Long-Term Environment and Anomaly Forecasts (LEAF)

Alex Boyd, Paul O'Brien, Jeff Cox

2023 SCAF Workshop
29 March 2023

Approved for public release. OTR 2023-00486.

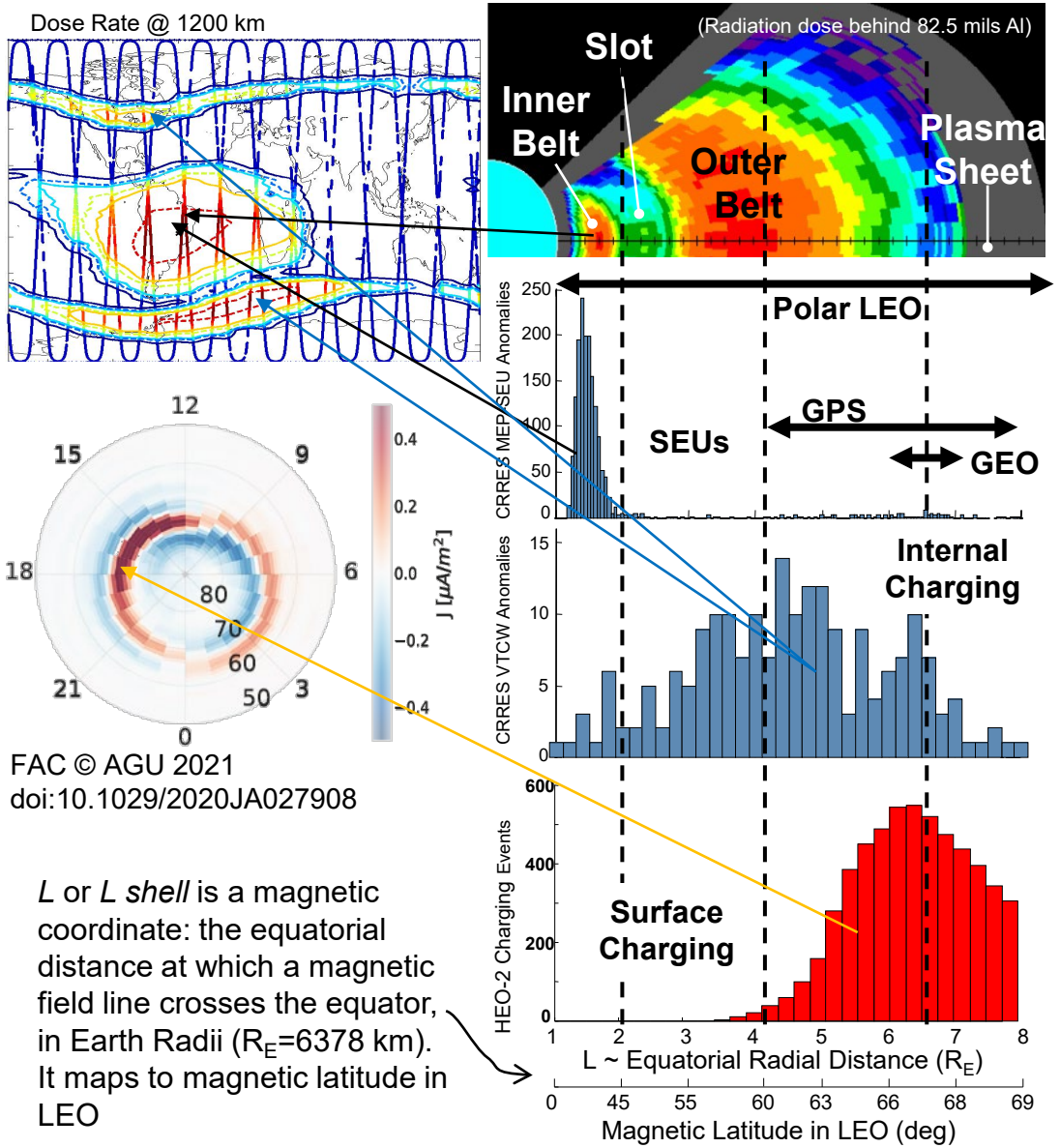
Overview

LEAF

- Long Term Environment and Anomaly Forecasts (LEAF) are a series of multi-week ahead forecasts of space weather observables that relate to satellite hazards
  - *Forecasts*
    - LEEF-GEO (28 day forecast of GEO electrons)
    - LEAF-Kp (7 day forecast of Kp Index)
    - LEAF-OBI (7 day forecast of POES Outer Belt Index)
  - *Dashboards*
    - LEAF-SSA (Forecast/Current Conditions Dashboard)
    - LEAF-HQ (Hazard Quotient Dashboard/Tool)
- Probabilistic 7 or 28-day ahead Forecasts built using Random Forest
  - *Instead of predicting flux will be x tomorrow, predict 60% chance flux will exceed x*
- Trained on 20+ years of Input time series:
  - *GOES Electron Fluxes, GOES Proton Fluxes, Vsw, Kp, IMF B, POES Outer Belt Index, Sunspot Number*
- Designed to take advantage of recurrence in the system due to the 27-day solar rotation
- Organized all these models along with the current conditions into convenient dashboards (LEAF-SSA and LEAF-HQ) organized by orbital regime

Long-Term probabilistic forecasts that are directly connected to satellite hazards at different orbit regimes

Space Environment Hazards to Space Vehicles



L or *L shell* is a magnetic coordinate: the equatorial distance at which a magnetic field line crosses the equator, in Earth Radii (R_E=6378 km). It maps to magnetic latitude in LEO

- **Event Total Dose** Damage accumulates over entire mission through ionizing and non-ionizing mechanisms. Caused by solar particle events (SEP) and transient slot or outer belts. Not an issue in LEO due to dominance of stable South Atlantic Anomaly (inner belt)
- **Single Event Effects (SEE)** tend to occur in the inner (proton) belt and at higher L shells when a solar particle event is in progress. Galactic Cosmic Rays (GCR) also cause SEE at all orbits.
- **Internal electrostatic discharges (ESD)** occur over a broad range of L values corresponding to the outer belt, when penetrating electron fluxes are high over extended periods of time.
- **Surface ESD** tends to occur when the spacecraft or surface potential is elevated: at 2000-0800 local time in the plasma sheet and in regions of intense field-aligned currents, e.g., auroral arcs.

Model to Hazard Connection

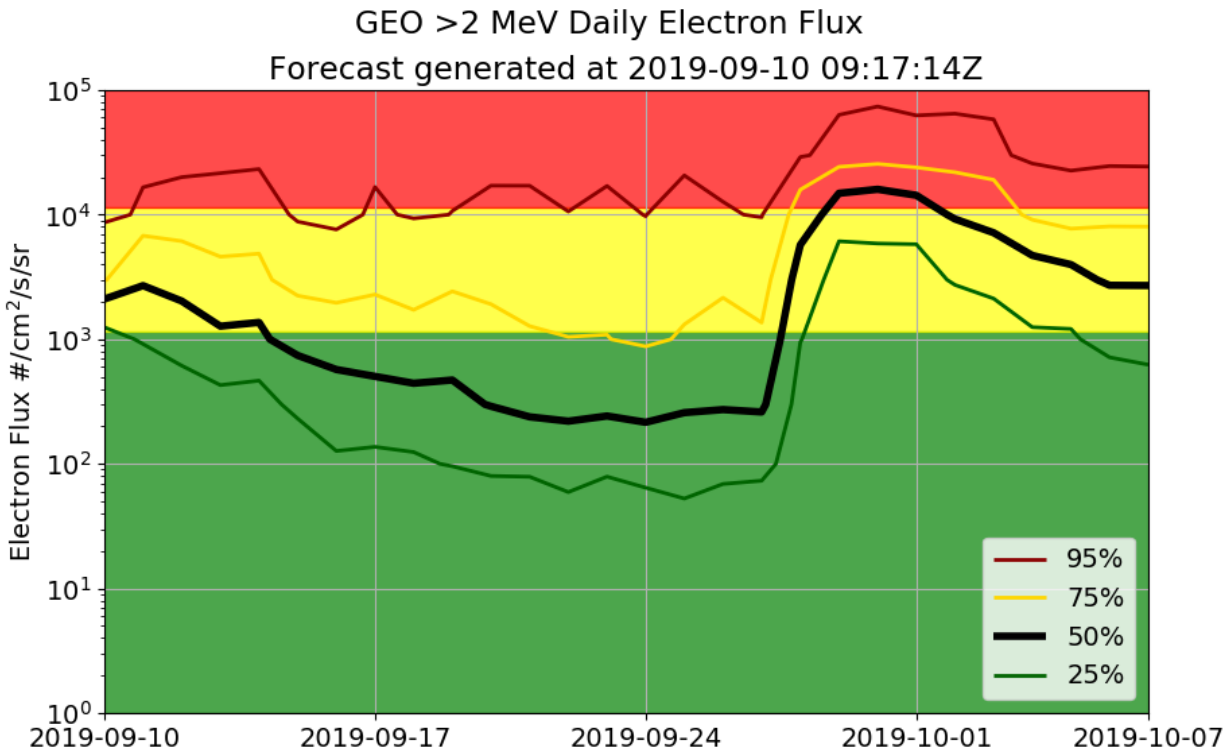
	GEO	LEO, HEO/MEO	
Internal Charging	GOES >2 MeV Electrons	POES >300 keV Outer Belt Index	**Observable**
	LEEF-GEO (28 day forecast)	**LEAF-OBI-1 (7 day forecast)**	**Model**
Surface Charging	Kp	Kp	
	LEAF-Kp (7 day forecast)	**LEAF-Kp (7 day forecast)**	
SEE/Total Dose	Solar Protons	Solar Protons	
	NOAA/SWPC PROTONS	NOAA/SWPC PROTONS	

Long-Term Environment and Anomaly Forecast (LEAF) Models

LEEF-GEO

Internal Charging (GEO)

- 28-day Probabilistic forecast of the daily GOES >2 MeV Electron flux
- Additional 24/72-hr fluence forecasts
- Running in real-time since May 2019

