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Mitigating LEO Debris Hazards: a Commercial Approach to a Thermospheric Density Testbed for Improving Operational Products and Space Traffic Management (STM)

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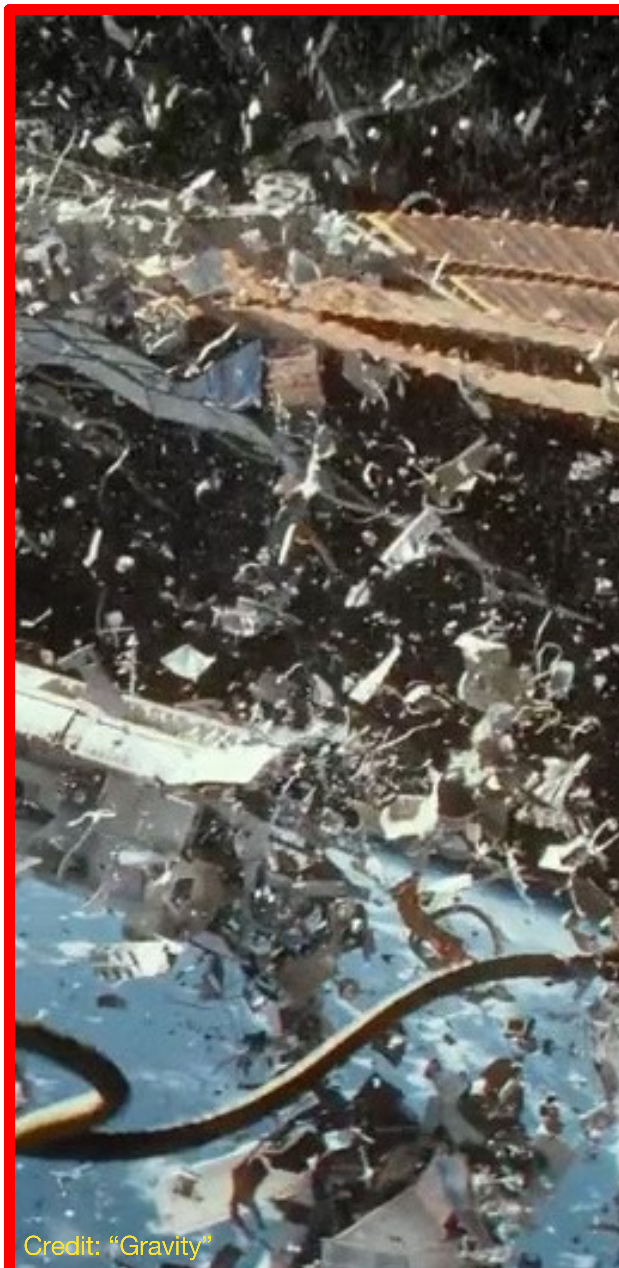
Space Environment Technologies

October 25,2023



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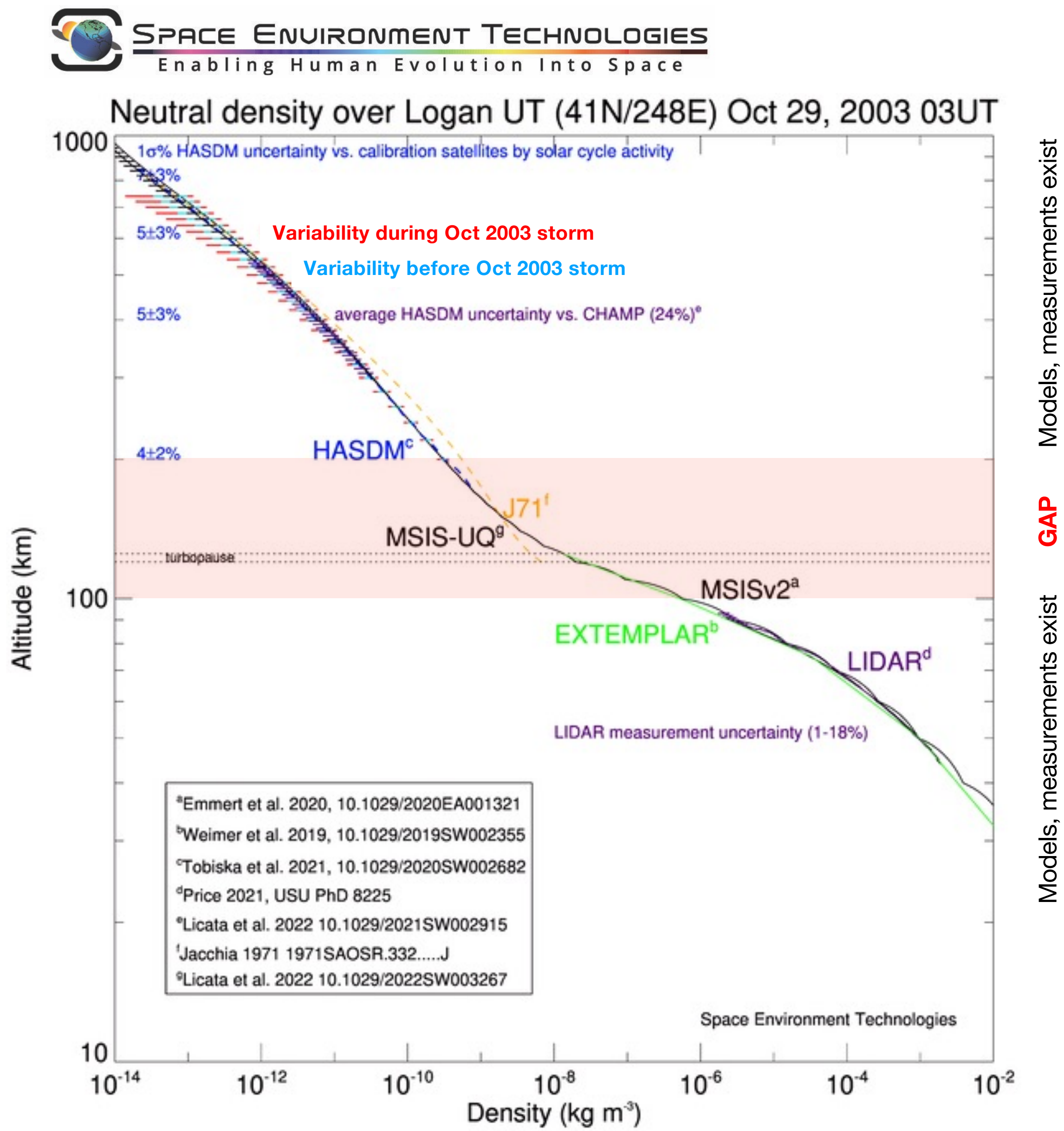
Our challenge: the number of Low Earth Orbit (LEO) objects will TRIPLE in the next 2 years and collisional hazards will increase – this is the largest hazard for STM

