





#### **TIE-GCM ROPE**





## Data Assimilation OSSE (PCA + LSSM ROM)



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Thank you!

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