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REACH Maps and Indices for UDL: Version 1

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Abstract

This document contains a description of the initial datasets pushed to the Unified Data Library (UDL). Described in this document are Responsive Environmental Assessment Commercially Hosted (REACH) maps and indices, along with potential future products.

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1. Background on REACH

1.1 The REACH Constellation

The Responsive Environmental Assessment Commercially Hosted (REACH) constellation is a set of 32 payloads hosted on a commercial low Earth orbit (LEO) satellite constellation Figure 1. Each payload (pod) carries two dosimeters which were designed by The Aerospace Corporation and manufactured by Teledyne Microelectronics. This constellation allows for the satellites to sample the different regions of the magnetosphere and radiation environments in LEO at an altitude of approximately 800 km. The REACH intra-calibration results show that there is less than 20% difference between the sensors for a given type [3].

Courtesy of Iridium

Figure 1. The Iridium satellites prior to launch.The REACH hosted payload is located inside the white hosted payload at the top of the satellite and circled in this figure [1].

1.2 The Flavors of Dosimeters

There are a total of six unique measurements determined by the physical design of the dosimeter and the inert shielding around the dosimeter detector. We refer to the various measurements with the term “flavor”, each of which have a different threshold for electrons and protons. The different flavors are often associated with different space-weather hazards: for example, internal charging in the outer radiation belt and single event effects in the inner proton belt or over the polar caps during solar particle events. The flavor designator and characteristics are shown in Table 1. The bow-tie analysis and results for the energies which each detector is sensitive to can be found in Reference [2]. The dosimeters are located on the ram-nadir side as shown in Figures 1 and 2. The effect of this is a systematic difference in the doses observed in the northern and southern hemispheres when the satellite is travelling either northbound or southbound in latitude. This difference is due to the orientation of the sensor along the magnetic field line which guides the path of the radiation belt particles as shown in Figure 2.

Table 1. The REACH Dosimeter Flavors, the Nominal Energy Threshold of Electrons and Protons it is Sensitive to, and the Number of Satellites Which have that Flavor.

Flavor	Mils Mallory	~mils Al	Type	Nominal Electron MeV	Nominal Proton MeV	# of Satellites
Z	0	0	LowLET	0.05	0.2	6
Y	24	183	MedLET	1.6	31	12
X	0	32	MedLET	0.36	12	20
W	0	332	HiLET	-	12	14
V	56	383	MedLET	3.41	47	7
U	80	533	MedLET	4.97	57	5

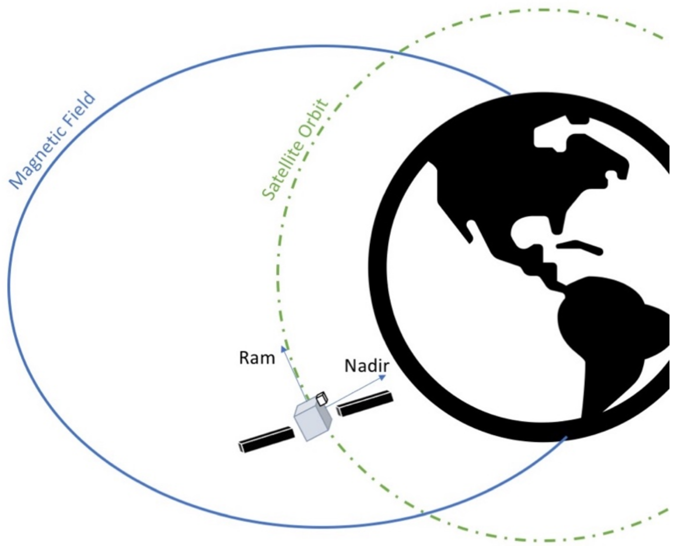

Figure 2. A cartoon of the satellite orbit relative to the field line.Due to the particle trajectories and the change of the field of view of the REACH dosimeters to the magnetic field line (the blue line) with respect to the orbit (green dotted line), REACH samples different pitch angles and portions of the trapped and lost particle populations during different parts of the orbit. This cartoon is not to scale.

2. REACH Dose-Rate Maps

2.1 Background

One benefit of the REACH constellation is the improved latitudinal and longitudinal coverage it provides. This improved coverage allows REACH to sample the global radiation environment more frequently than has been demonstrated before.

The maps provided in UDL currently have 1 by 1-degree latitudinal and longitudinal resolution. In order to ensure near complete spatial coverage for each flavor of dosimeter, the median dose rate is taken from all instruments within a 1 by 1-degree latitude and longitude bins over a period of 24 hours. The time frame and latitudinal and longitudinal bins will be limited to the number of satellites and planes which the satellites are in. The REACH team is exploring different combinations of spatial resolution (larger bins) and timeliness (shorter aggregation intervals) to update these files in the future.