Four LEO debris hazard reduction mitigation options:

- ✗ ~~Reduce launch rates – unfeasible: not economically viable with continued space development~~
- Reduce number of objects – difficult: small object removal is unfeasible and large object removal is expensive
- ✓ Reduce debris creation – feasible but very long term: consensus exists for managing vehicle-released objects, fragmentation, operations through ISO 24113
- ➢ Improve orbit accuracy – feasible in short term: operationally improve density specification/forecast & uncertainty reduction



Improve orbit accuracy

current uncertainty in the 2003 Halloween storm example

- **>200 km**: models and measurements exist for this region that is driven primarily by 26–34 nm bandpass solar EUV augmented with secondary joule heating during storms
- **100–200 km**: **gap** in models and measurements for region that is driven primarily by 160 nm (SRC) solar FUV augmented by electron precipitation plus joule heating during storms and post-storm regulated by nitric oxide cooling
- **<100 km**: models and measurements exist for this region that is driven primarily by 0.1–0.8 nm and 121 nm solar XUV and Lyman-α irradiances augmented with dynamics from upward propagating lower atmosphere waves

Improve orbit accuracy

Machine learning Enabled Thermosphere Advanced by HASDM (META-HASDM) project

- **Industry–university collaboration: Space Environment Technologies, West Virginia University, Kayhan Space, and Orion Space**
- **Leverage the SET HASDM density database space weather benchmark:**
  - two solar cycles (23, 24) publicly released https://spacewx.com/hasdm/
  - no comparable dataset for global scale accuracy and time resolution.
- **Goal of reducing uncertainty in thermospheric densities for operational users through technology and science pathways**
  - Technical R/R&D question "*how can we create an operationally viable uncertainty solution for the global thermosphere across all altitudes and time frames?*"
  - Scientific R/R&D question "*what are the physical processes we need to understand to improve the uncertainty solution for the global thermosphere across all altitudes and time frames?*"

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Improve orbit accuracy

Pathway for thermospheric density improvements

- META-HASDM leverages the USSF HASDM system to characterize thermosphere density uncertainty.
- It will operationally serve conjunction assessment for DoD & DoC global Space Traffic Management (STM).
- Project goals:
  - ✓ Leverage as a baseline HASDM's absolute atmosphere density uncertainty of 2–10%
  - ✓ Extend densities for operations via machine learning (ML) algorithms
  - ● Improve LEO ballistic coefficients above 500 km
  - ● Improve solar and geomagnetic indices' forecasts
  - ○ Make global density predictions outside HASDM's historic 20-year time frame (2000-2019)
  - ○ Dynamically calculate current HASDM, JB2008 as well as forecast drivers' uncertainties

Epoch→ Focus↓	Historical	Current	Future
Accuracy goal	**Highest accuracy**	**Lowest uncertainty**	**RMS Error estimation**
Methodology	• Re-analyses	• Data assimilation • Super Ensemble of models • Localized Density comparisons	• Historical statistics • Machine learning error • Uncertainty quantification
Basis	• HASDM database • Satellite densities • Physics-based models	• Measurements (GNSS POD, NO) • Modeling (all types)	• Data-driven • Science measurements • Range of variability
Tools	• SET HASDM Density Database • GRACE, CHAMP • NOAA WAM-IPE	• Orion Space DRAGSTER • VT EXTEMPLAR/MSIS2 • SET SOLEItool drivers • Kayhan Space SPIRE-Starlink	• SET JB2008 forecast • WVU HASDM-ML forecast • SET Solar, Ap, Dst predicts • SET Hi-alt Cd improvements

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Improve orbit accuracy

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Science tasks:

Improve solar and geomagnetic forecasts

Geomagnetic disturbances

- High speed streams (HSS) couple with Earth's magnetosphere-ionosphere-thermosphere (M-I-T) system during relatively quiet geomagnetic conditions resulting in increased density uncertainties; not yet modeled in JB2008; we have assessed existing driver algorithms as a function of solar wind speed at Earth and are incorporating them into operations (*Hu*)
- The Dst index characterizes large geomagnetic storm evolution; the forecast uncertainties are inconsistent compared to the HASDM database; we are assessing ML driver algorithms now in development to better forecast large storm perturbations, including their magnitudes and arrival times (*Hu*)

Solar irradiances

- Solar farside irradiance evolution from behind the solar East limb can improve density accuracies out to 7 days beyond current state-of-art; we have assessed ADAPT model data feeds (Henney *et al.,* 2012; 2015) that capture forecast solar irradiance when geomagnetic storms are not present and are incorporating (*Henney – ADAPT*)

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Science tasks:

improve LEO B for objects >500 km and cooling specifications

LEO ballistic coefficients above 500 km

- the atmosphere's oxygen (O) – helium (He) transition between solar minimum and solar maximum is identified in the HASDM database at the 500–600 km altitude regime; we are developing an algorithm as a function of altitude and solar/geomagnetic activity levels that will modify drag coefficients (*Pilinski*)

