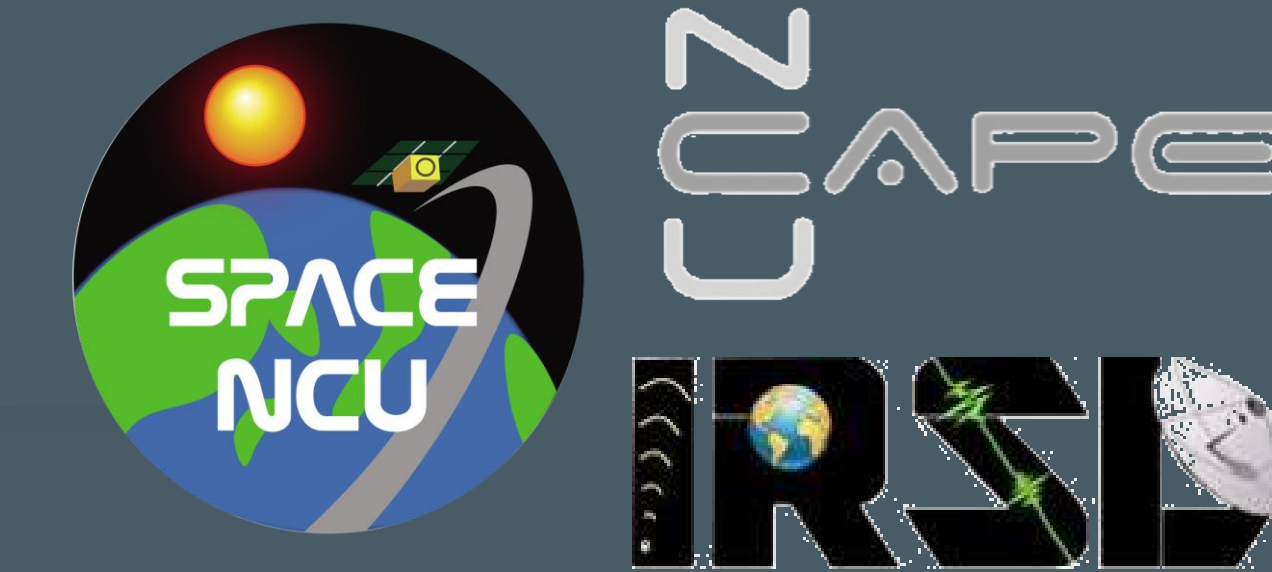


# Study of single event effects on commercial off-the-shelf GPS receivers onboard FORMOSAT-7/COSMIC-2 constellation in low-Earth orbit