2.2 Dose-Rate Map CSV Files

We produce a comma separated value (CSV) file for each flavor which is copied to UDL every hour. This CSV file is formatted to have the mid-point for the longitudinal bin in column A (Figure 3) and the mid-point for the latitudinal bin in row 1 (Figure 3). The data corresponding to each longitude/latitude bin is then in the appropriate cell (e.g., longitude = -172.5, latitude = -83.5 is in bin H9 as shown in Figure 3). The values are provided in rads per second and are the median dose rate of all dosimeters of a given flavor sampling within that latitude/longitude bin in the last 24 hours. Where there is no spatial coverage, the bin is filled with a “not a number”, or nan. This is to distinguish between intervals where the observed dose is 0 (e.g., I4 in Figure 3), and where there is no spatial coverage (e.g., B2 in Figure 3). Currently, each of these files is updated every 10 minutes.

	A	B	C	D	E	F	G	H	I	J	K	L
1	lon/lat	-89.5	-88.5	-87.5	-86.5	-85.5	-84.5	-83.5	-82.5	-81.5	-80.5	-79.5
2	-179.5	nan	nan	nan	6.07E-07	2.04E-07	7.13E-07	nan	8.10E-07	0	3.11E-07	nan
3	-178.5	nan	nan	nan	2.43E-06	3.04E-07	8.10E-07	2.06E-07	3.02E-07	8.16E-07	2.07E-07	5.45E-07
4	-177.5	nan	nan	nan	4.11E-07	7.16E-07	4.08E-07	2.06E-07	0	6.08E-07	4.07E-07	3.94E-07
5	-176.5	nan	nan	nan	3.03E-07	2.04E-07	8.10E-07	2.06E-07	0	6.08E-07	4.07E-07	2.07E-07
6	-175.5	nan	nan	nan	2.05E-07	4.01E-07	4.05E-07	nan	1.02E-07	6.03E-07	4.08E-07	nan
7	-174.5	nan	nan	nan	6.07E-07	1.22E-06	1.37E-06	2.07E-07	nan	4.07E-07	4.08E-07	nan
8	-173.5	nan	nan	nan	4.13E-07	4.07E-07	4.08E-07	2.02E-07	2.05E-07	4.07E-07	4.02E-07	4.08E-07
9	-172.5	nan	nan	nan	4.08E-07	2.01E-07	1.02E-06	3.06E-07	2.05E-07	4.07E-07	nan	4.02E-07
10	-171.5	nan	nan	nan	2.04E-07	1.52E-06	3.10E-07	2.02E-07	4.07E-07	2.05E-07	nan	5.07E-07
11	-170.5	nan	nan	nan	4.14E-07	3.05E-07	1.07E-06	5.08E-07	4.07E-07	2.05E-07	nan	1.01E-06

Figure 3. An example of a CSV file for the REACH latitudinal and longitudinal maps.The values are in rads/sec and where there is no data coverage is shown as nans.

2.3 Dose-Rate Map Portable Network Graphics (PNG) Files

Different particle populations within the magnetosphere pose distinct hazards to spacecraft operations and changes in these populations occur on different time scales. We can map out these regions which satellites in LEO orbits will encounter. These regions use the same and similar definitions used previously for space weather products such as SEAES, and POES. Figure 4 shows the regions mapped to an altitude of 800 km. The South Atlantic Anomaly (SAA) is a region of decreased magnetic field and identified as +1 in Figure 4. The inner zone, or inner radiation belt, is a region of particles which are considered trapped in the magnetosphere and identified as -1 IZ Untap in Figure 4. The inner zone and SAA is found to be very steady and are plotted in Figure 5 in red. The slot region is defined as mapping to the magnetic equator between 1 to 2 Earth Radii is labeled as +/- 2 in Figure 4. The slot region is defined as between 2.0 and

2.5 Earth Radii at the magnetic equator which maps to a narrow band in Figure 4. It is often depleted of radiation except during extreme storms is plotted in green in Figure 5. The outer zone (OZ) or outer radiation belts as defined as between 2.5–8 Earth Radii. This region is highly variable and is plotted in blue in Figure 5. The slot and outer zone regions have a further complication of either being trapped or un-trapped. The Trapped regions are filled with particles which are expected to stay in the magnetosphere. The un-trapped regions have a portion of the particle population which is expected to be lost to the upper atmosphere. The polar caps are defined as mapping to the outer magnetosphere and the solar wind, at distances in the magnetic equator of 10 Earth Radii and further identified as +/- 4 in Figure 4. This region can change dramatically and quickly during episodic solar particle events is plotted in yellow in Figure 5.