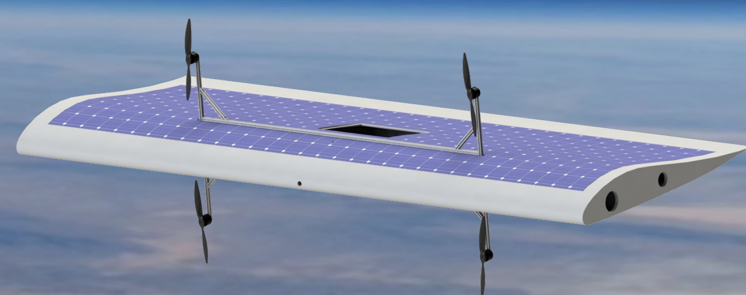
Event and secular cooling

- nitric oxide (NO) radiative cooling during post-storm events appears in the SET HASDM density database; we have assessed modeling and are developing observational methods to characterize this cooling (*EXTEMPLAR, MSIS-UQ, NOMAD*)
  - carbon dioxide (CO_2) radiative cooling collapses the thermosphere during solar minimum conditions; we will develop an algorithm as a function of solar activity level and secular trend of increasing CO_2 from historical observations

ARGOS HALE UAV will host multiple instruments for 24/7/365 monitoring capability

ARGOS features

- lightweight UAV designed to fly autonomously up to a year at 20 km in mid latitudes.
- Low-cost access to the stratosphere that will open new markets for lightweight payloads (≤5 kg).
- Provide continuous ARMAS radiation measurements above NoPac, NAT, and CONUS air traffic corridors.
    - *provide closure on SEPs and excess high latitude atmospheric radiation science.*
- Provide nitric oxide monitoring for E-F1-regions, regional VHF sounding of D-region, dual frequency GNSS receivers without tropospheric water signal, platform for high radiation environment parts and biological testing.
- Objective: a fleet beginning in late-2024.



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SUMMARY

- Community goal is to improve orbit accuracy as a near-term solution in the LEO debris hazard reduction mitigation effort.
- Joint industry and academia efforts towards developing a thermospheric density testbed within the META-HASDM project are already helping to improve operational products and Space Traffic Management (STM).
- Current state-of-art density uncertainties during storms have been quantified.
- Several science and technology pathways for thermospheric density improvements are underway (geomagnetic disturbances, solar irradiances, ballistic coefficients, and cooling).
- ARGOS will provide nitric oxide (NO) monitoring data for assimilation into models across regions during post storm cooling.


Credit: "Gravity"

Backup slides

Summary of META-HASDM SBIR Phase I

Summary of Phase I objectives

- **Technology feasibility study main elements**

SGI = solar and geophysical indices

SET HASDM Density Database (SHDB)
[U1] Absolute error between HASDM:Satellite data

HASDM-ML using SGI
[U2] error between HASDM-ML:SHDB densities

JB2008 using SGI
[U3] error between JB2008:SHDB densities

EXTEMPLAR using SGI
[U4] error between EXTEMPLAR:SHDB densities

SGI Forecast Analysis (AFWERX/Phase II)
[U5] O-He transition error above 500 km

SGI Forecast Analysis (AFWERX/TACFI)
[U6] cooling error during solar minimum characterization

SGI Forecast Analysis (AFWERX/TACFI)
[U7] HSS error between Dst SGI actual:forecast

SGI Forecast Analysis (NASA/Comporeale)
[U8] ML error between SGI Dst actual:forecast

SGI Forecast Drivers (ADAPT)
[U9] error between SGI original:ADAPT

past | present | future

- **Science feasibility study main elements**

[U5] Oxygen–Helium transition affecting ballistic coefficients and density from Phase I study

[U6] Carbon dioxide and nitric oxide cooling in lower thermosphere using SABER NO and NCAR studies

[U7] Coronal hole – high speed stream (HSS) effects

[U8] Dst magnitude and arrival effects using machine learning (ML)

[U9] Solar far-side evolution of irradiances using ADAPT for S10 and F10

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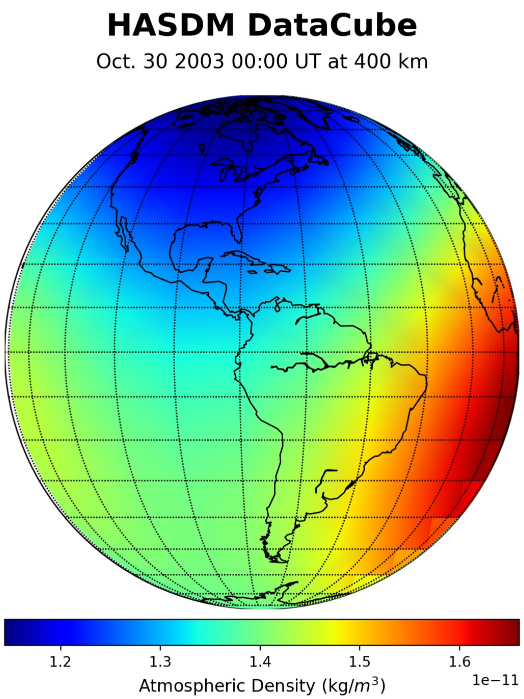
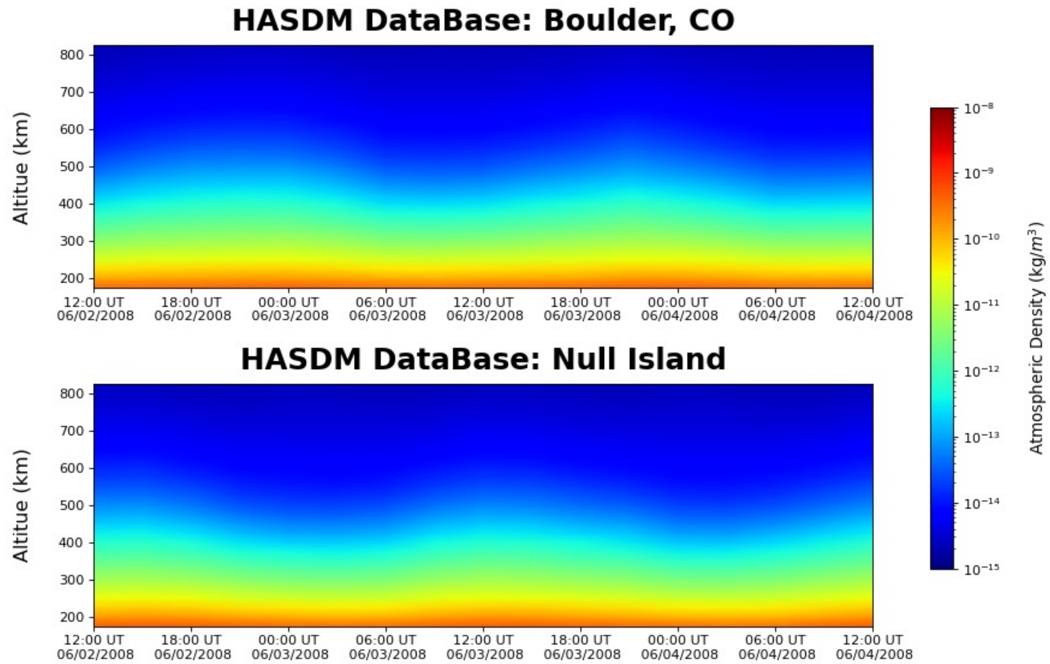
SET HASDM density database:

spatial/temporal granularity
two solar cycles
3-h & 25 km steps





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AtmoSense:

SET HASDM density database storm time variation

Onset date	Min Dst (nT)	Max Kp	Max Ap	NOAA G	Peak X-ray	% variability	Comments
2003-10-30	-383	9	400	5	X10	+22 to +178	Only extreme event after 1989
2003-11-20	-422	9-	300	4	M4.2	+11 to +56	Last severe event of cycle 23
2015-03-17	-222	8-	179	4	M1.8	+7 to -10	Shock-led multi-structure CME
2015-06-22	-204	8+	236	4	M6.5	-15 to -58	Multiple CME impacts
2015-10-07	-124	7+	154	3	NA	-9 to -74	CIR-driven storm
2017-09-08	-122	8+	236	4	X9.3	-13 to -76	Largest eruption of cycle 24

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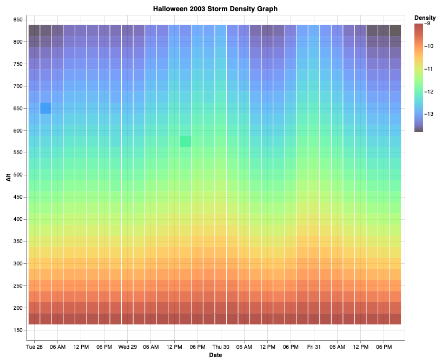
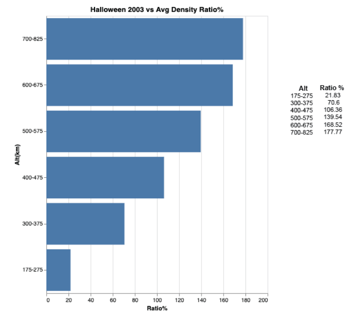
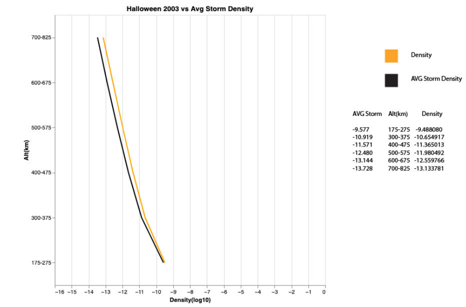
AtmoSense:
SET HASDM density database storm time variation