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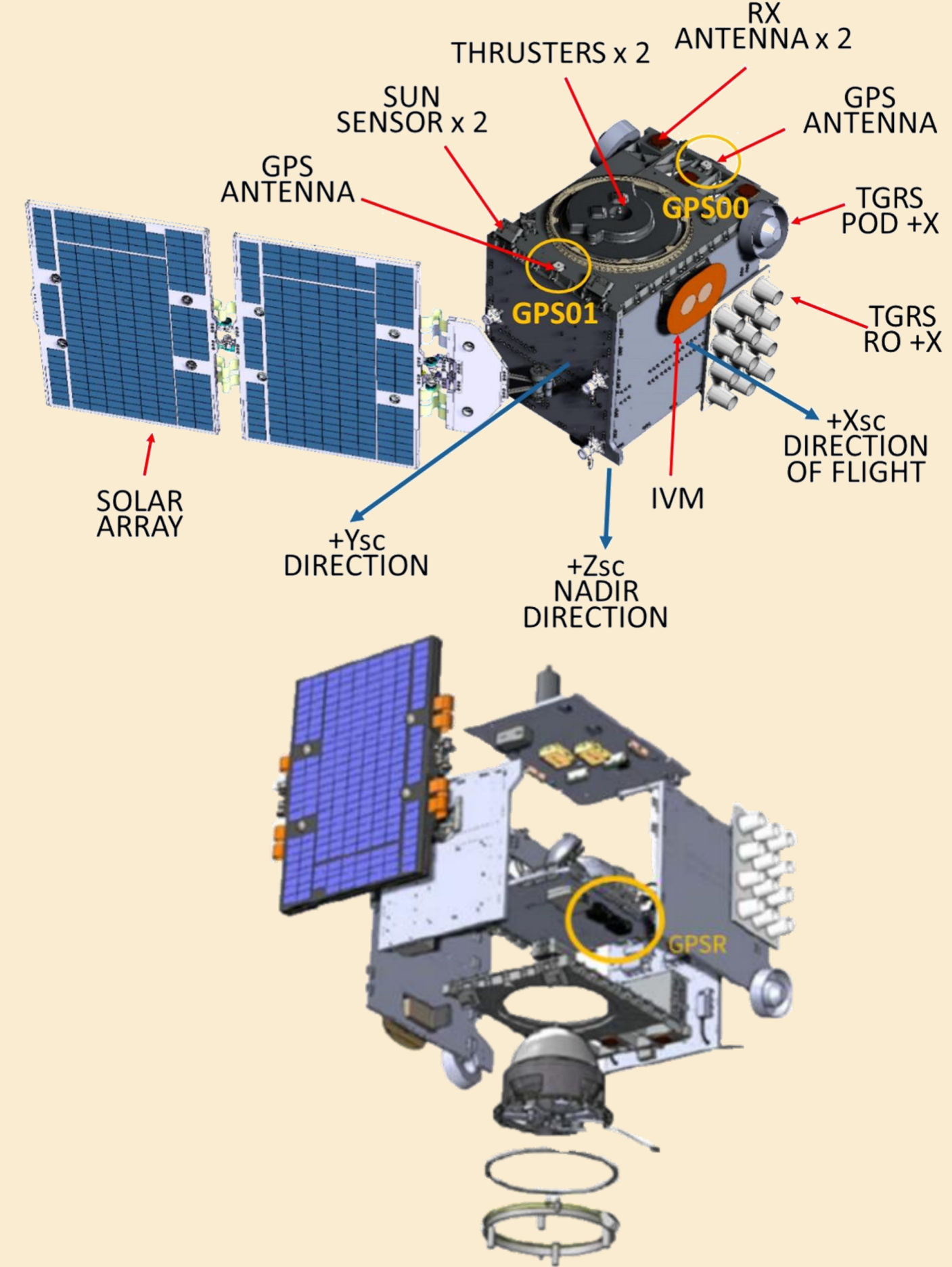
## ABSTRACT

The FORMOSAT-7/COSMIC-2 (F7/C2) is a six-satellite constellation of the Taiwan-US program. The constellation launched to the parking orbit of 720 km on 25 June 2019 and then transferred to the mission orbit of 550 km sequentially. Each satellite bus equips with two commercial off-the-shelf (COTS) global positioning system receivers (bus GPSR) for positioning, navigation, and timing functions. Three years after commissioning, more than 7,000 times "GPS Receiver Warm Start Requested (WSR)" messages, a type of single event effect (SEE), have been documented. The SEEs result from the radiations and energetic particles in space, and may even lead to the failure of the mission. This study investigates the cumulative rate, distribution of WSRs, and their relationships with altitude, geomagnetic field, and space weather. The SEE warning area of this kind of component is also reported based on the geomagnetic field with strengths of 21,200/20,550 nT at both orbits, which can also be regarded as the border of the South Atlantic Anomaly (SAA) area. The weighting centers, standard deviations, and the longitudinal drift of the SAA are simultaneously interpreted.

## INTRODUCTION & MOTIVATIONS

### Introduction

- The SEE mainly results from energetic particles and radiation hazards, which could lead to software errors or hardware damages.
- The WSR is a kind of SEE that occurs in the bus GPS receiver due to the bit-flip of the onboard memory.
- F7/C2 maneuvers from 720 km altitude to 550 km altitude in 20 months, which is the first LEO satellite constellation that can be used to study the SEEs in various altitudes.