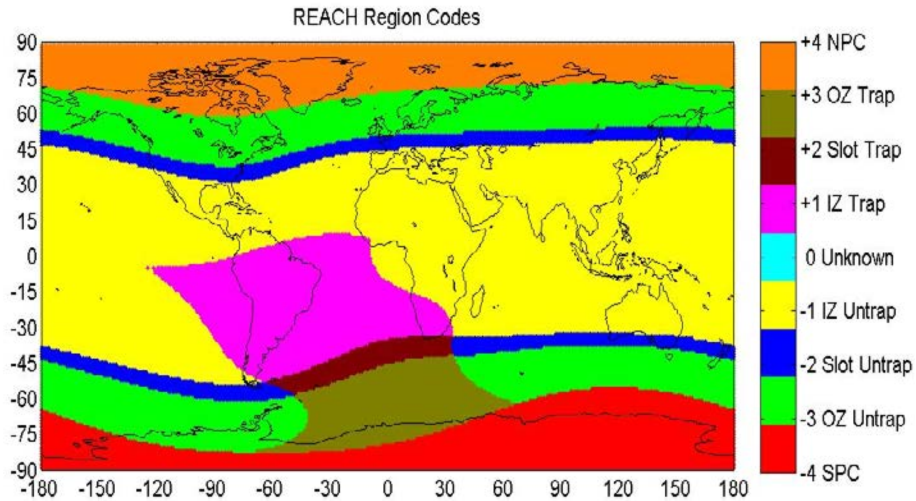

Figure 4. A PNG map of the magnetospheric regions mapped to an altitude of 800 km.NPC and SPC are defined as the northern and southern polar cap. OZ is the outer zone, or outer radiation belt region. IZ is defined as the inner zone, or inner radiation belt region.

The offset of the magnetic pole from the rotational axis of the Earth, along with its intrinsic asymmetries contribute to the asymmetry of the radiation environments on the geographic latitudinal and longitudinal grid. The look-direction of the sensor on the spacecraft also affects the asymmetry of the dose values observed in the northern and southern hemisphere of a given region.