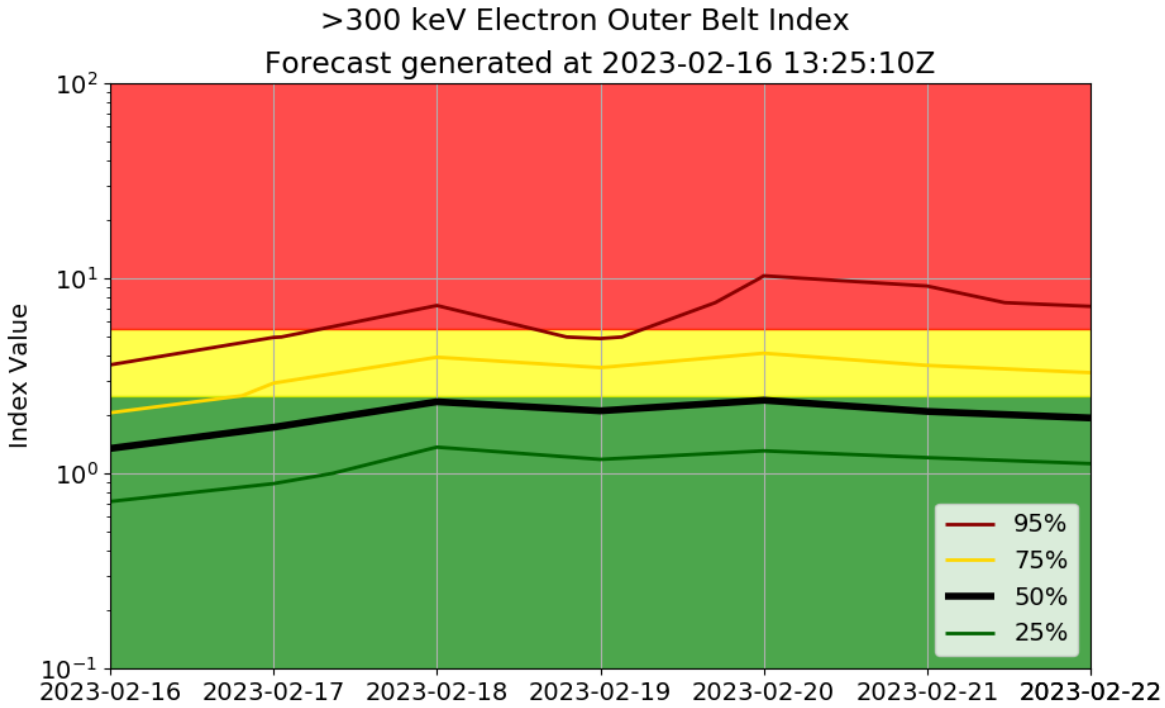


Exceedance Probability vs >2 MeV Electron Flux (#/cm²/s/sr)											
Flux:	1E+00	3E+00	1E+01	3E+01	1E+02	3E+02	1E+03	3E+03	1E+04	3E+04	1E+05
2019-09-10	100%	100%	100%	100%	96%	92%	82%	24%	1%	0%	0%
2019-09-11	100%	100%	100%	100%	96%	90%	73%	46%	7%	1%	0%
2019-09-12	100%	99%	99%	98%	94%	84%	64%	37%	10%	0%	0%
2019-09-13	100%	100%	100%	99%	94%	80%	53%	29%	10%	1%	1%
2019-09-14	100%	100%	100%	98%	93%	81%	55%	29%	14%	0%	0%
2019-09-15	100%	100%	100%	97%	84%	70%	38%	17%	3%	0%	0%
2019-09-16	100%	100%	99%	93%	78%	59%	36%	13%	1%	0%	0%
2019-09-17	100%	100%	99%	96%	79%	56%	36%	19%	7%	1%	0%
2019-09-18	100%	99%	97%	91%	78%	55%	29%	18%	4%	1%	0%
2019-09-19	100%	100%	98%	94%	74%	55%	33%	22%	5%	1%	0%
2019-09-20	100%	100%	99%	91%	68%	49%	30%	19%	7%	1%	0%
2019-09-21	100%	100%	98%	91%	68%	42%	27%	15%	8%	0%	0%
2019-09-22	100%	99%	93%	83%	64%	41%	25%	14%	5%	0%	0%
2019-09-23	100%	100%	97%	88%	69%	42%	25%	17%	7%	1%	0%
2019-09-24	100%	100%	95%	84%	66%	39%	22%	9%	5%	1%	0%
2019-09-25	100%	98%	92%	81%	63%	46%	27%	17%	11%	0%	0%
2019-09-26	100%	98%	95%	87%	65%	48%	32%	20%	6%	0%	0%
2019-09-27	100%	100%	96%	89%	66%	46%	27%	14%	4%	2%	0%
2019-09-28	100%	100%	99%	99%	90%	84%	74%	60%	34%	4%	0%
2019-09-29	100%	100%	100%	100%	98%	97%	92%	85%	63%	10%	0%
2019-09-30	100%	100%	100%	99%	97%	96%	87%	82%	66%	13%	0%
2019-10-01	100%	100%	100%	99%	98%	96%	88%	84%	61%	9%	0%
2019-10-02	100%	100%	100%	98%	96%	94%	90%	73%	47%	10%	0%
2019-10-03	100%	100%	100%	100%	98%	97%	86%	66%	39%	8%	0%
2019-10-04	100%	100%	99%	99%	92%	86%	77%	60%	20%	1%	0%
2019-10-05	100%	100%	100%	98%	95%	90%	77%	57%	10%	2%	0%
2019-10-06	100%	100%	99%	97%	91%	85%	68%	47%	17%	1%	0%
2019-10-07	100%	99%	99%	95%	90%	82%	67%	47%	16%	1%	0%

LEAF-OBI-1

Internal Charging (LEO/MEO)

- 7-day Probabilistic forecast of the POES >300 keV electron Outer Belt Index
- Normalized Daily average of POES measurements for L>2.5 (https://satdat.ngdc.noaa.gov/sem/poes/data/belt_indices/)
- Running in real-time since Feb 2020



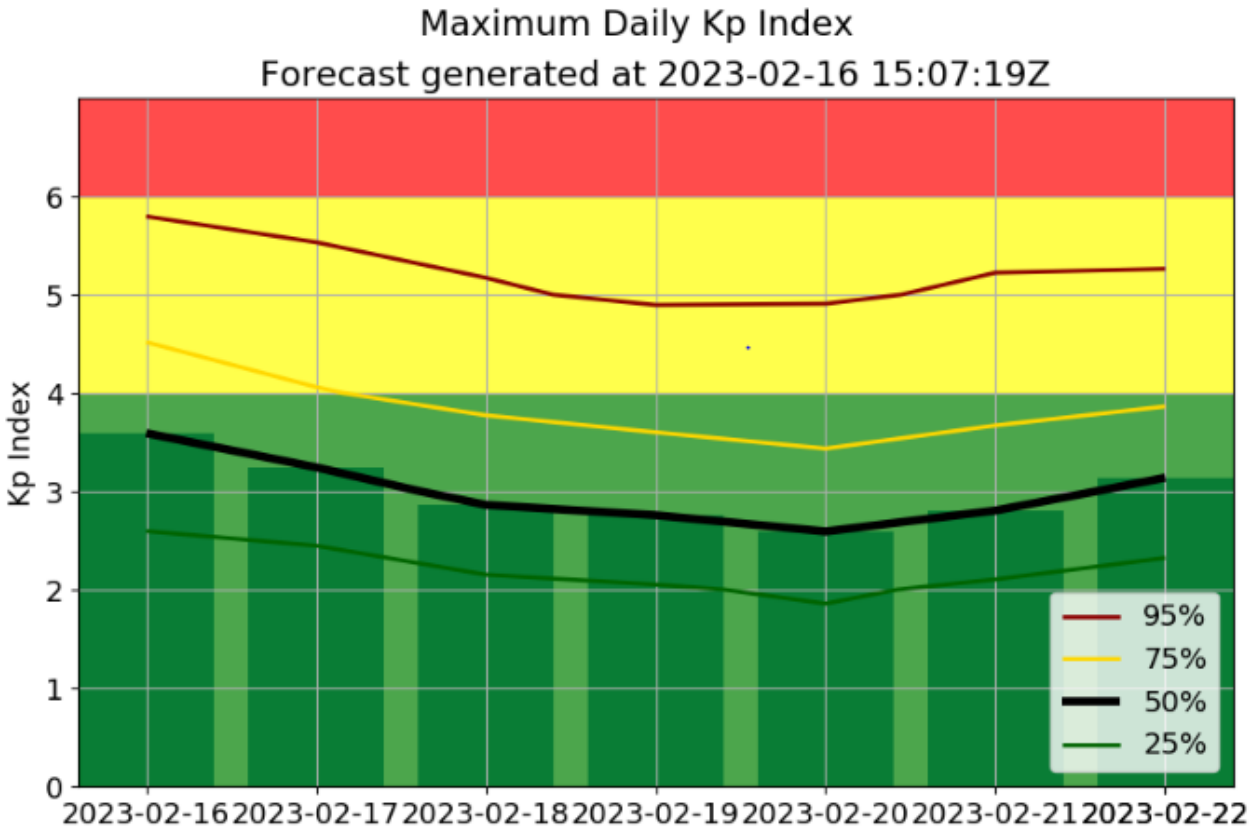
Exceedance Probability vs Outer Belt Index Index										
Outer Belt Index:	**0.5**	**1.0**	**2.5**	**5.0**	**7.5**	**10.0**	**25.0**	**50.0**	**75.0**	**100.0**
2023-02-16	85%	62%	9%	0%	0%	0%	0%	0%	0%	0%
2023-02-17	93%	70%	29%	5%	2%	0%	0%	0%	0%	0%
2023-02-18	96%	84%	46%	10%	4%	1%	0%	0%	0%	0%
2023-02-19	91%	80%	39%	4%	2%	1%	0%	0%	0%	0%
2023-02-20	95%	82%	47%	13%	6%	5%	0%	0%	0%	0%
2023-02-21	93%	81%	38%	8%	6%	5%	0%	0%	0%	0%
2023-02-22	95%	79%	32%	10%	4%	3%	0%	0%	0%	0%

LEAF-Kp

Surface Charging

- 7-day Probabilistic forecast of the **daily maximum** Kp Index (up to Kp>6)
- Running in real-time since Jan 2020

Exceedance Probability vs Kp Index							
Kp:	0	1	2	3	4	5	6
2023-02-16	100%	98%	87%	67%	38%	13%	3%
2023-02-17	100%	98%	89%	58%	26%	8%	3%
2023-02-18	100%	98%	80%	45%	19%	6%	2%
2023-02-19	100%	96%	77%	41%	14%	4%	1%
2023-02-20	100%	91%	72%	35%	12%	4%	1%
2023-02-21	100%	97%	79%	43%	16%	6%	2%
2023-02-22	100%	98%	85%	55%	20%	6%	2%



Dashboard

LEAF-SSA

LEO

Conditions from last 3 days

Current					
Observation:	Hazard:	2021-10-09	2021-10-10	2021-10-11	2021-10-12
OBI	Internal Charging	0.19	0.16	0.62	0.62
Kp	Surface Charging	2.00	4.00	3.00	4.00
Solar Protons	SEE/Total Dose*	0.54	0.84	0.71	0.54

Probability of falling in G/Y/R range

Forecast for next 7 days

Forecast																							
Observation:	Hazard:	2021-10-12			2021-10-13			2021-10-14			2021-10-15			2021-10-16			2021-10-17			2021-10-18		
OBI	Internal Charging	100%	0%	0%	95%	4%	0%	96%	3%	1%	95%	4%	1%	85%	10%	5%	83%	13%	4%	85%	10%	5%
Kp	Surface Charging	82%	14%	4%	75%	22%	3%	63%	23%	14%	67%	15%	18%	71%	17%	12%	71%	19%	10%	58%	14%	28%
Kp (NOAA)	Surface Charging	5.0			3.0			2.0			2.0			2.0			2.0			3.0		
Solar Protons	SEE/Total Dose*	N/A			95%	5%		95%	5%		95%	5%		N/A			N/A			N/A		