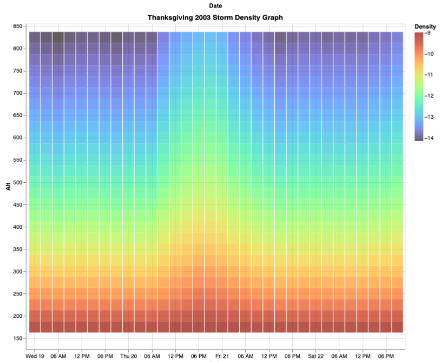
Oct 2003

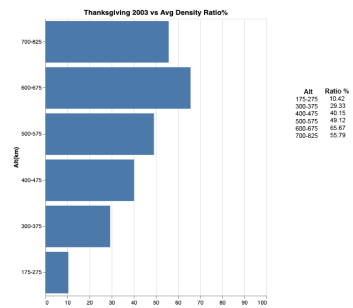


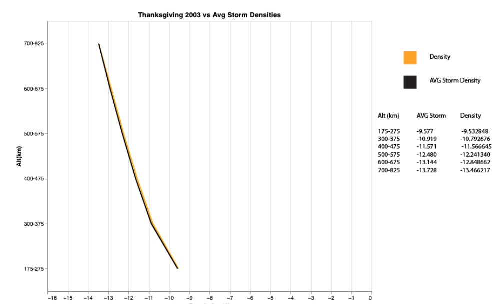




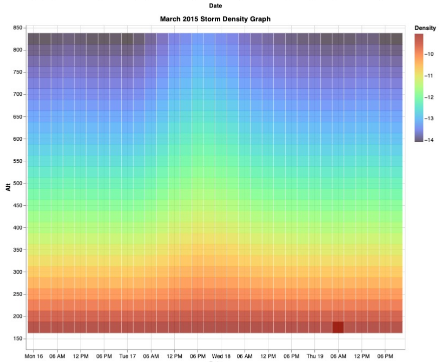
Nov 2003

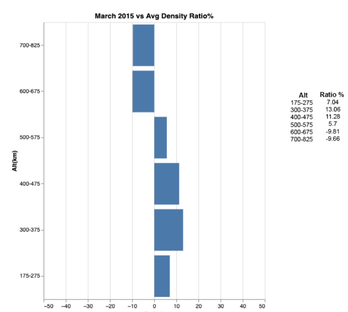


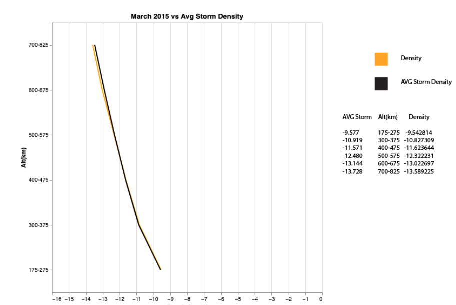




Mar 2015







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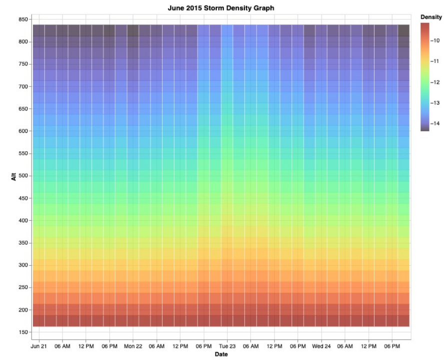
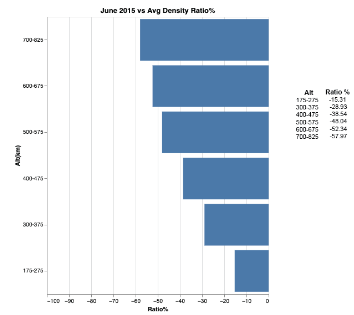
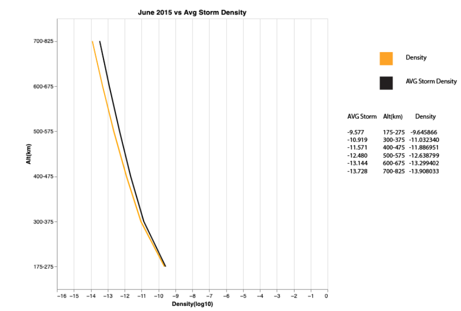
AtmoSense:
SET HASDM density database storm time variation