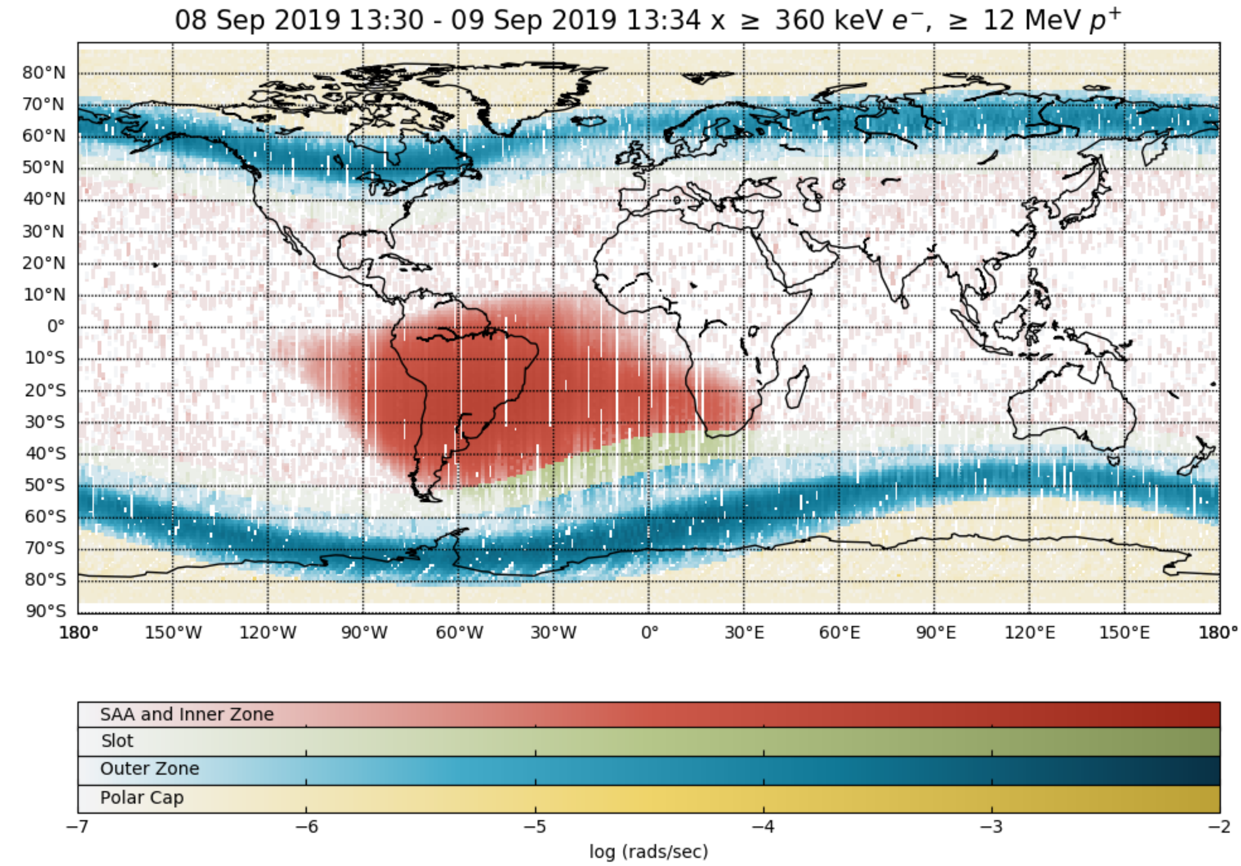

Figure 5. A PNG map of the average dose rates for REACH flavor X.Each of the different magnetospheric regions are identified in different colors. The SAA and inner zone are shown in red, the slot region in green, the outer radiation belt in blue, and the polar cap in yellow. The deeper the intensity of the color, the higher the level of radiation is present.

2.4 Production Frequency

The REACH maps are made at Aerospace on a 10-minute cadence. Currently, the latest maps are copied to UDL every hour. In the future the REACH team will make these available more frequently.

2.5 Uses

The primary use of the maps is as a quick-look global and archival view of the radiation environment at 800 km. Because there is significant correlation between structure at all altitudes, the presence or absence of radiation in the slot, outer zone, or polar cap at 800 km implies its presence or absence at lower and higher altitudes in the same region.

3. REACH Indices

3.1 Background

While the dose-rate maps provide a global view of the space radiation environment, a single index can provide a quick look temporal understanding of the radiation environment in a given region for a given energy. Each flavor associated with a different set of nominal energy thresholds has four indices related to each of the regions defined in Figure 4. The value of the index is the median dose rate within a given region for that day. For example, the median of all dose rate records of flavor X in the SAA defined as above for September 13th, 2019 consists of approximately 26,460 samples from 20 satellites. When using the high time resolution, the number of samples is closer to 1.3 million. Thus, when using the 24-hour integration period, the medians are very robust values.

3.2 REACH Index CSV Files

The reach indices CSV files are formatted to contain 19 lines of meta data followed by the rows of data from the start of the nominal REACH mission to the present. The meta data includes the name of the file, the date it was created along with a description of the data and what is found in each column. Currently, as shown in Figure 6, the columns contain the year, month, day, number of satellites which were used to create the indices, the SAA, slot, outer zone, and polar cap indices. As with the maps discussed above, nans are used to identify when there is no data coverage.

The current version of the UDL REACH indices provide a daily median of the dose in rads per second within a given region. The current day's data is the median of the last 24 hours. This is done to ensure that sufficient spatial coverage of each region is included in the distribution which the median is computed. This also allows for updated files to be created at 15-minute intervals. These files are periodically updated when new versions of the REACH data are made available.

	A	B	C	D	E	F	G	H
1	:Data_list: /tcs/ago/group/ampere2_reach/UDL/reach_x_index.csv							
2	:Created: 2019-09-08 21:46:51							
3	#							
4	# Source: The Aerospace Corporation REACH indices							
5	# This file contains the REACH indices for different magnetospheric regions.							
6	# This file contains the REACH indices from the model X dosimeter.							
7	# This responds to electrons greater than approximately 0.36 MeV and protons greater than approximately							
8	# This is a Std type dosimeter with the ~ equivalent to 32 mills of AL shielding							
9	# There are 20 REACH satellites with a model X dosimeter							
10	# format: comma separated values with the following columns							
11	# column 01 Year							
12	# column 02 month							
13	# column 03 day							
14	# column 04 Number of satellites which were used to generate the data point labeled as numSat							
15	# column 05 South Atlantic Anomaly index labeled RI_SAA							
16	# column 06 Slot region index labeled RI_Slot							
17	# column 07 Outer zone index labeled RI_OZ							
18	# column 0 8Polar Cap index labeled RI_PC							
19	Year	Month	Day	numSat	RI_SAA	RI_Slot	RI_OZ	RI_PC
20	2017	4	10	1	7.21E-05	2.14E-07	1.01E-06	4.16E-07
21	2017	4	11	1	3.07E-05	2.19E-07	1.57E-06	4.34E-07
22	2017	4	12	1	3.24E-05	2.19E-07	1.72E-06	4.34E-07
23	2017	4	13	1	3.08E-05	2.19E-07	2.71E-06	4.34E-07
24	2017	4	14	1	3.09E-05	2.19E-07	1.22E-06	4.34E-07
25	2017	4	15	1	3.00E-05	2.19E-07	1.00E-06	4.34E-07
26	2017	4	16	1	3.66E-05	2.19E-07	1.27E-06	4.33E-07
27	2017	4	17	1	3.74E-05	2.18E-07	1.24E-06	4.34E-07
28	2017	4	18	1	2.89E-05	2.19E-07	1.29E-06	4.34E-07
29	2017	4	19	1	3.07E-05	2.19E-07	8.71E-07	4.34E-07
30	2017	4	20	1	3.74E-05	2.18E-07	9.73E-07	4.34E-07
31	2017	4	21	1	2.33E-05	2.19E-07	1.05E-06	4.34E-07
32	2017	4	22	1	2.98E-05	2.18E-07	1.13E-06	3.85E-07