GEO

Current					
Observation:	Hazard:	2021-10-09	2021-10-10	2021-10-11	2021-10-12
GEO Electrons	Internal Charging	1.26E+06	1.10E+06	2.58E+06	3.54E+06
Kp	Surface Charging	2.00	4.00	3.00	4.00
Solar Protons	SEE/Total Dose	0.54	0.84	0.71	0.54

Forecast																							
Observation:	Hazard:	2021-10-12			2021-10-13			2021-10-14			2021-10-15			2021-10-16			2021-10-17			2021-10-18		
GEO Electrons	Internal Charging	100%	0%	0%	99%	1%	0%	99%	1%	0%	98%	2%	0%	100%	0%	0%	99%	1%	0%	99%	1%	0%
Kp	Surface Charging	82%	14%	4%	75%	22%	3%	63%	23%	14%	67%	15%	18%	71%	17%	12%	71%	19%	10%	58%	14%	28%
Kp (NOAA)	Surface Charging	5.0			3.0			2.0			2.0			2.0			2.0			3.0		
Solar Protons	SEE/Total Dose	N/A			95%	5%		95%	5%		95%	5%		N/A			N/A			N/A		

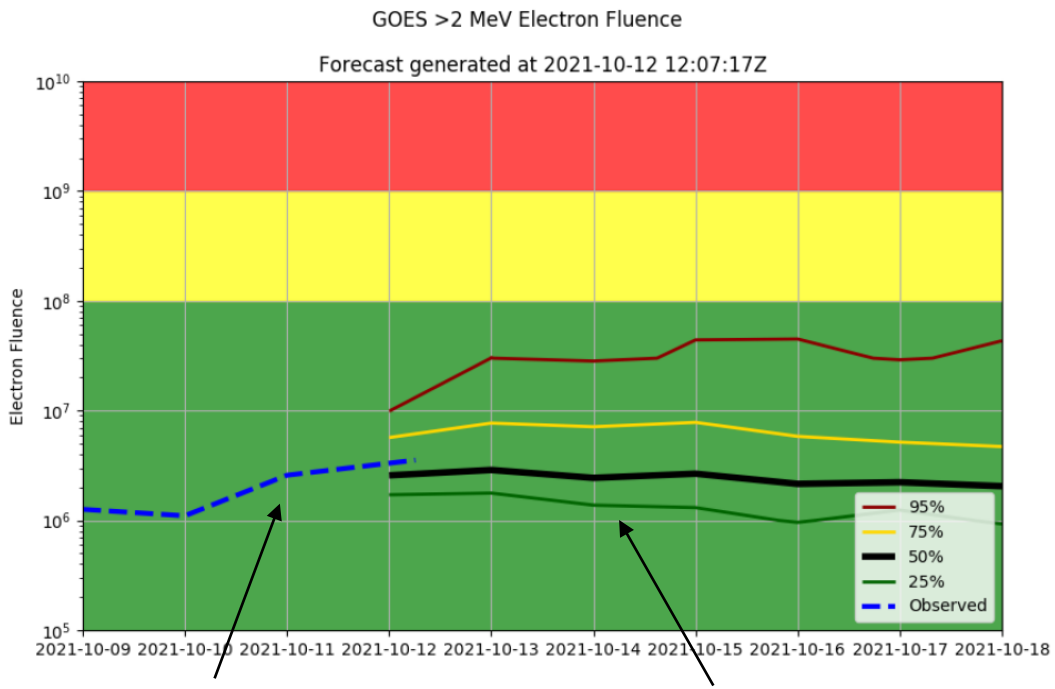
NOAA SWPC Forecasts

Dashboard

LEAF-SSA

- Links to summary plots and model pages that give more details, downloadable .csv forecasts and realtime validation plots

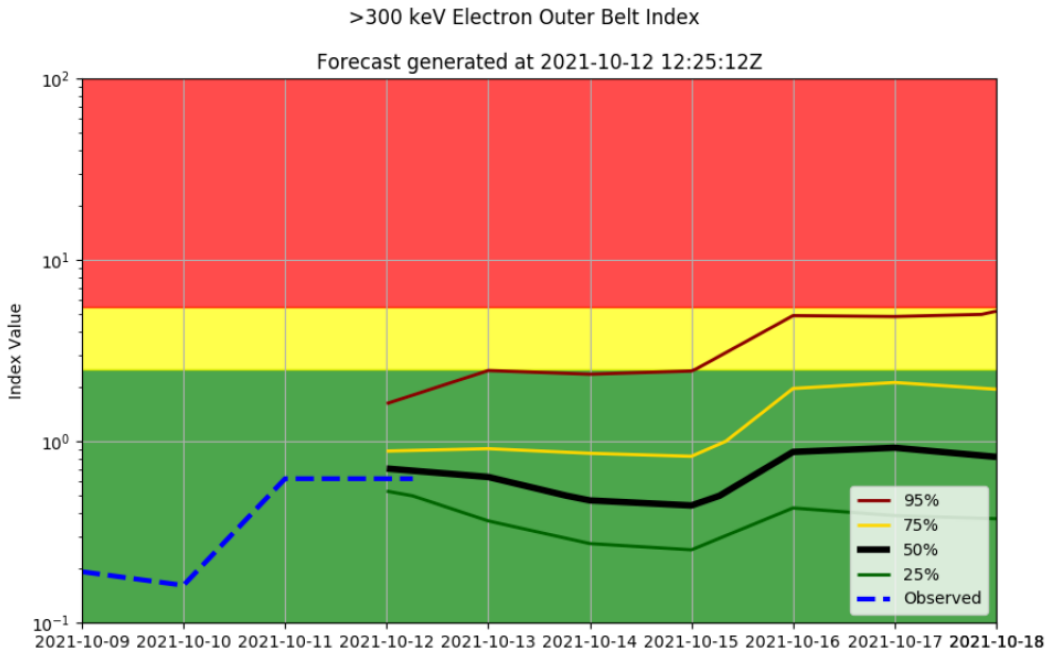
GOES Electron Flux



Current/Past Observations

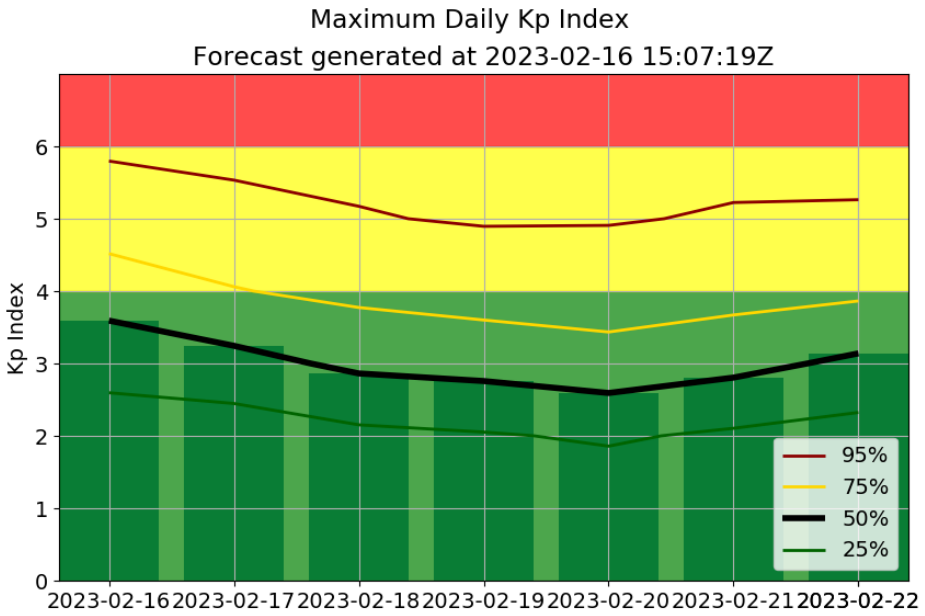
Forecast

Outer Belt Index

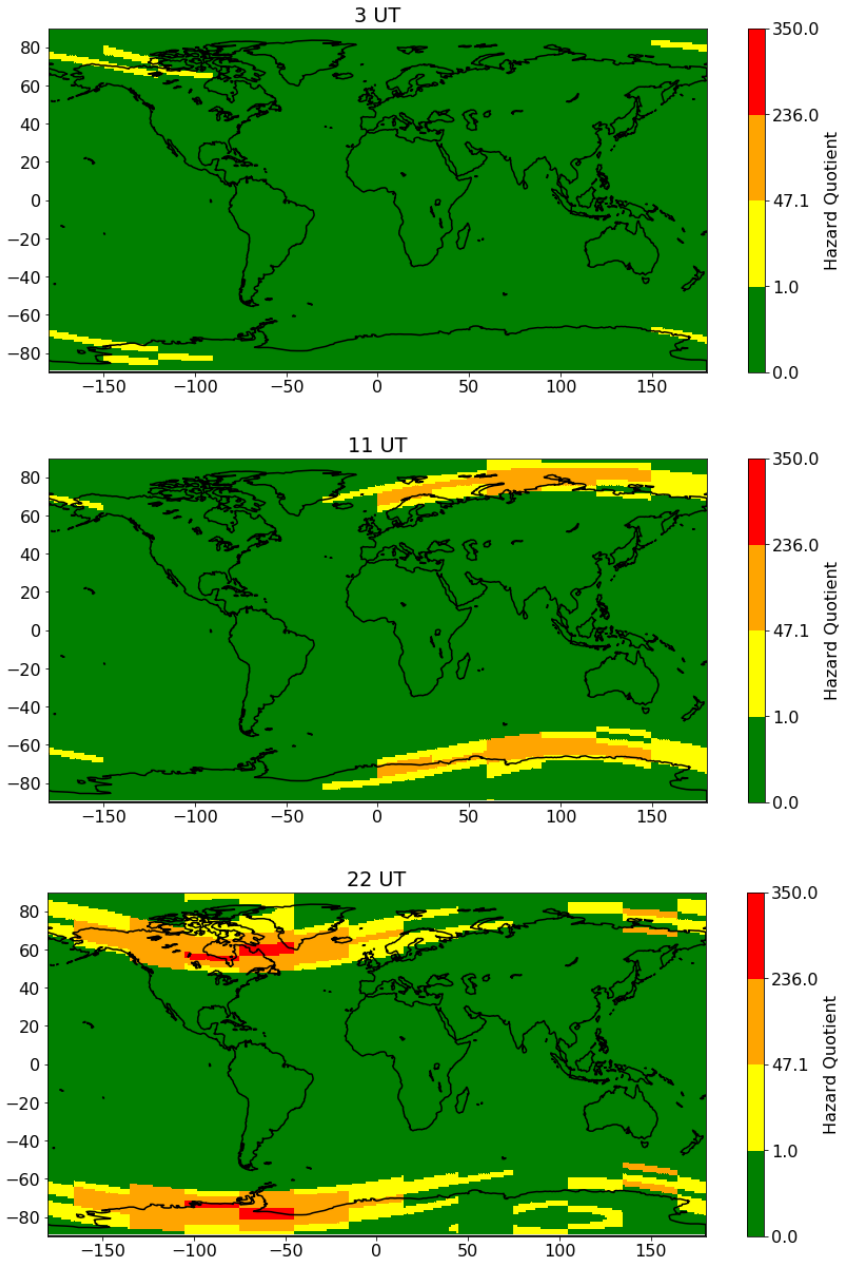


LEAF-HQ

Hazard Quotient Forecasts



Forecast of Kp Index



Forecasts of LEO Surface Charging Hazard

Transitioning to actionable forecasts

LEAF-HQ

Hazard Quotients

- SEAES Hazard Quotient:
  - $z(t) = \frac{\text{Instantaneous Anomaly Rate}}{\text{Long Term Average Anomaly Rate}} \propto \text{Probability of an anomaly}$
  - *Computed based on fits to real anomaly datasets*
- For LEAF-HQ: Transition from forecasts of observables to forecast of Hazard Quotients
- 3 orbit regime pages: LEO, HEO/MEO and GEO
- 2 different methods for displaying the results
  - *General: Quick look maps, tables*
  - *Satellite Specific: Hazards tailored to user provided satellite (TLE entry or UDL lookup)*

