National Aeronautics and Space Administration

Monitoring the Small Debris Environment with Ground-based Radar: An Assessment of Data from 2016-2023

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Outline

- **Introduction**
- **Radar System Overview**
- **Evolution of the Orbital Debris Environment**
- **Significant Debris-Generation Events**
  - Major Collisions
  - Prominent Explosions
  - NaK
  - 82° Cloud
- **Conclusion**

INTRODUCTION

Introduction

- NASA Orbital Debris Program Office (ODPO) uses ground-based radars to statistically sample the orbital debris (OD) environment in low Earth orbit (LEO)
- Measurements of OD with sizes from a few mm up to the limit of the public U.S. Space Surveillance Network (SSN) catalog at approx. 10 cm
- Data used to develop, verify, and validate models of the OD environment, in particular the NASA Orbital Debris Engineering Model (ORDEM)
- Consistent radar measurements are essential to capture the dynamic behavior of the OD environment and support regular and timely model updates

Data Assessments

- **Snapshot of millimeter- and centimeter-sized OD as of 2023**
- **Evolution of OD over 2016-2023**
- **Background, evolution, and status of major debris-generating events**
  - Collisions:
    - **Fengyun 1C (FY-1C) anti-satellite (ASAT) test**
    - **Accidental collision of Iridium 33 (I33) and Cosmos 2251 (C2251)**
    - **Cosmos 1408 (C1408) ASAT test**
  - Explosions:
    - **NOAA-16 spacecraft**
    - **Long March 6A (CZ-6A) upper stage**
  - Special populations:
    - **Sodium-potassium (NaK) droplets**
    - **Anomalous “82° cloud”**

RADAR SYSTEM OVERVIEW

HUSIR

- **Haystack Ultrawideband Satellite Imaging Radar (HUSIR)**
  - Originally named Haystack prior to upgrades completed in 2013
  - Located in Westford, Massachusetts
  - Data collected since 1990 through partnership with the U.S. Department of Defense and the Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL)
  - Primary radar used by the ODPO, provides coverage of debris down to a completeness limit of approximately 5 mm at altitudes less than 1000 km and 2-3 cm throughout LEO

Credit: Bethany P. Dominick

Goldstone

- **Goldstone Orbital Debris Radar (Goldstone)**
  - Part of the Deep Space Communications Complex
  - Located near Barstow, California
  - Operated by the NASA Jet Propulsion Laboratory (JPL), data provided since 1993
  - Complements HUSIR coverage with sensitivity down to a completeness size of approximately 2 mm at altitudes less than 1000 km

Credit: NASA/JPL-Caltech

HUSIR and Goldstone Comparison

- **Operate in beampark (staring) mode at fixed elevation and azimuth angles**
  - Statistically sample the population of OD that pass through the radar beam
  - Smaller limiting size than possible for sensors operating in a typical tracking mode
- **Operate at X-band**
- **Transmit right-hand circularly polarized waveforms, receiving both right- and left-hand circularly polarized returns (orthogonal polarization, OP, and principal polarization, PP)**

HUSIR

- **Monostatic**
- **Pulsed continuous wave waveform**
- **Frequency modified from 10.0 GHz to 10.1 GHz starting in 2020 to mitigate RFI**
- **3 pointings**
  - 75° elevation, due east (75E)
    - **2/3 of data collected with 75E**
  - 20° elevation, due south (20S)
  - 10° elevation, due south (10S)

Goldstone

- **Bistatic**
- **Pulsed linear frequency modulated "chirp" waveform**
- **Transmitter (DSS-14) points at 75E**
- **Receiver pointing changes after 2017 due to decommissioning of DSS-15 receiver**
  - Through 2017: single pointing for full LEO coverage
  - 2018: targeted 800 km range pointing
  - 2020-2023: 4 pointings to cover 700-1000 km altitude

HUSIR and Goldstone Overview

HUSIR and Goldstone nominal operating parameters

Operating Parameter	HUSIR	Goldstone
Peak Transmit Power (kW)	250	440
Transmit Frequency (GHz)	10.1	8.56
Wavelength (cm)	3.0	3.5
Antenna Diameter (m)	36.6	70 (Transmit) 34 (Receive)
Half-power Beamwidth (deg)	0.058	0.03 (Transmit) 0.06 (Receive)
Sensitivity* (dB)	59.2	67.7
Intermediate Frequency Bandwidth (MHz)	1.25	1.5
Pulse (chirp) Duration (ms)	1.6384	2.9
Pulse (chirp) Bandwidth (kHz)	N/A	300
Pulse Repetition Frequency (Hz)	60	55.6

*Sensitivity = single pulse signal-to-noise ratio (SNR) for an object with a radar cross section (RCS) of one square meter at 1000 km slant range