Figure 6. An example of the CSV files for a set of REACH indices.This is an example from REACH flavor X and shows the metadata along with the start of the data arrays.

3.3 REACH Index PNG Files

An example of the PNG files associated with the REACH indices for a given flavor can be seen in Figure 7. The top panel is the SAA index followed by the slot index, the outer zone index and the polar cap (PC) index. The REACH index plots show the current and recent environments with respect to the environments which REACH has historically observed. These PNG files are produced from the data in the CSV files simply to enable quick inspection of data availability vs time and data quality.

Data gaps do currently exist. Within the Z-index files, there is also a shift in the baseline due to a change in the processing of the dose rate. This new processing will be applied to the entire REACH time periods at a future date. As new versions of the data are made available, the indices are periodically updated.

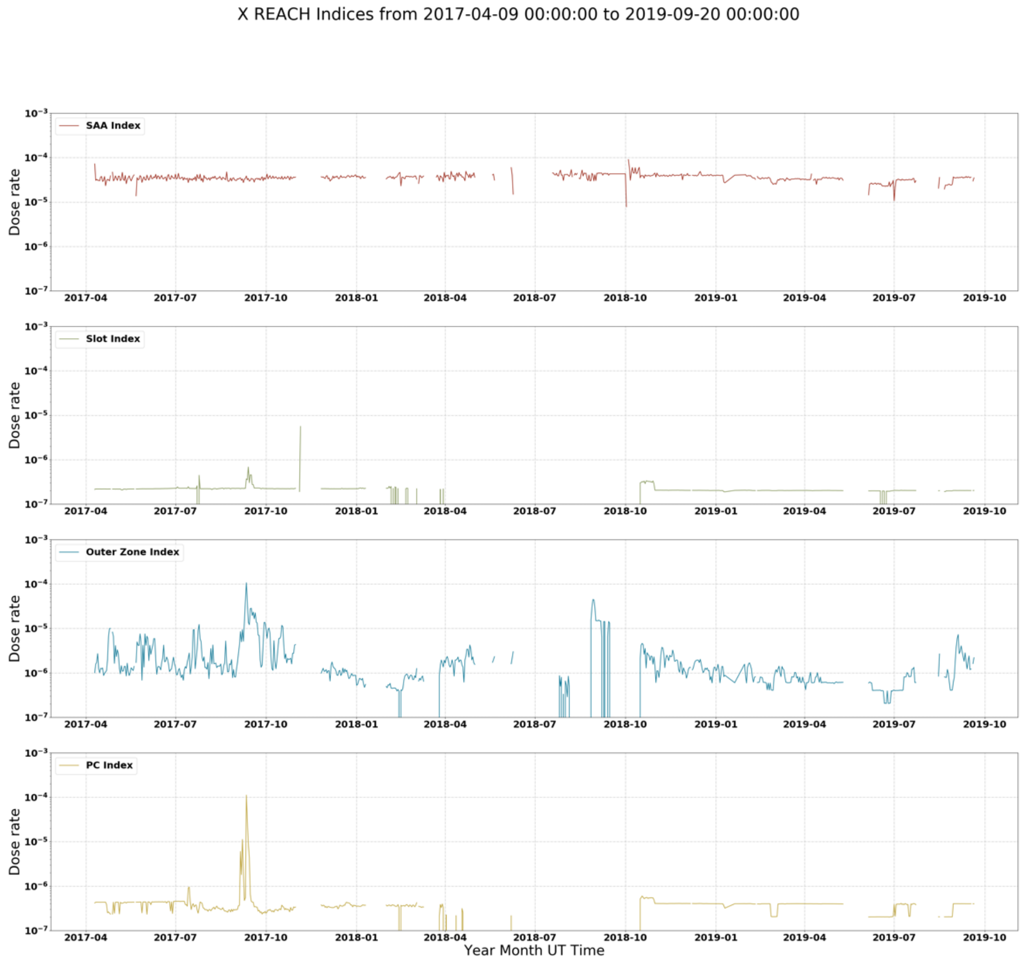

Figure 7. An example of the REACH indices for flavor X.The top panel shows the very stable SAA index followed by the slot, outer zone, and polar cap indices.