UDL Username: Password:

Orbit		
○ Specify Location	◉ NORAD ID / Catalog Lookup	○ Enter TLEs
• Orbit Longitude Run For This Location	GOES Keyword/ID Search Selected NORAD ID:43226 Select ID | Intl. Des. | Name 43226 | 2018-022A | GOES 17	1 43226U 18022A 22217.29116267 +.00000105 +00000+0 +00000+0 0 99991 TLE Line 1 2 43226 0.0898 264.3200 0000363 203.8624 173.1391 01.00271745016265 TLE Line 2 Set Type and Location from TLE

LEAF-HQ

LEO

Internal Charging

Internal Charging Hazard based on LEAF-OBI

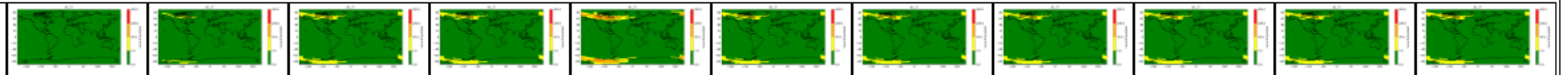
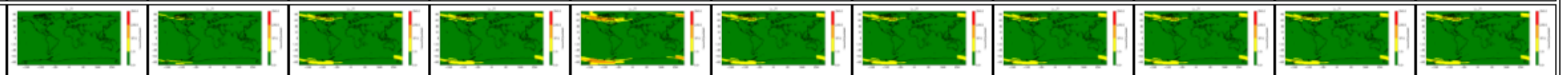
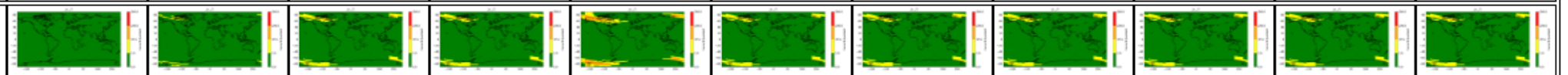
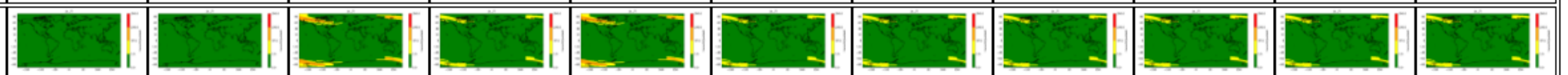
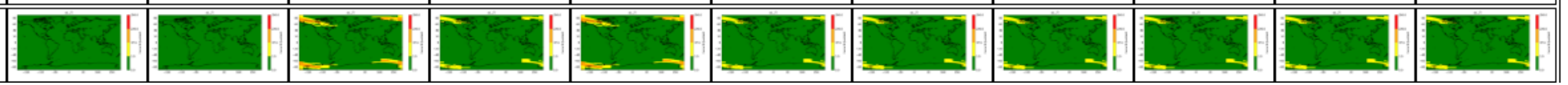
Past			Current	Forecast																			
2023-02-13	2023-02-14	2023-02-15	2023-02-16	2023-02-16			2023-02-17			2023-02-18			2023-02-19			2023-02-20			2023-02-21			2023-02-22		
0.75	0.54	0.20	0.20	100%	0%	0%	97%	3%	0%	93%	6%	1%	97%	2%	1%	90%	5%	5%	93%	2%	5%	93%	5%	3%

Past/Current Conditions based on observations

Surface Charging

Surface Charging Hazard based on LEAF-Kp

Select Percentile: ○ 25 ◉ 50 ○ 75 ○ 95

	Past			Current	Forecast						
Universal Time	2023-02-13	2023-02-14	2023-02-15	2023-02-16	2023-02-16	2023-02-17	2023-02-18	2023-02-19	2023-02-20	2023-02-21	2023-02-22
0											
1											
2											
3											
4											