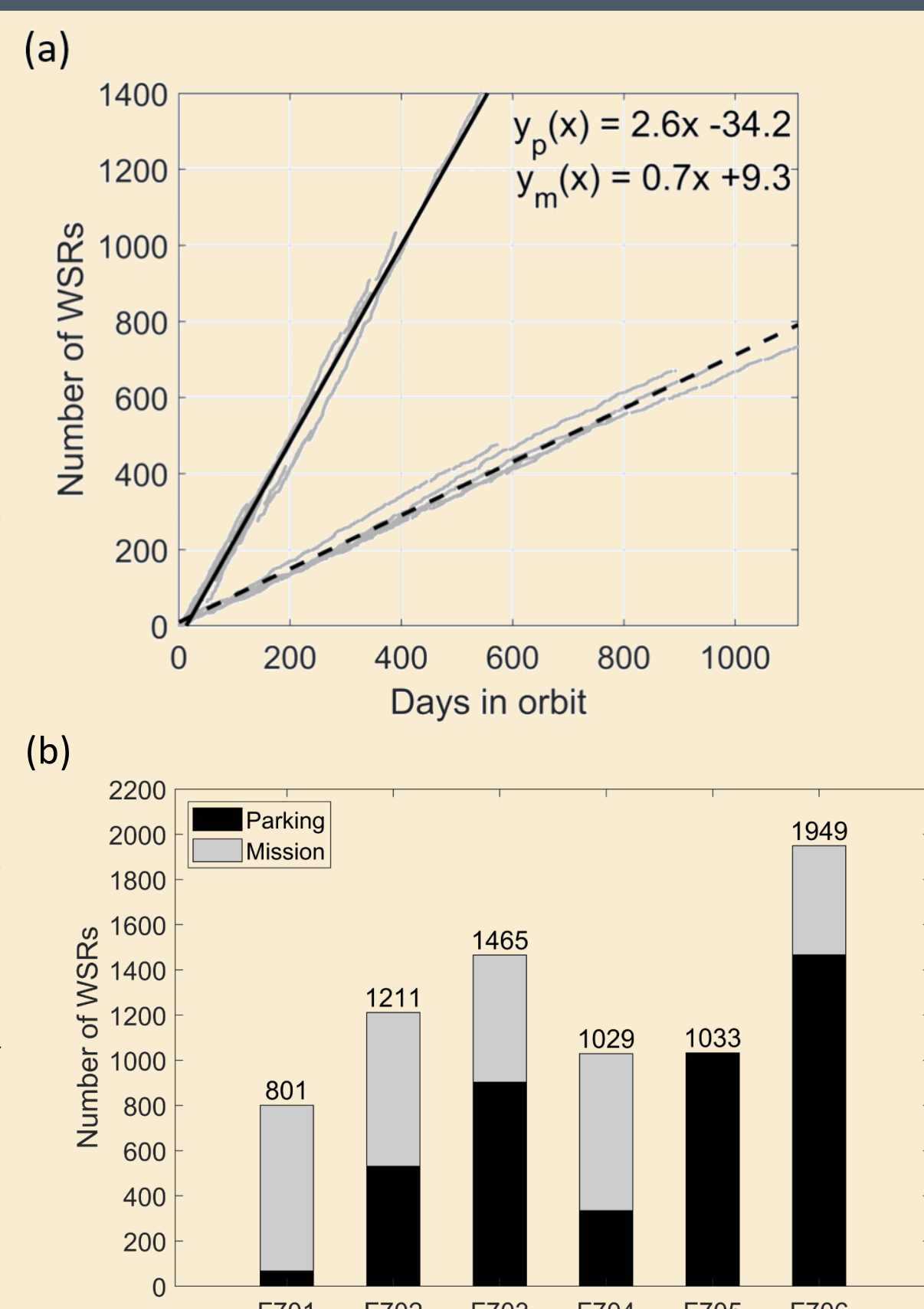


### Motivations

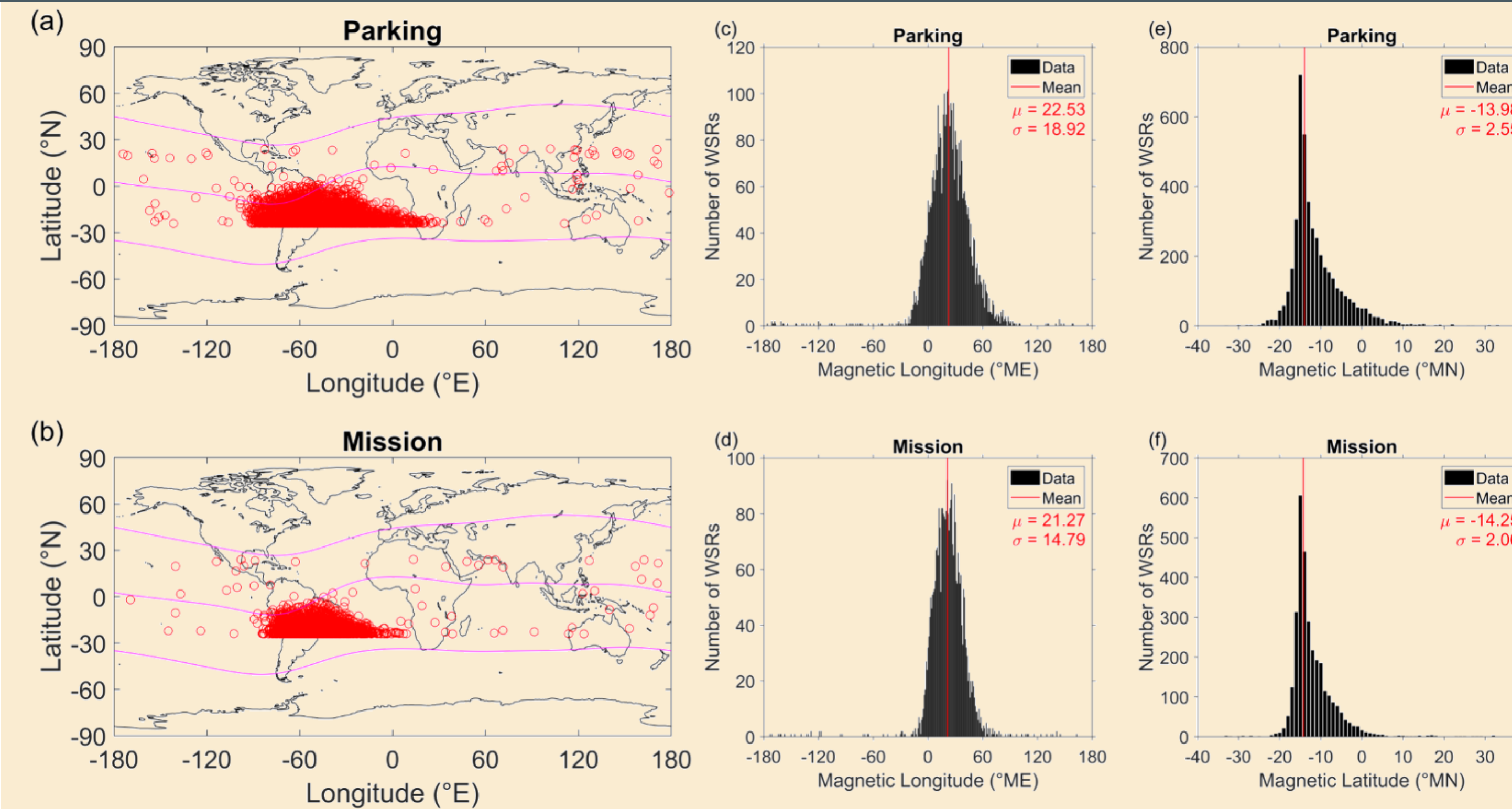
- There are 7,488 WSRs occurred in 3 years after launching, while F3/C has only 385 SEEs in about 5 years (Lee et al., 2014).

## DATA

- The WSR is recorded in onboard computer logs, with only the occurring time tag.
- AGI STK is applied to determine the orbital information and location of WSRs.
- The slopes of WSR accumulation are 2.6 and 0.7 for the parking and mission orbits, with the former being 3.7 times higher than the latter.
- The statistical result of WSRs in each satellite, generally shows an increasing trend with the F7/C2 decreasing order, except for F705.
- Due to some unknown reasons, the WSR do not be recorded in F705 after descending to the mission orbit.