3.4 Production Frequency

The REACH indices are updated at Aerospace on a 15-minute cadence. Currently, these are copied to UDL every hour. In the future the REACH team will make these available more frequently.

3.5 Uses

The belt indices can be used as quantitative global indicators of the state of the different radiation belt populations. The time series can be used to determine how a given day compares to recent or long past history. Values on specific days can be used as inputs to anomaly forensic tools such as the one described in Aerospace Report ATR-2011(8181)-2, see Reference [2].

4. Potential Additions

There are many different use cases for this data, as well as modifications which can be made to these products. Below we will identify some which may be of interest to the user community.

4.1 Maps of Percent Difference From a Standard Interval

One may be interested not in what the radiation environment is like today, but how it compares to a standard interval. Figure 8 provides a map of such a standard interval between February 20th, 2019 and April 30th, 2019. This extended interval was relatively quiet and provided a long enough interval for a single satellite's orbital motion to cover all latitudinal and longitudinal bins. The median dose rate within each 1 degree latitudinal and longitudinal bin can be seen plotted in Figure 8 for HPL 171 when the vehicle is travelling southward. As discussed briefly in Section 1.2 and in Reference [3], the orbit direction has an effect in the dose-rate at certain locations.

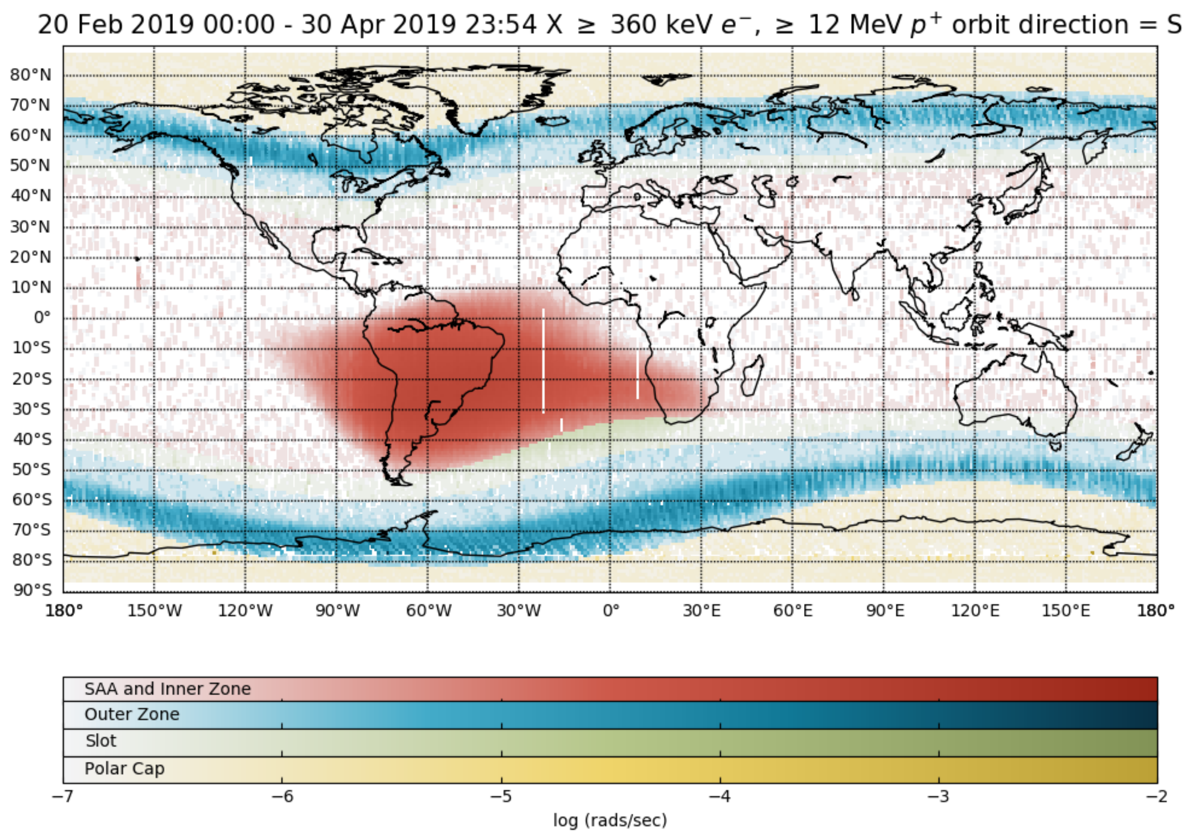

Figure 8. The standard interval for flavor X on satellite 171 when on the south bound potion of its orbit.The regions are mapped and plotted in the same scheme as shown in Figure 4.