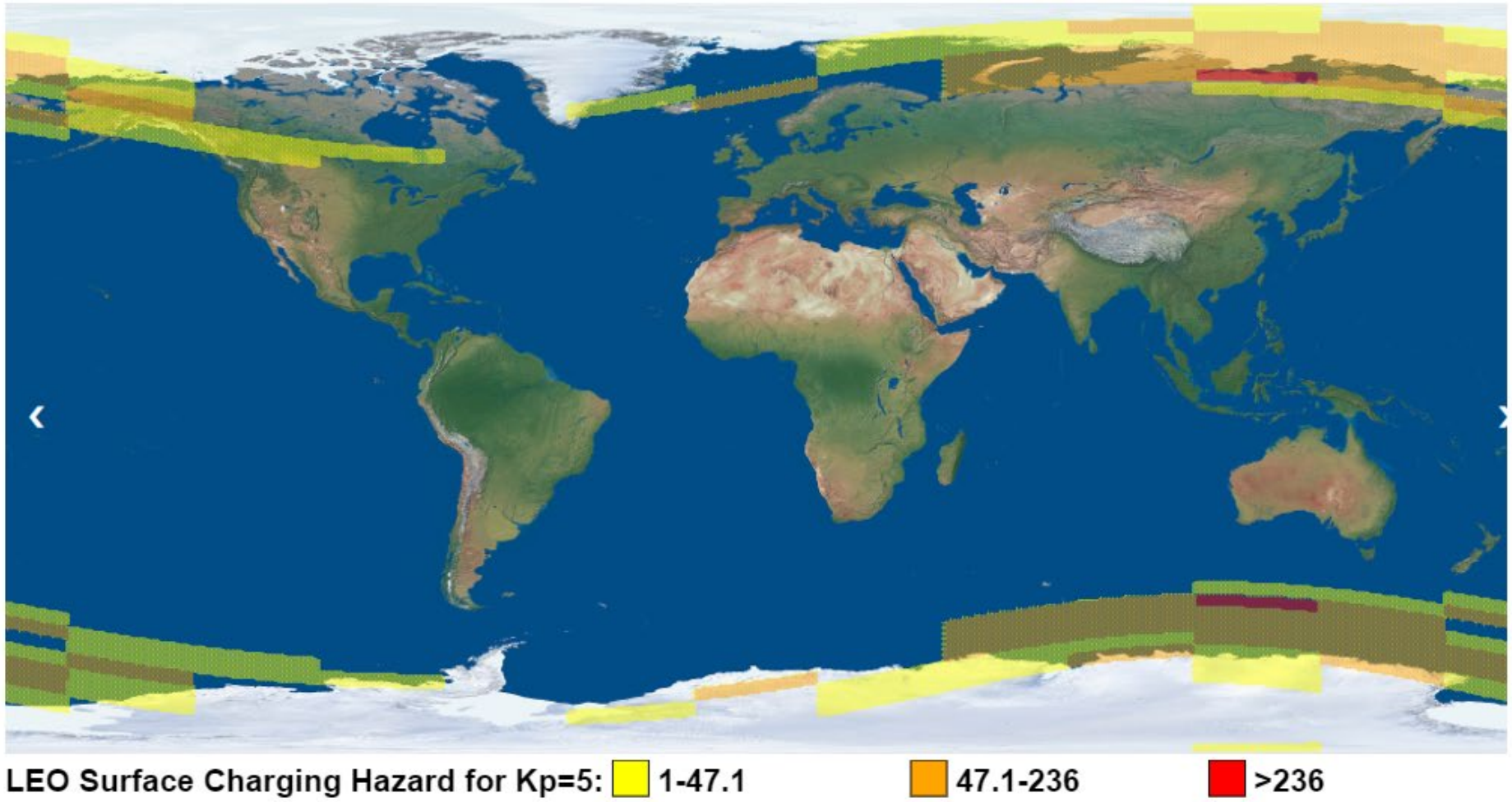
Hourly maps of Surface Charging hazard

LEAF-HQ

LEO

Date: 2023-02-13
UT: 0 UT

Update



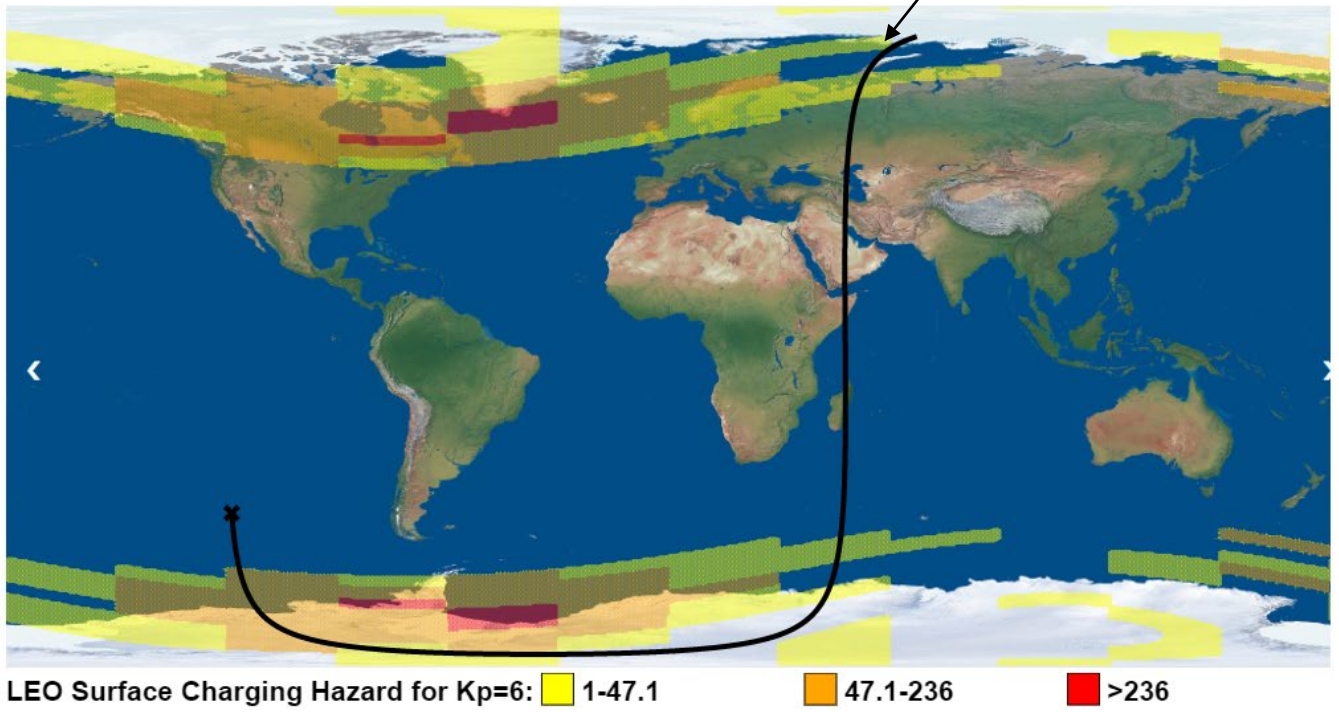
LEAF-HQ

LEO

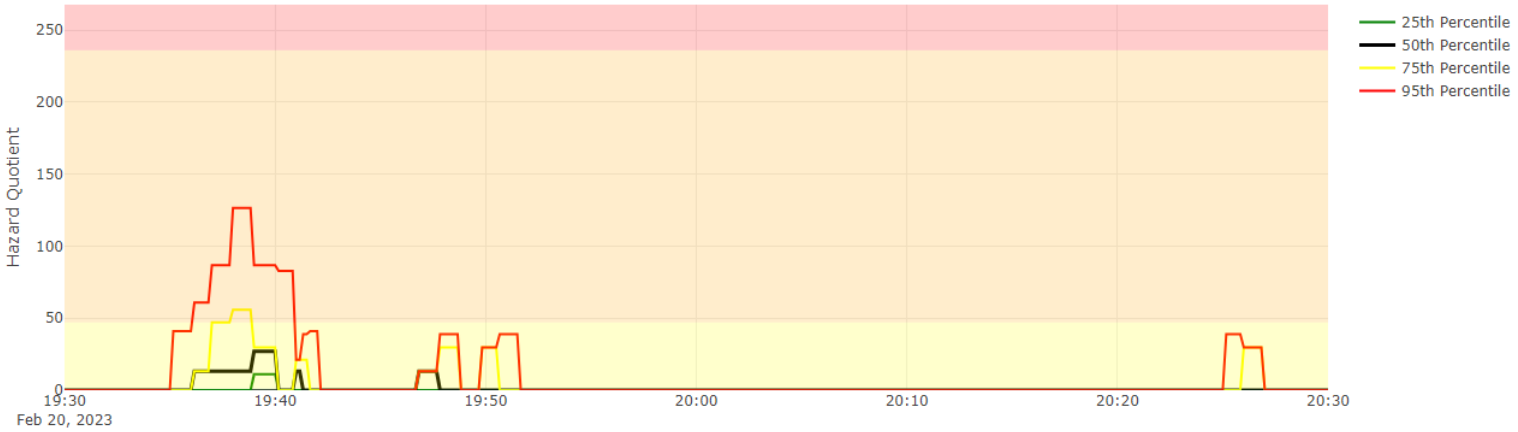
- Example output for specific satellite (IRIDIUM-170)

Date: 2023-02-13
UT: 0 UT
Update

Hour long orbit track centered on the map time



Interactive plot of the hazard along the orbit track



LEAF-HQ

HEO/MEO

Internal Charging Hazard
based on LEAF-OBI

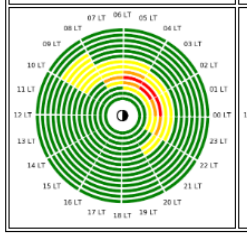
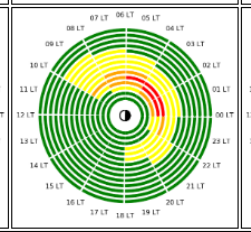
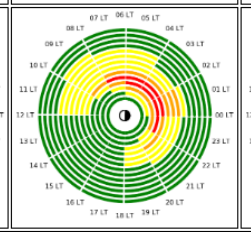
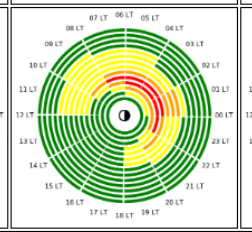
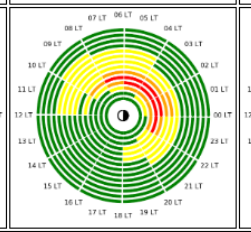
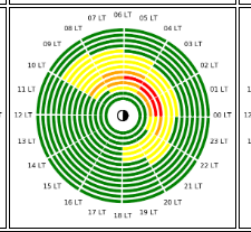
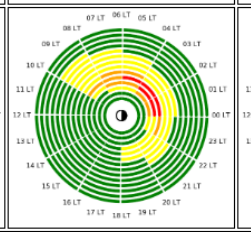
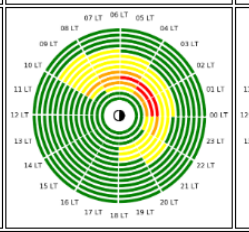
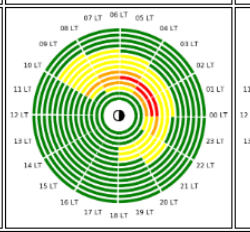
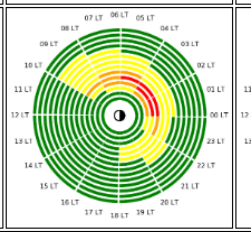
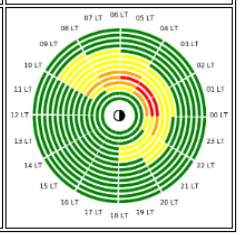
Internal Charging

Past			Current	Forecast																	
2023-02-13	2023-02-14	2023-02-15	2023-02-16	2023-02-16			2023-02-17			2023-02-18			2023-02-19			2023-02-20			2023-02-21			2023-02-22		
0.75	0.54	0.20	0.20	100%	0%	0%	97%	3%	0%	93%	6%	1%	97%	2%	1%	90%	5%	5%	93%	2%	5%	93%	5%	3%

Surface Charging Hazard
based on LEAF-Kp

Surface Charging

Select Percentile: ○ 25 ◉ 50 ○ 75 ○ 95

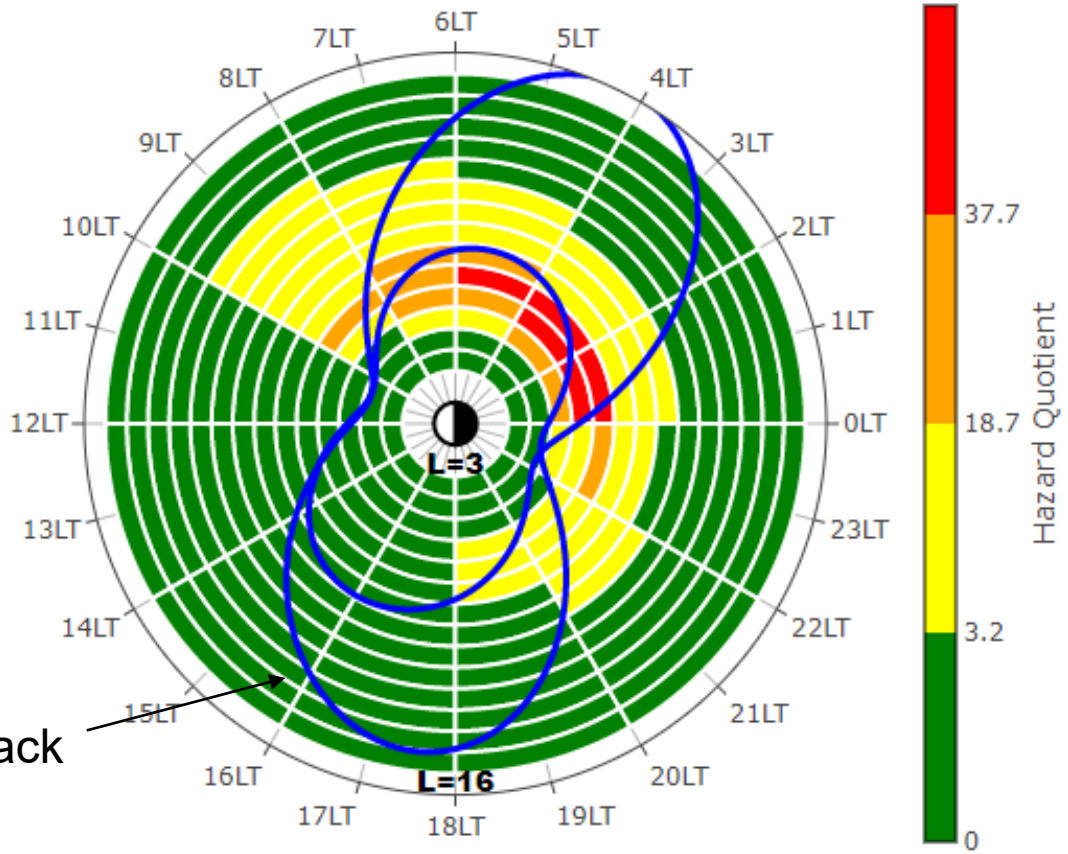
Past			Current	Forecast						
2023-02-13	2023-02-14	2023-02-15	2023-02-16	2023-02-16	2023-02-17	2023-02-18	2023-02-19	2023-02-20	2023-02-21	2023-02-22
										