## RESULT 1: SPATIAL DISTRIBUTION

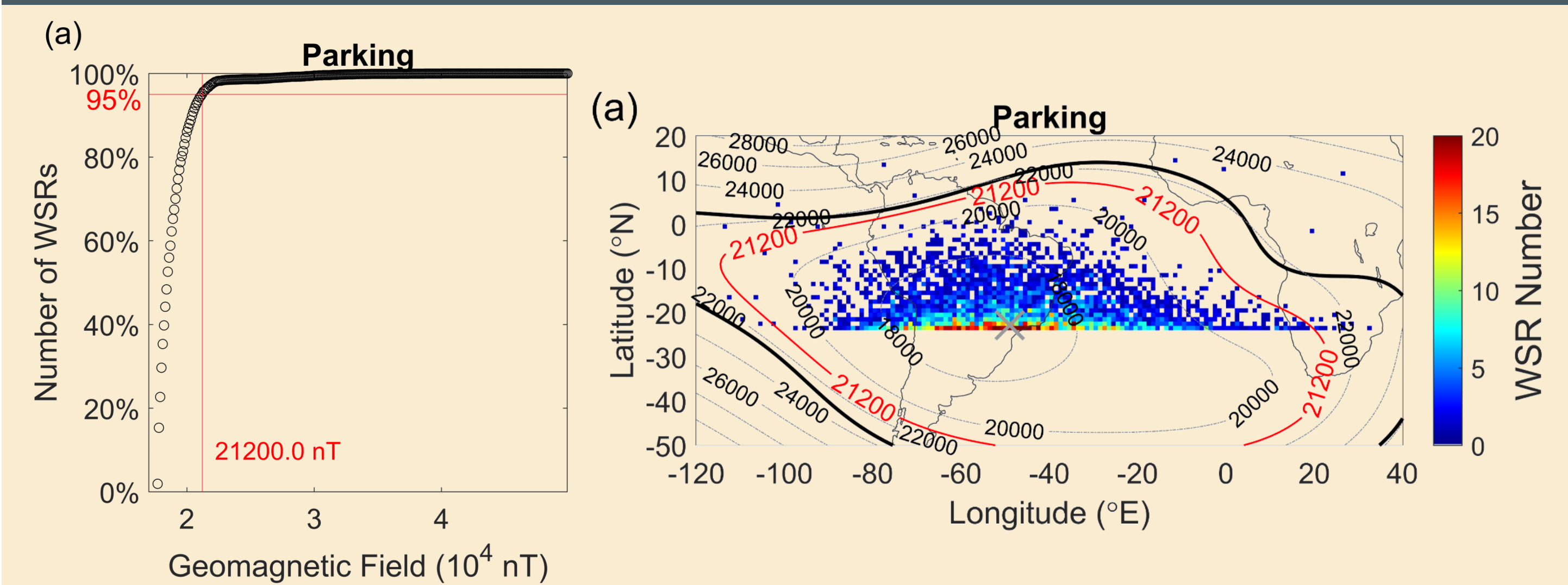


- Because of F7/C2 inclination angle, two clear cut-off edges are at around 24°N and 24°S.
- Most of the events are in the regions of South America and the south Atlantic.
- Due to the SEEs being resulted from ionized particles that are trapped by magnetic fields, the WSRs distribution is further analyzed along the magnetic coordinate.

Orbit	Geomagnetic Coordinate	Geographic Coordinate
Parking (720km)	WC (14.0°MS, 22.5°ME)	(22.8°S, 49.0°W)
	SD (2.6°, 18.9°)	-
Mission (550km)	WC (14.3°MS, 21.3°ME)	(23.2°S, 50.2°W)
	SD (2.1°, 14.8°)	-

- The weighting centers are first calculated in the geomagnetic and transformed into geographic coordinates.
- The standard deviation is smaller in the mission orbit because the magnetic tube is wider at higher altitudes.