Episodic radiation environment enhancements, often associated with geomagnetic storms, can be compared to this standard interval as shown in Figure 9. In Figure 9, observed dose rates which are below the standard interval are plotted in green while those which are above the standard are shown on the yellow to red scale. A contour plot of the SAA is plotted as this region underneath the values, so the region of the peak SAA is visible even when data is not available in the region. While not necessarily above average doses, the SAA always poses a finite threat to satellites.

The top left panel of Figure 9 shows the low Earth radiation environment prior to the geomagnetic storm onset on August 30th, 2019. The top right panel shows the change in the radiation environment during the start of the storm on September 3rd, 2019. The bottom two plots show the radiation environment recovering back to the standard level. When the dose is below the standard interval level, it is plotted in green scale. When the dose observed above the value of the standard interval, it is plotted in the yellow to red scale. Here we can see that the outer zone was highly elevated during the geomagnetic storm.

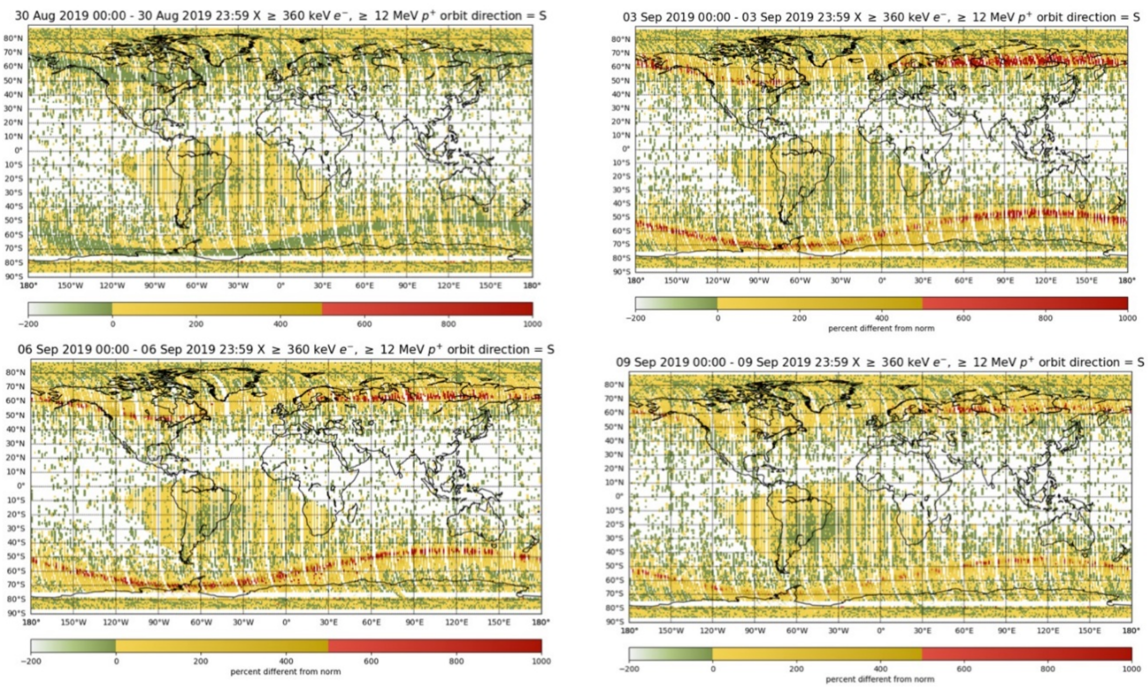

Figure 9. The percentage difference of the radiation environment observed during a geomagnetic storm time interval which resulted in an outer belt enhancement.

4.2 Quartiles and All Time Maximum for Index Values

The REACH constellation contains a lot of information which is boiled down to a single value, described in Section 3. To add more context these plots can be slightly modified as shown in Figure 10. The index value discussed in Section 3 is plotted for flavor X with a few modifications, most notably the time scale. Here the index, the median of 1x1 degree median dose rates in a region as described in Section 2, is calculated every 3 hours and shown in blue. The quartiles, the 25th and 75th percentiles of the distribution of the 1x1 degree binned medians in the region which determine the index value, are filled in showing the natural spatial distribution of doses within a region. This distribution can be seen in the difference of the colors seen in the maps such as in Figure 8. The maximum index value seen to date is tracked and shown in orange providing a historical comparison of the worst observed case to today's values. Today's value is denoted by the yellow circle with horizontal (dose-rate) and vertical (time) lines highlighting the values.