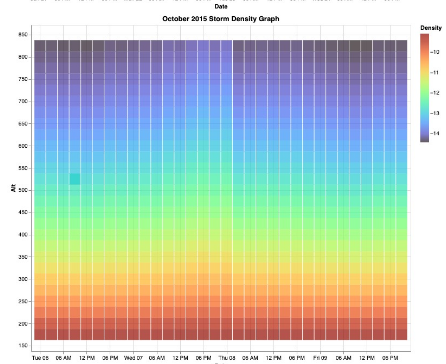
Jun 2015

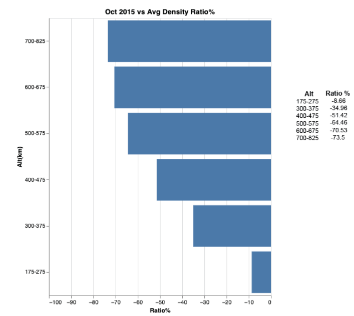


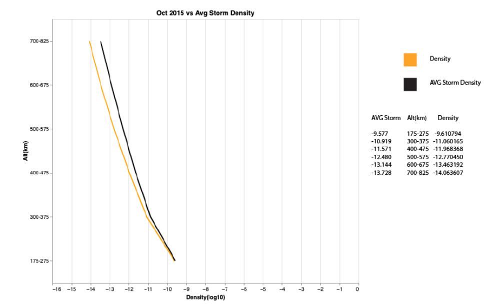




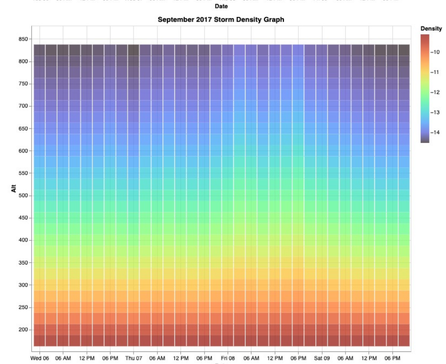
Oct 2015

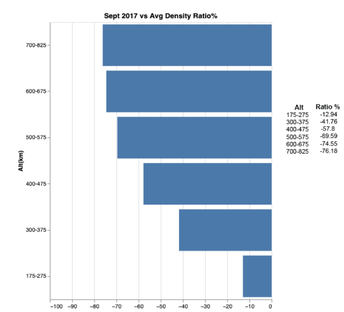


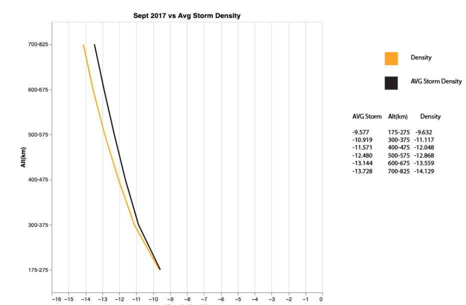




Sep 2017







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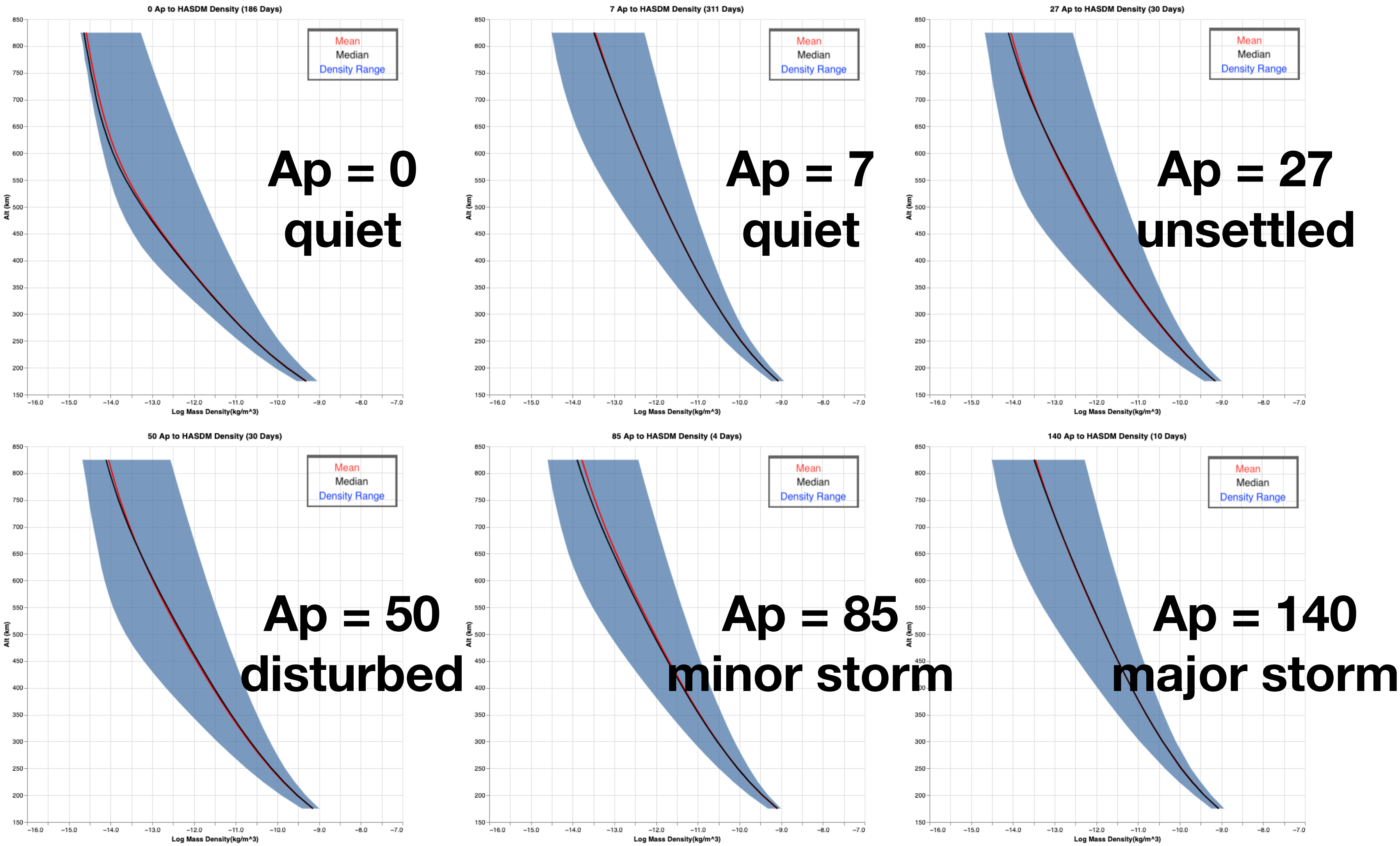
AtmoSense:
Ap variation for six levels of geomagnetic activity



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HASDM–ML:

represents HASDM density database outside of 2000–2019

Development of HASDM–ML

- Used machine learning (ML) techniques to develop a model trained on the SET HASDM database (20 years of HASDM density grids)
- HASDM-ML is the resulting model that finds the optimal relationship between a set of space weather inputs and the HASDM density grid
- Used Principal Component Analysis (PCA) to identify and examine the dominant modes for both the JB2008 and HASDM models
- Used ML to identify the optimal drivers for HASDM-ML
- Optimized neural network architecture and hyperparameters
- Trained ML model on JB2008 data for comparison (JB08-ML)
- Investigated Monte Carlo (MC) dropout for approximating model uncertainty
- Licata *et al.,* 2021b; Licata et al., 2022

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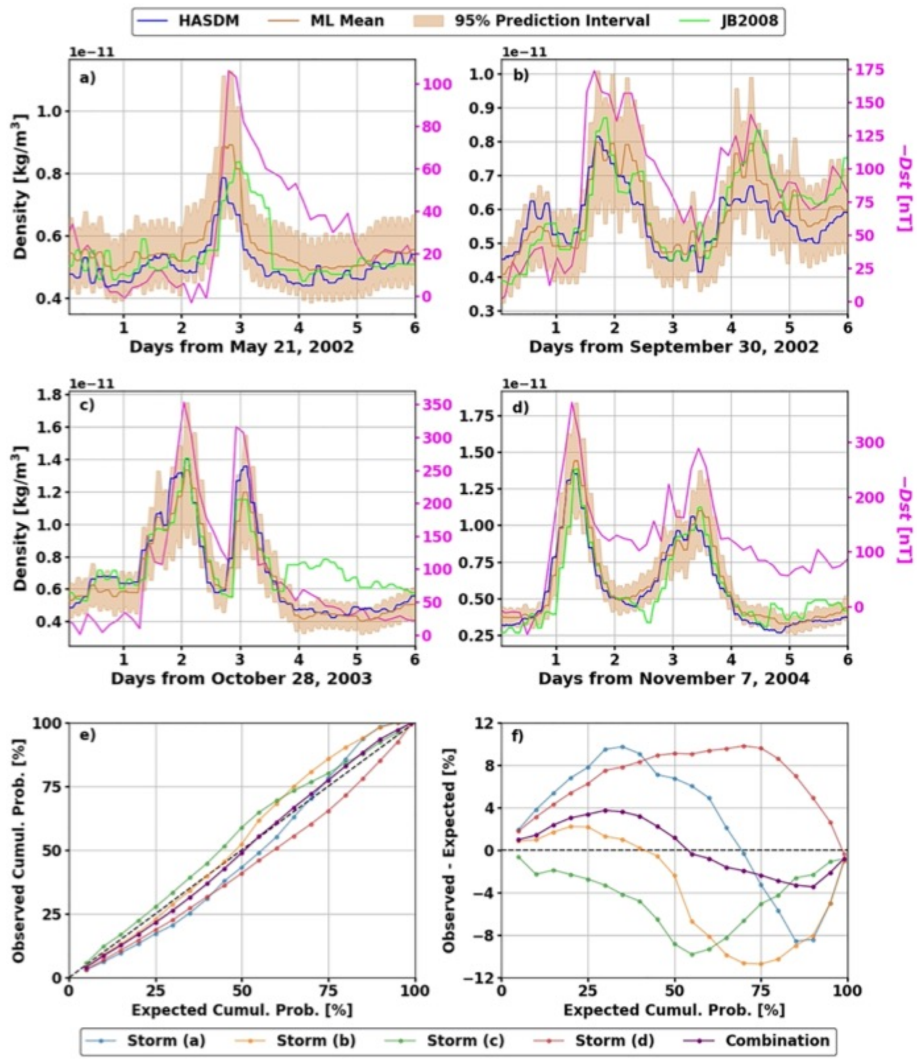
HASDM–ML results – CHAMP storm compa