Daily L/MLT maps of Surface charging hazard

LEAF-HQ

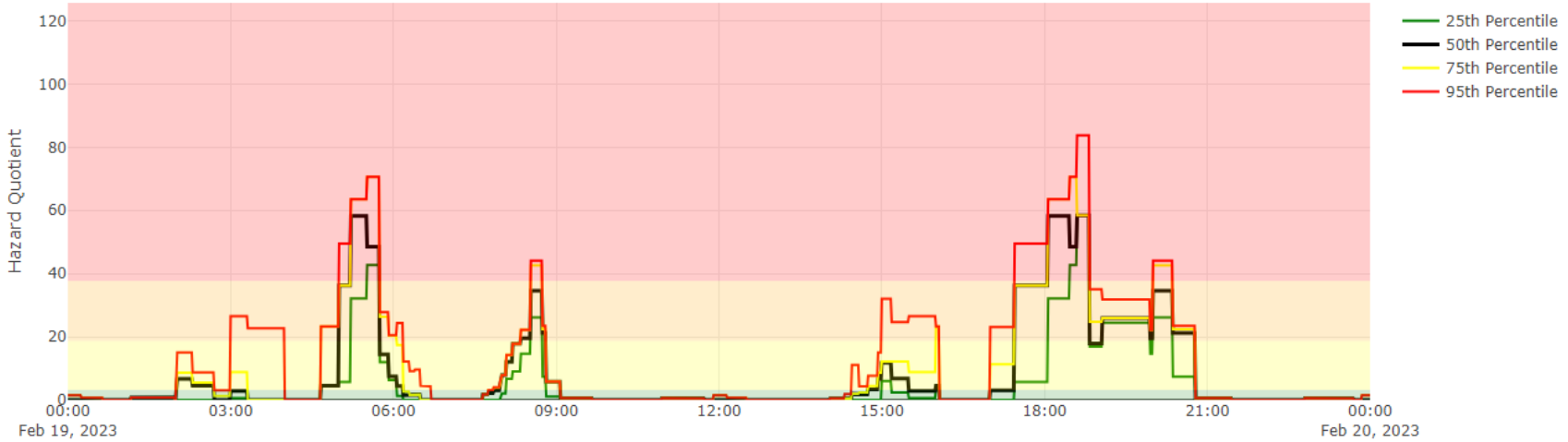
HEO/MEO

- Example output for specific satellite (NAVSTAR-60)



Daily orbit track

Interactive plot of the hazard along the orbit track



LEAF-HQ

GEO

Internal Charging Hazard based on LEEF-GEO

Internal Charging

Past			Current	Forecast																				
2023-02-13	2023-02-14	2023-02-15	2023-02-16	2023-02-16			2023-02-17			2023-02-18			2023-02-19			2023-02-20			2023-02-21			2023-02-22		
1.00	0.36	0.01	0.01	100%	0%	0%	98%	2%	0%	96%	2%	1%	98%	2%	0%	98%	2%	0%	98%	2%	0%	100%	0%	0%

Surface Charging Hazard based on LEAF-Kp

Surface Charging

Local Time

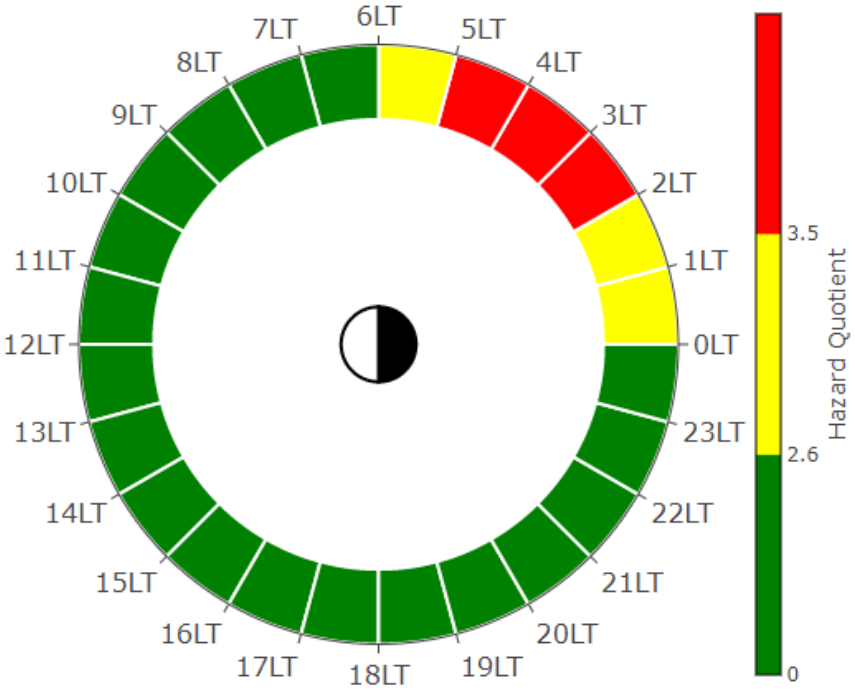
	Past			Current	Forecast																			
Local Time	2023-02-13	2023-02-14	2023-02-15	2023-02-16	2023-02-16			2023-02-17			2023-02-18			2023-02-19			2023-02-20			2023-02-21			2023-02-22		
0	1.80	2.81	3.19	0.64	10%	90%	0%	19%	81%	0%	26%	74%	0%	36%	64%	0%	42%	58%	0%	37%	63%	0%	26%	74%	0%
1	2.49	3.39	3.49	0.99	2%	14%	84%	6%	22%	72%	9%	27%	64%	21%	25%	54%	21%	31%	48%	18%	30%	52%	13%	22%	65%
2	2.64	3.69	3.78	1.05	1%	9%	89%	5%	16%	79%	7%	20%	72%	18%	20%	62%	18%	26%	56%	15%	24%	61%	11%	17%	72%
3	2.48	3.72	4.02	1.04	2%	9%	89%	6%	14%	79%	9%	19%	72%	20%	18%	62%	21%	23%	56%	17%	22%	61%	13%	15%	72%
4	2.28	3.54	4.14	0.84	4%	30%	67%	9%	24%	67%	13%	32%	55%	24%	26%	50%	26%	33%	41%	22%	29%	49%	16%	22%	63%
5	1.76	2.99	4.00	0.55	9%	52%	39%	17%	47%	35%	23%	52%	24%	34%	43%	23%	39%	39%	23%	34%	43%	22%	24%	42%	34%
6	0.72	1.28	1.64	0.25	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%
7	0.15	0.24	0.21	0.10	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%
8	0.08	0.08	0.00	0.08	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%
9	0.08	0.08	0.00	0.08	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%
10	0.08	0.07	0.00	0.09	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%
11	0.08	0.07	0.00	0.08	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%
12	0.08	0.05	0.01	0.09	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%
13	0.04	0.04	0.10	0.11	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%
14	0.04	0.03	0.12	0.11	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%
15	0.04	0.04	0.11	0.11	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%
16	0.08	0.07	0.10	0.09	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%
17	0.12	0.11	0.17	0.11	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%
18	0.08	0.07	0.27	0.07	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%
19	0.06	0.15	0.79	0.07	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%

LEAF-HQ

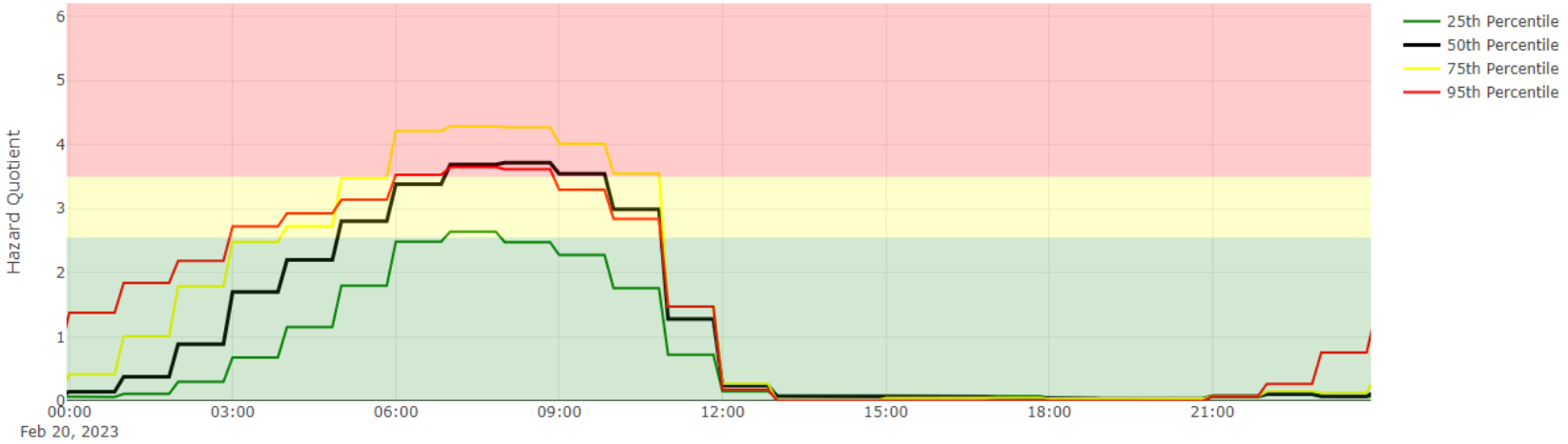
GEO

- Example for GOES-16
- For GEO, can use TLE or orbit longitude

Daily Hazard vs. MLT (similar to SEAES-RT)



Interactive plot of the hazard along the orbit track (LT->UT translation)



Summary

- Long Term Environment and Anomaly Forecasts (LEAF) are a series of multi-week ahead forecasts of space weather observables that relate to satellite hazards
  - *Forecasts*
    - LEEF-GEO (28 day forecast of GEO electrons)
    - LEAF-Kp (7 day forecast of Kp Index)
    - LEAF-OBI (7 day forecast of POES Outer Belt Index)
  - *Dashboards*
    - LEAF-SSA (Forecast/Current Conditions Dashboard)
    - LEAF-HQ (Hazard Quotient Dashboard/Tool)

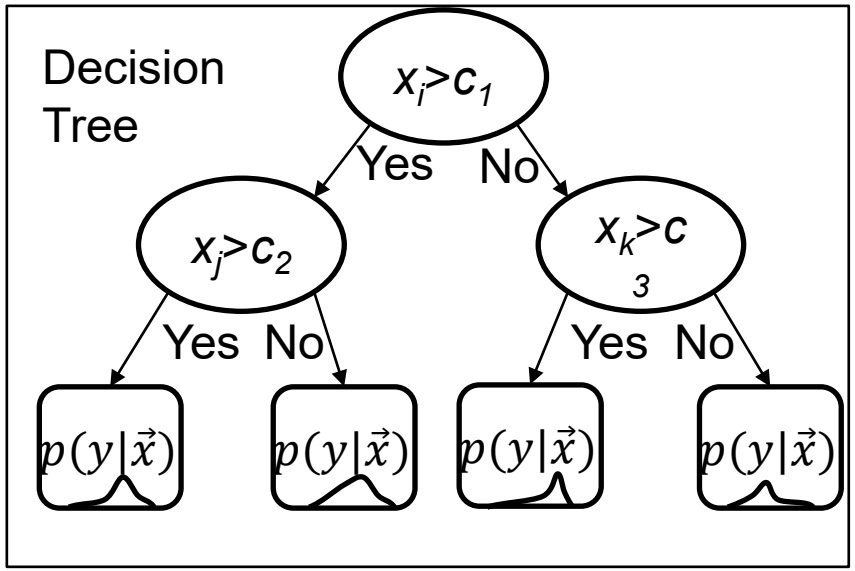
- Forecasts/SSA dashboard available on UDL for FOUO Users: https://unifieddatalibrary.com/sfm/rest/downloadFile/External/Aerospace/leef_geo/index.html
- LEAF-HQ prototype running internally at Aerospace
- Planned integration for all LEAF tools into SET4D, endorsed by USSF/Delta 9