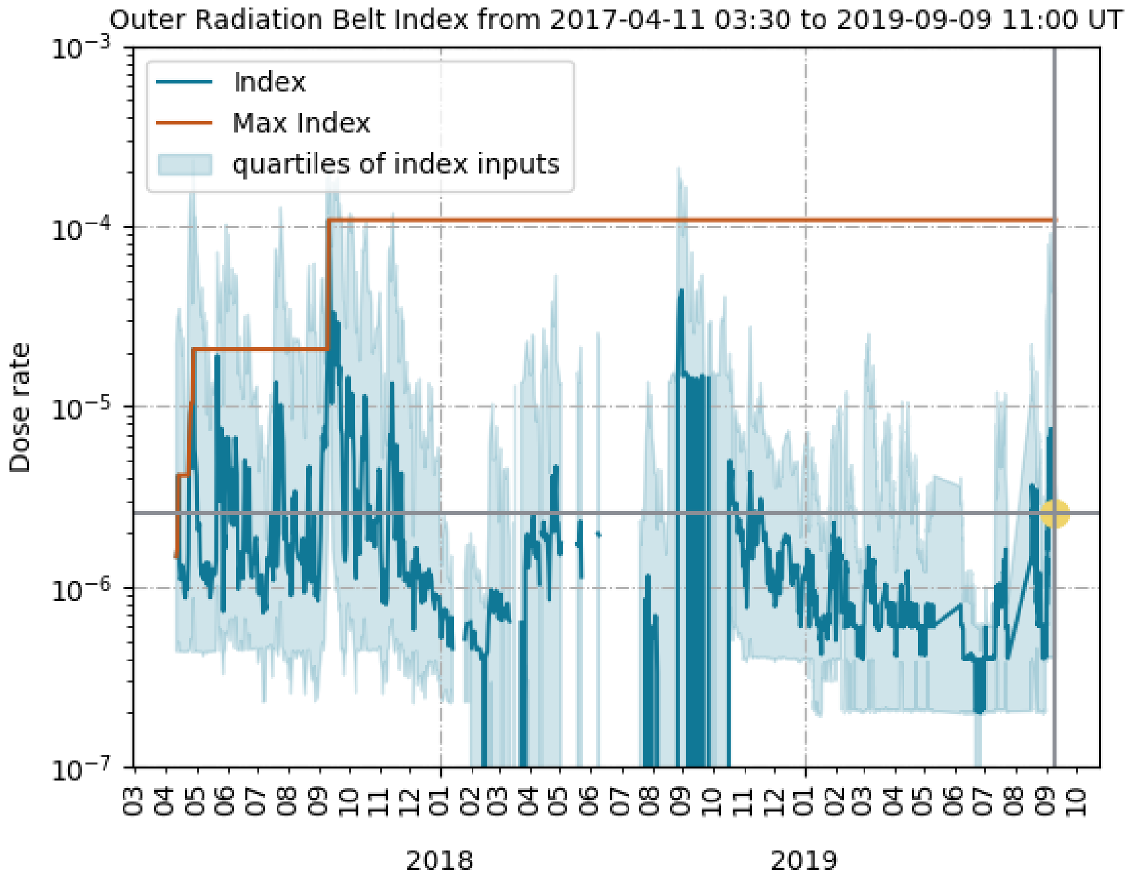

Figure 10. More information can be added to the indices including the quartiles of the distribution used to determine the index as well as continuous tracking of the largest index value seen by REACH for this index.A vertical and horizontal line have been added to help identify where the current day (shown by the yellow dot) compare to historical values.

5. References

1. "REACH and Iridium Launch", Los Angeles Air Force Base, Photos, 2019, VIRIN: 190111-F-ZZ999-102.PNG, https://www.losangeles.af.mil/News/Photos/igphoto/2002103790/.

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3. O'Brien, T. P., et al., A human-in-the-loop decision tool for preliminary assessment of the relevance of the space environment to a satellite anomaly, Aerospace Report ATR-2011(8181)-2, 2019.

4. Halford, A. J.; T. Guild; T. P. O'Brien; A. J. Boyd; and J. E. Mazur, Intra-calibration of REACH Dosimeters, Aerospace Report TOR-2019-02361, 2019.

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