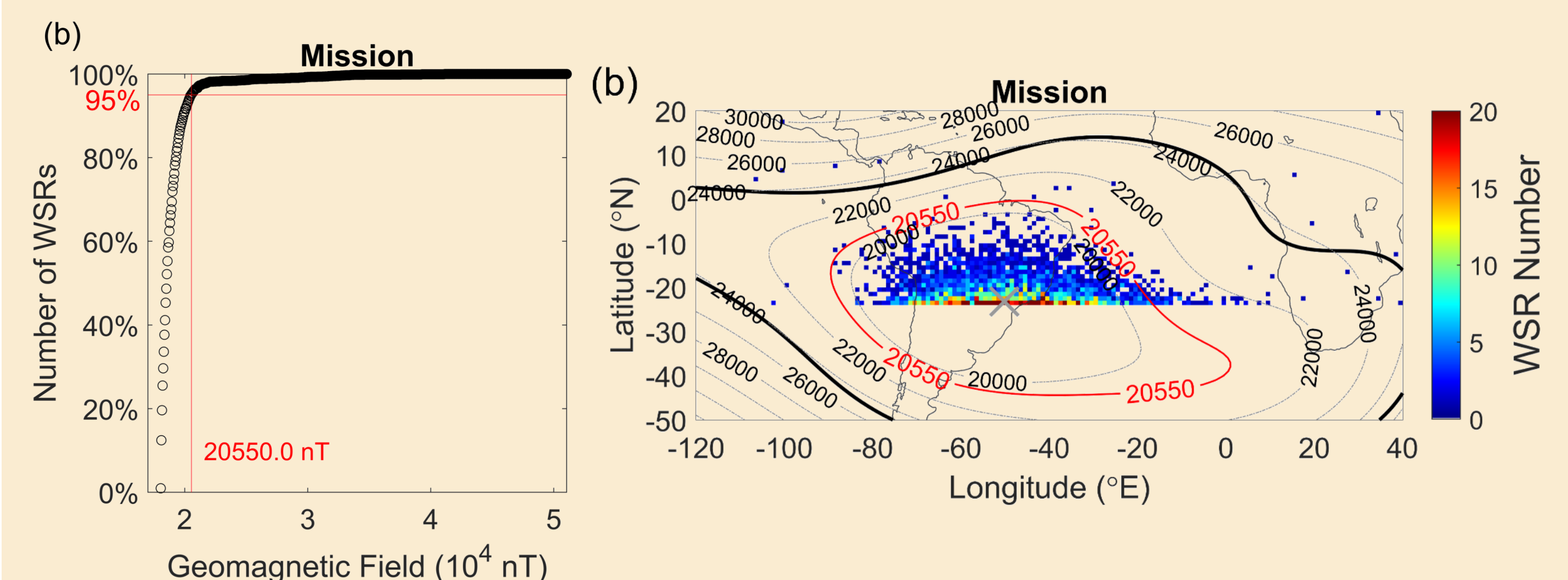
## RESULT 2: GEOMAGNETIC FIELD



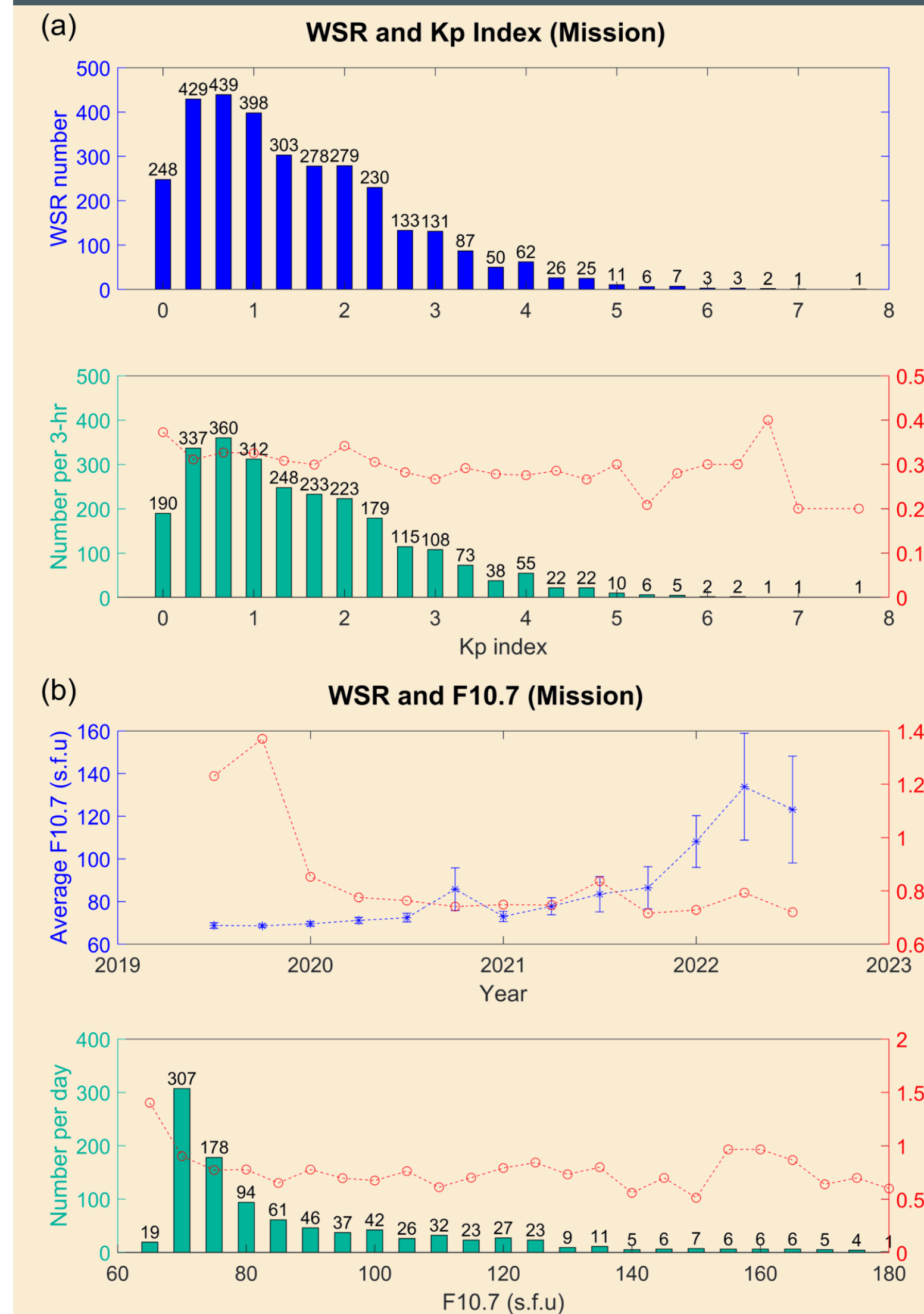
- The 95% of WSRs occurred in the area where the magnetic strength is less than 21,200 and 20,550 nT in the parking and mission orbits, respectively.
- New reference boundaries of SAA as well as a possible warning area of occurring SEEs on these COTS components at 720 km and 550 km altitudes.
- Jones et al. (2017) reported the center of SAA was located at (23°S, 47°W) in 2011, and the weighting center of WSRs is (23.2°S, 50.2°W) in 2020. The longitudinal difference is about 2° which agrees with their result the SAA moves westward 0.2° each year.

Orbit	WSR	Percentage
Parking (720km)	East	241 (5.56%)
	West	101 (2.33%)
Mission (550km)	East	163 (5.17%)
	West	56 (1.78%)

- Both altitudes show similar results that more than 3% of events occur outside the eastern border than the west. This could be due to the IGRF might not describe the small-scale structure.



## RESULT 3: SPACE WEATHER



- To cover more space weather conditions and avoid differences in orbital altitudes, this analysis only involves WSRs in the mission orbit.
- The incidence rate appears stable under active/high geomagnetic conditions/solar activity with fewer WSRs occurring.