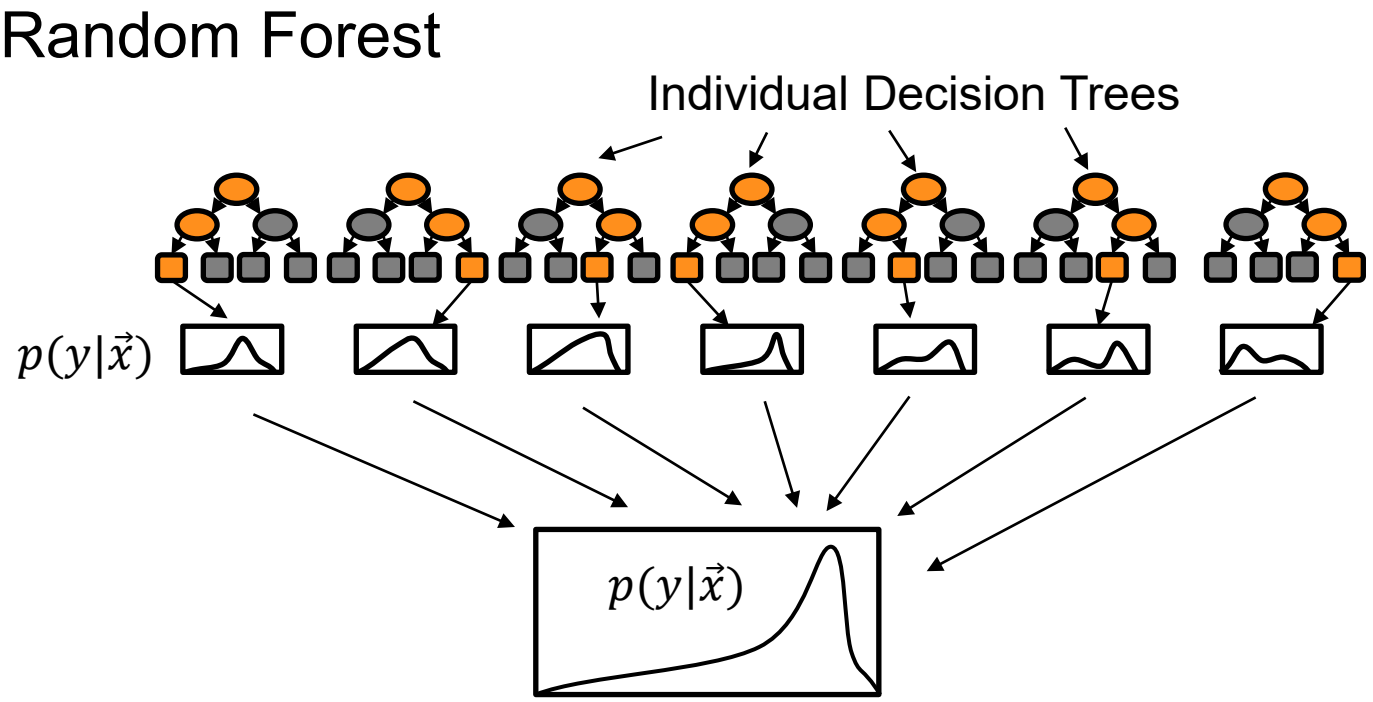
Backup

Model Setup

Random Forests

- Each of the LEAF models is constructed using a ML technique called Random Forest

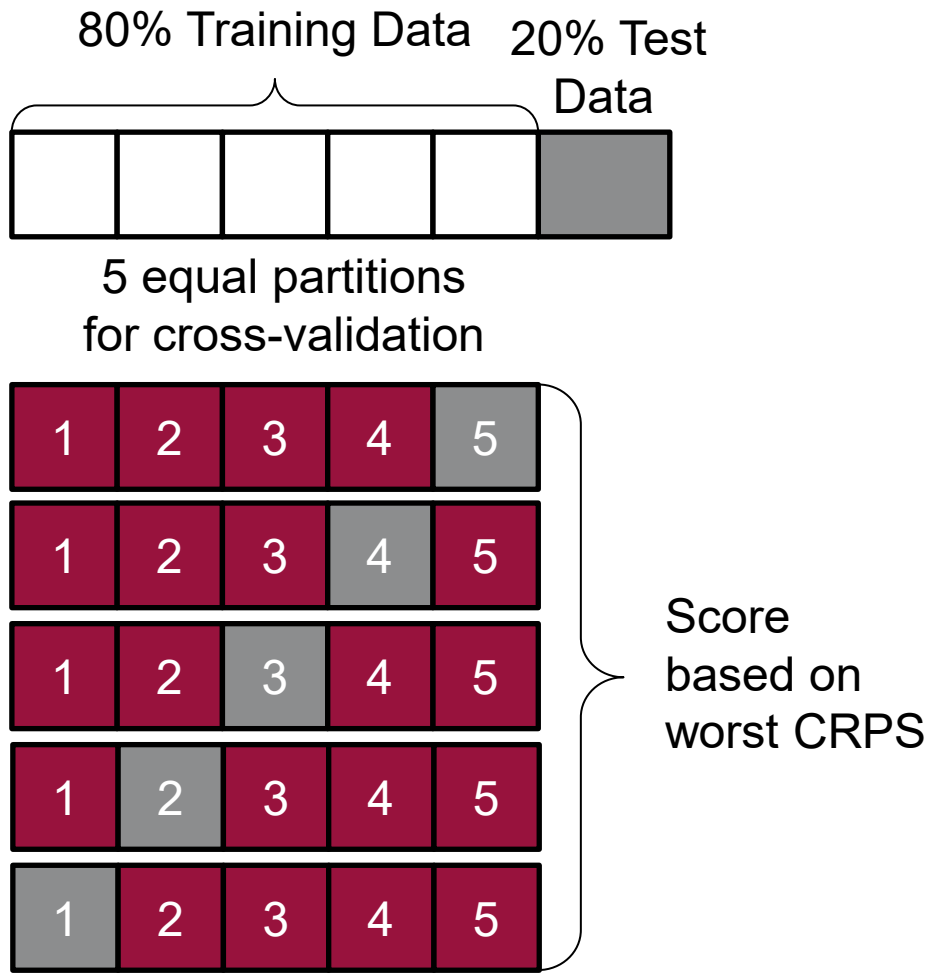




Model Setup

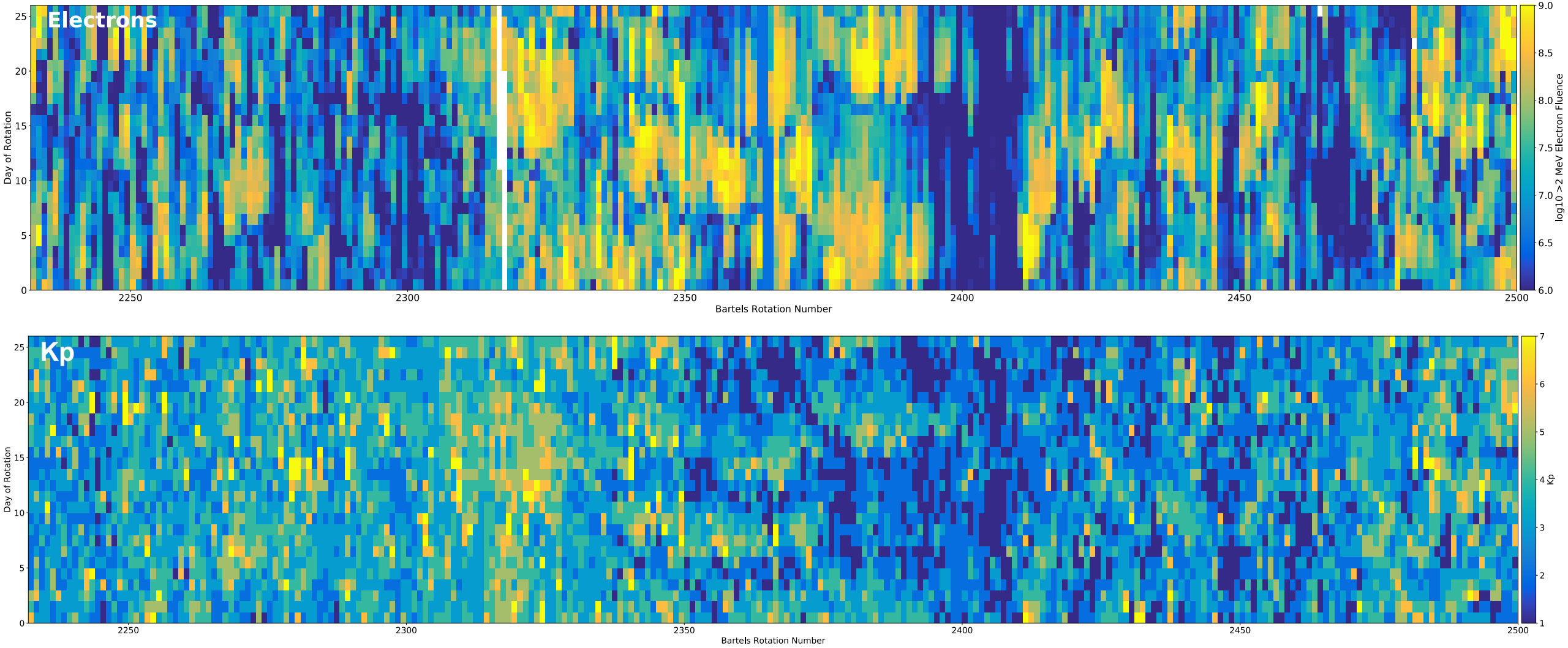
Training

- 20+ year training dataset
- Potential Inputs (45 day histories):
  - *>2 MeV GEO Electron Flux*
  - *Kp Index*
  - *Sunspot Number*
  - *Solar Wind Velocity*
  - *>5 MeV GEO Proton Flux*
  - *POES Outer Belt Index*
  - *Interplanetary magnetic field magnitude*
- Output cumulative probability distribution
- Try different combinations of inputs, model parameters to find best out-of-sample score
- Each forecast horizon trained separately