- ✓ The shaded region is the 95% prediction interval for HASDM-ML.
- ✓ HASDM-ML captures post-storm cooling.
- The Dst index is shown on the right axis in each panel.
- Panels a–d show the HASDM, HASDM-ML mean, and JB2008 orbit-averaged densities for CHAMP's orbit during various geomagnetic storms.
- Panel (e) shows the calibration curves corresponding to panels a–d along with the composite calibration curve (bottom legend).
- Panel (f) shows the difference between the observed and expected cumulative probability for all the curves in panel (e).



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Multi-Model Ensemble:

provides range of variability

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- **MME density and temperature output at distinct altitude layers will be compared and range of variability will be quantified**
- **Output results will be provided to operational users**
- **9 Multi-Model Ensemble (MME) being implemented for real-time runs**
  - JB2008 Q3 2022 operational, implemented on server
    - ✓ [Bowman *et al.*, 2008; Tobiska *et al.*, 2008]
  - EXTEMPLAR Q3 2022 prototype, implemented on server
    - ✓ [Weimer *et al.*, 2020; Weimer *et al.*, 2021]
  - JB08–ML Q4 2022 operational, being delivered by WVU
  - HASDM–ML Q4 2022 operational, being delivered by WVU
    - ✓ [Licata *et al.*, 2021b; Licata et al., 2022]
  - EXTEMPLAR–ML Q1 2023 in development, WVU & VT
  - MSIS-UQ Q3 2023 in development, WVU
  - TIE–GCM Q3 2023 available, to be implemented on server
  - DRAGSTER Q1 2024 in development, OrionSpace
  - WAM–IPE Q3 2024 prototype, implemented at NOAA

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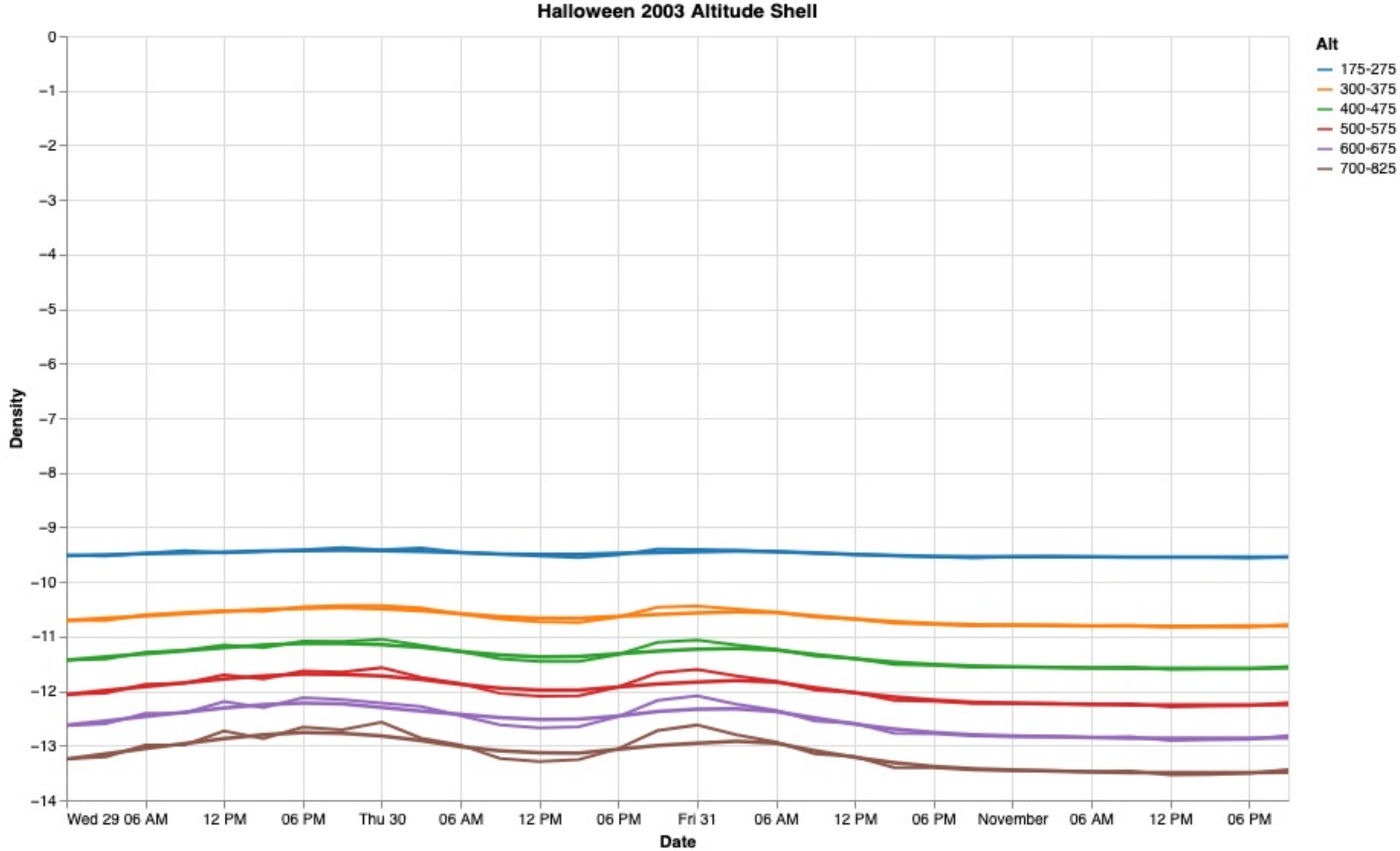
Notional concept to demonstrate MME density range of variability