- The altitude of the Earth's upper atmosphere would expand to higher altitudes during active geomagnetic conditions and high solar activities (Lühr and Liu, 2006; Wang et al., 2022; Fang et al., 2022), resulting in lower flux in the SAA region.
- The WSR incidence rate and the space weather do not reveal obvious correlations, due to the lower altitudes or no severe space weather conditions.

## SUMMARY

- F7/C2 is the first LEO satellite constellation to investigate the SEEs in various altitudes.
- The WSR cumulative rate is greater while the F7/C2 orbiting at the high orbit.
- The spatial distribution analysis provides that the weighting centers of the parking orbit and the mission orbit are at (22.8°S, 49.0°W) and (23.2°S, 50.2°W), respectively.
- The 95% WSRs are located within the magnetic strength of 21,200 nT and 20,550 nT in the parking and mission orbits, suggesting the SAA and the SEE warning area of this kind of COTS components.
- Both Kp and F10.7 indices do not reveal clear relationships with the WSR incidence rate.

Kao, T.H., Lee, I.T., Fong, C.J., Liu, J.Y., Chang, M.S. (2023). Investigation of the Aberrant Record from Bus GPS Receiver Onboard FORMOSAT-7/COSMIC-2 Satellite Constellation in Low Earth Orbit, *Advances in Space Research*, under review.

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