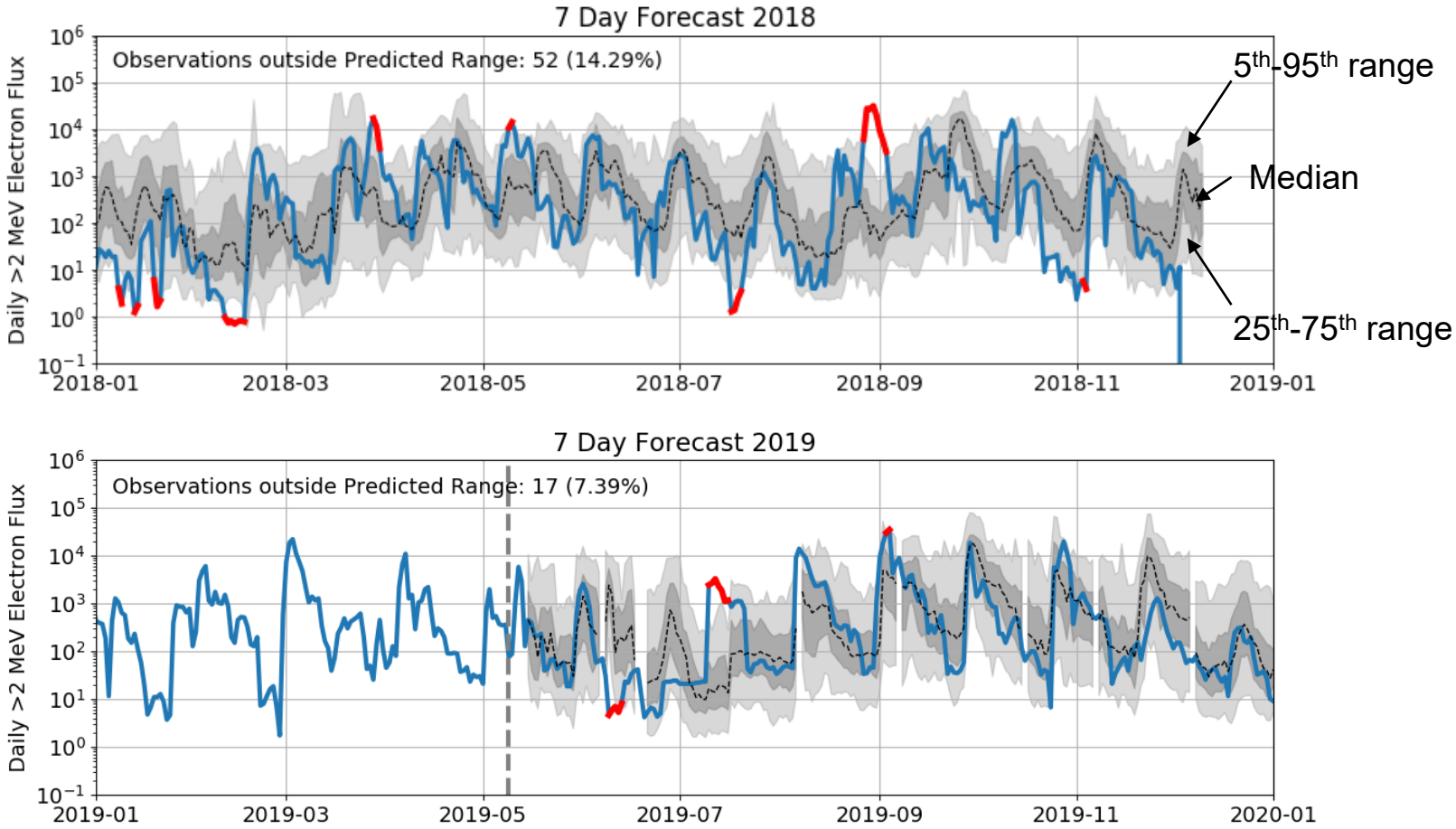
Forecast Tools

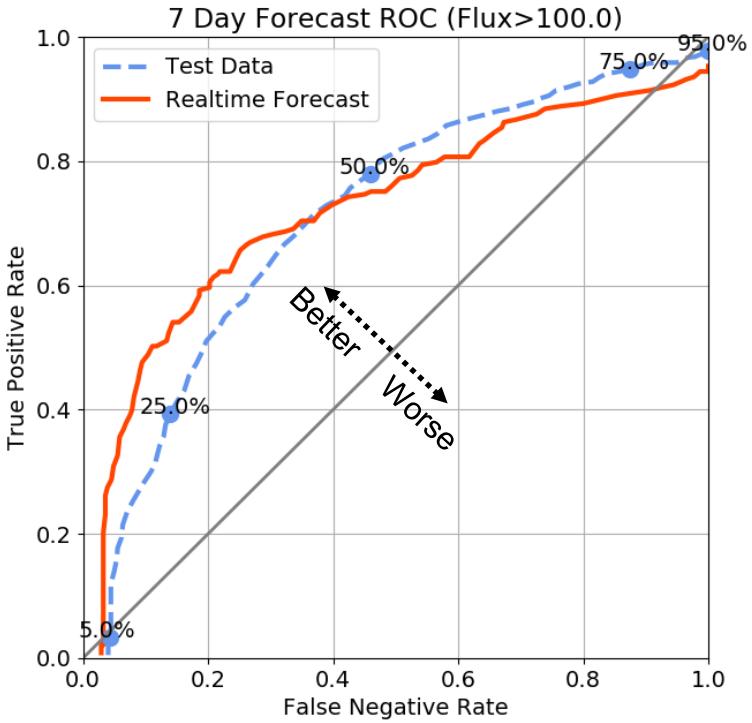
Bartels' Rotation Plots



LEEF-GEO

Validation

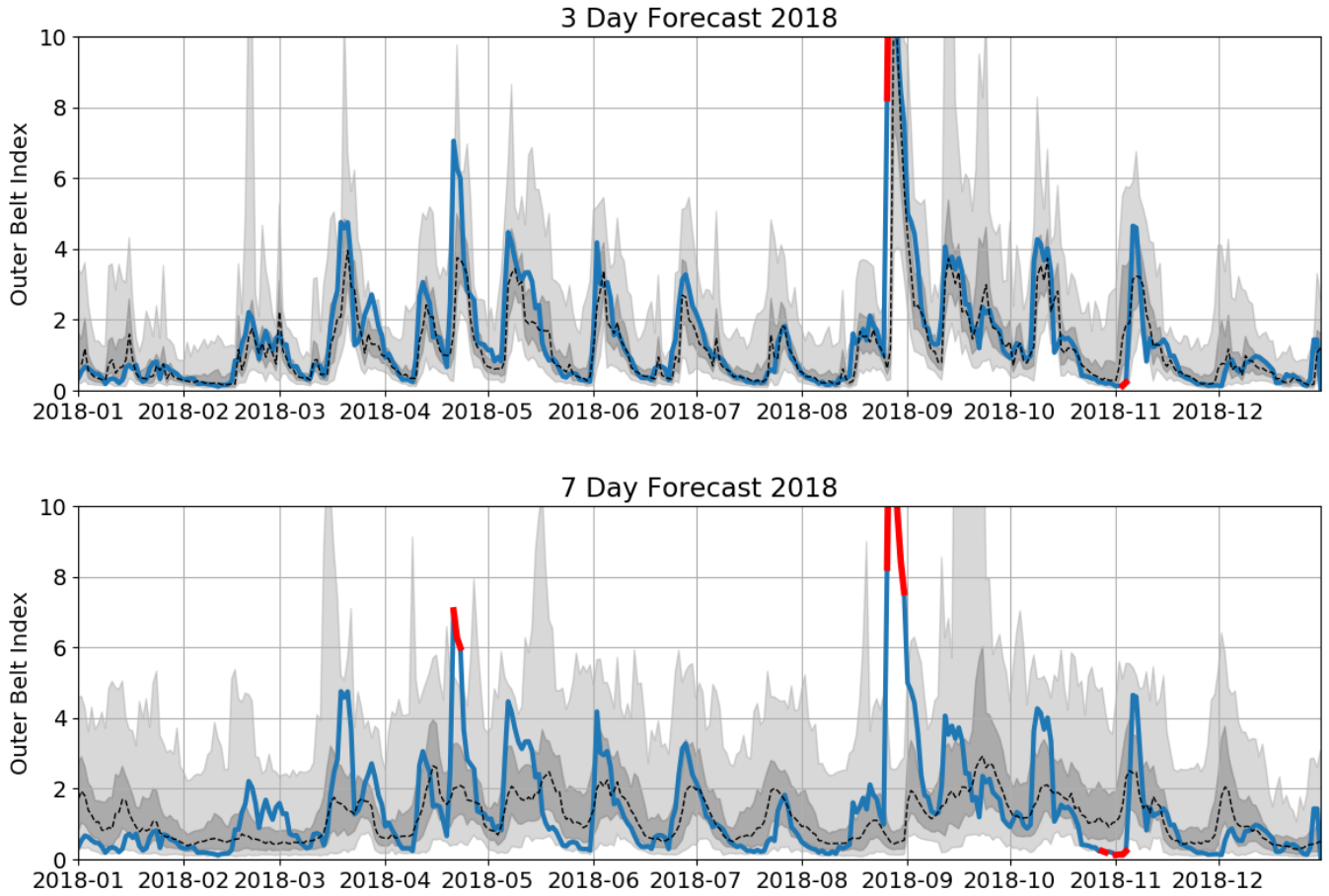


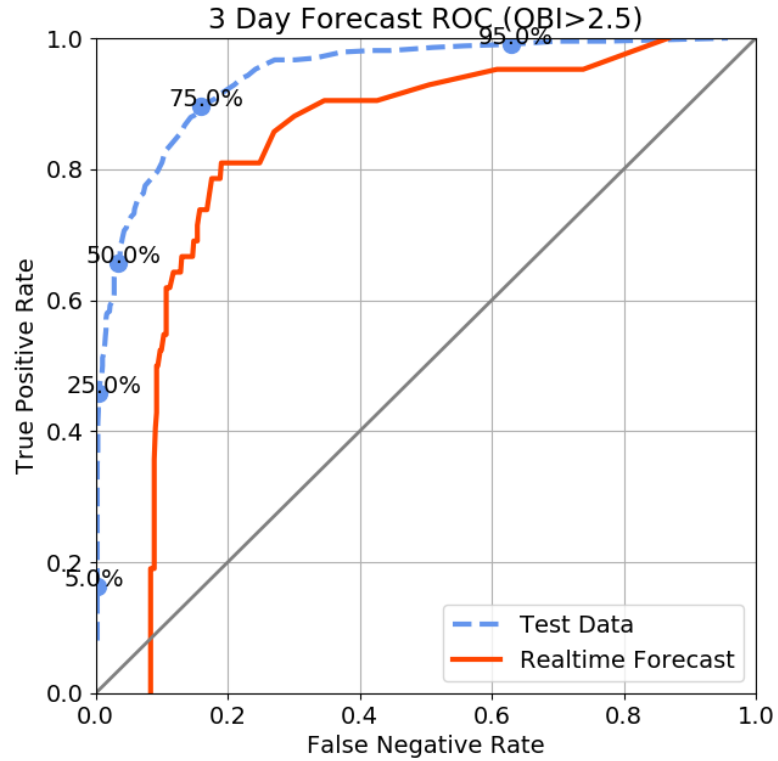


Comparison of real-time 7 day forecast to GOES observations

LEAF-OBI

Validation





Comparison of real-time 7 day forecast to POES observations

LEAF-Kp

Validation