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Lowest uncertainty verification:

Measurements using GNSS POD and remote sensed NO

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- Kayhan Space example of using SPIRE constellation data
- Validation metrics can be supplied to operational users in real-time via JBHSGI.txt file metadata
- Remotely sensed nitric oxide in the lower thermosphere for post-storm cooling

Draft format for information dissemination of the MME range of variability via JBHSGI.TXT UDL files

```
:Product: JBH09 Solar and Geomagnetic Index file        JBHSGI.TXT
:Issued: 202210281751
:Validation_code: 7E64046D77E612FA02588EB41B41353955F5AE5DE562551008000033
:Number_of_Data_Records: 64
:Missing_data: -1 (Dst 9999, SRC 0)
:Source: hasdm.jbh54 database
:Is_monotonic: true
:Updated_by: Report_jbh_DBvec
:SPIRE_Kayhan_475_500_km_shell_RMSE_unc_pct_vs_HASDM: 0
:SPIRE_Kayhan_500_525_km_shell_RMSE_unc_pct_vs_HASDM: 0
:SPIRE_Kayhan_525_550_km_shell_RMSE_unc_pct_vs_HASDM: 0
:SPIRE_Kayhan_550_575_km_shell_RMSE_unc_pct_vs_HASDM: 0
# Prepared by Space Environment Technologies/Space Weather Division
```

JBHSGI.TXT file showing added metadata lines for the SPIRE-Kayhan Space shell RMSE percent uncertainty vs. HASDM at 4 discrete layers.

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Summary of SET META-HASDM activity

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- Critical need to address improvements in thermospheric densities for all epochs to provide debris hazard mitigation
- Commercial sector provide a testbed and pathway to commercialization for reduced uncertainties and validated densities at all epochs
- Use of multiple models, datatypes, technology and science advances with rapid prototyping

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ARGOS HALE UAV v0 build using SET IR&D

- Establish avionics experience
- Manufacturing prototype and challenges
- V0 build complete in fall 2022

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ARGOS HALE UAV v1 build using SET IR&D

- 1 km altitude goal using VTOL
- ARGOS laboratory established in April 2023 in Compton California
- Test prototype avionics in vertical flight and flip over to horizontal flight
- Avionics testing complete August 2023
- First flight test November 4 2023

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ARGOS v1

- 1 km altitude goal, battery powered, VTOL
- 2 hours on station for all avionics and aerodynamics testing
- Manufactured and delivered April 2023
- Avionics flight tests validated summer 2023

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ARGOS v1

- Vehicle and avionics integration completed fall 2023
- First vehicle vertical lift tests November 2023

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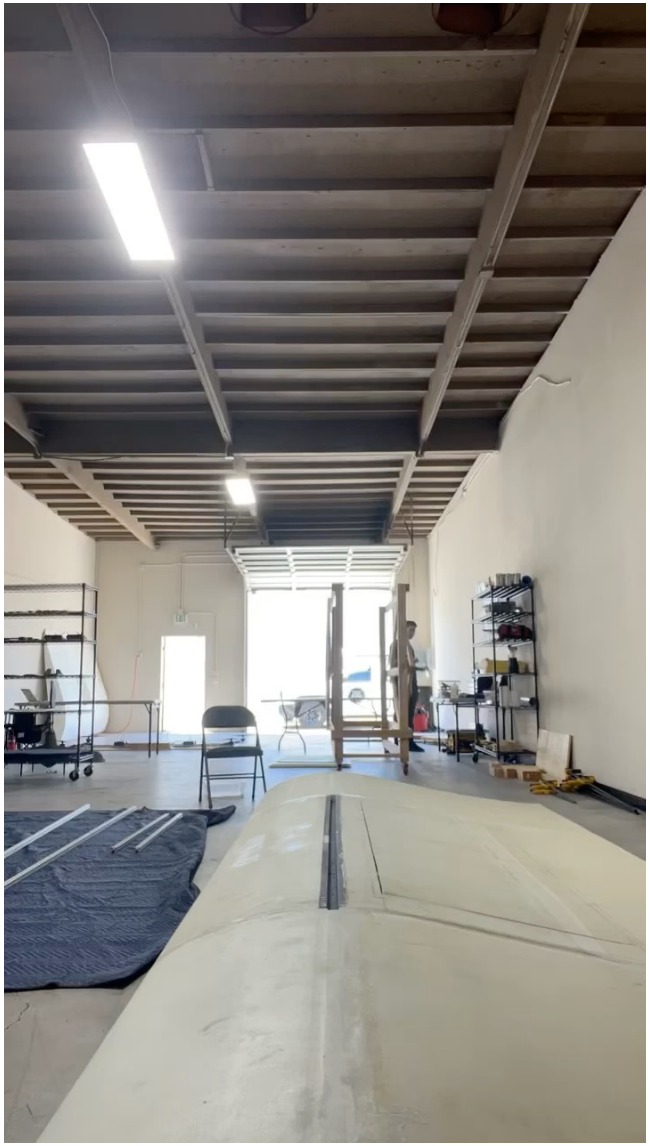
ARGOS v1

- V1 wing prototype built and ready for testing
- Avionics mated with the wing structure
- Motors wired and electrically integrated
- Motors mechanically integrated
- Prep for November 4, 2023 desert flight test



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ARGOS v2 goal for 24/7 monitoring:

3 regions (NoPac, CONUS, NAT) starting late 2024 with use of 12–20 vehicles