HUSIR and Goldstone altitude coverage

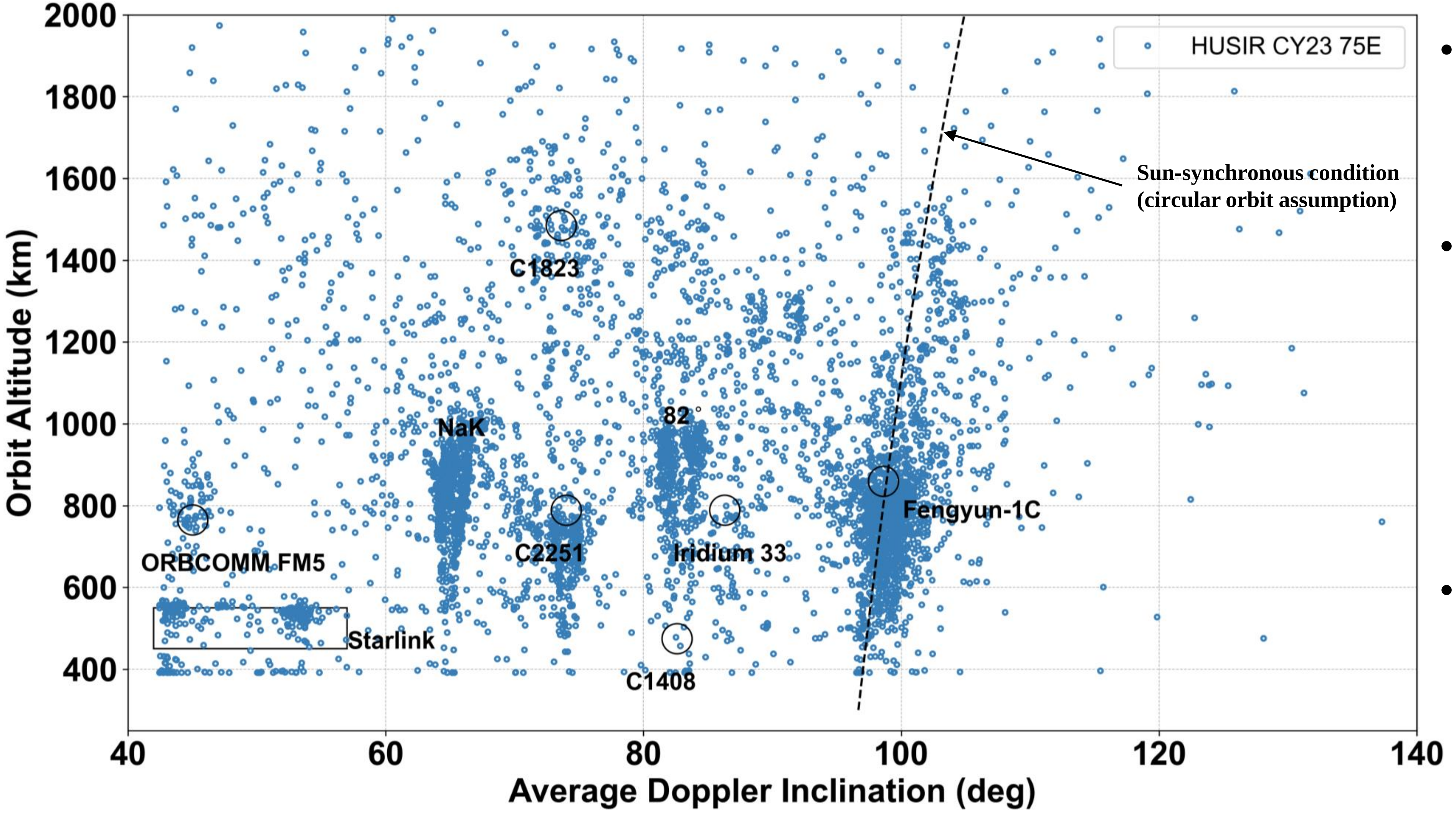
Sensor	Min Altitude (km)	Max Altitude (km)
Haystack/HUSIR 75E	392	2166
Goldstone (legacy pointing, before 2018)	374	3373
Goldstone 800 km pointing (2018 only)	696.6	857.2
Goldstone Pointing A (2020-2023)	660.3	806.4
Goldstone Pointing B (2020-2023)	709.7	881.0
Goldstone Pointing C (2020-2023)	770.4	976.1
Goldstone Pointing D (2020-2023)	847.5	1102.8

Radar Measurements

- **Fundamental measurements are range, range-rate (Doppler velocity), and received power from which RCS can be calculated**
- **Assume circular orbits to convert range and range-rate to orbit altitude and Doppler inclination**
  - Due to short arc of object's path through the beam
- **Use NASA Size Estimation Model (SEM) to convert RCS to size**
  - Based on laboratory measurements of representative debris objects over many orientations and a range of frequencies

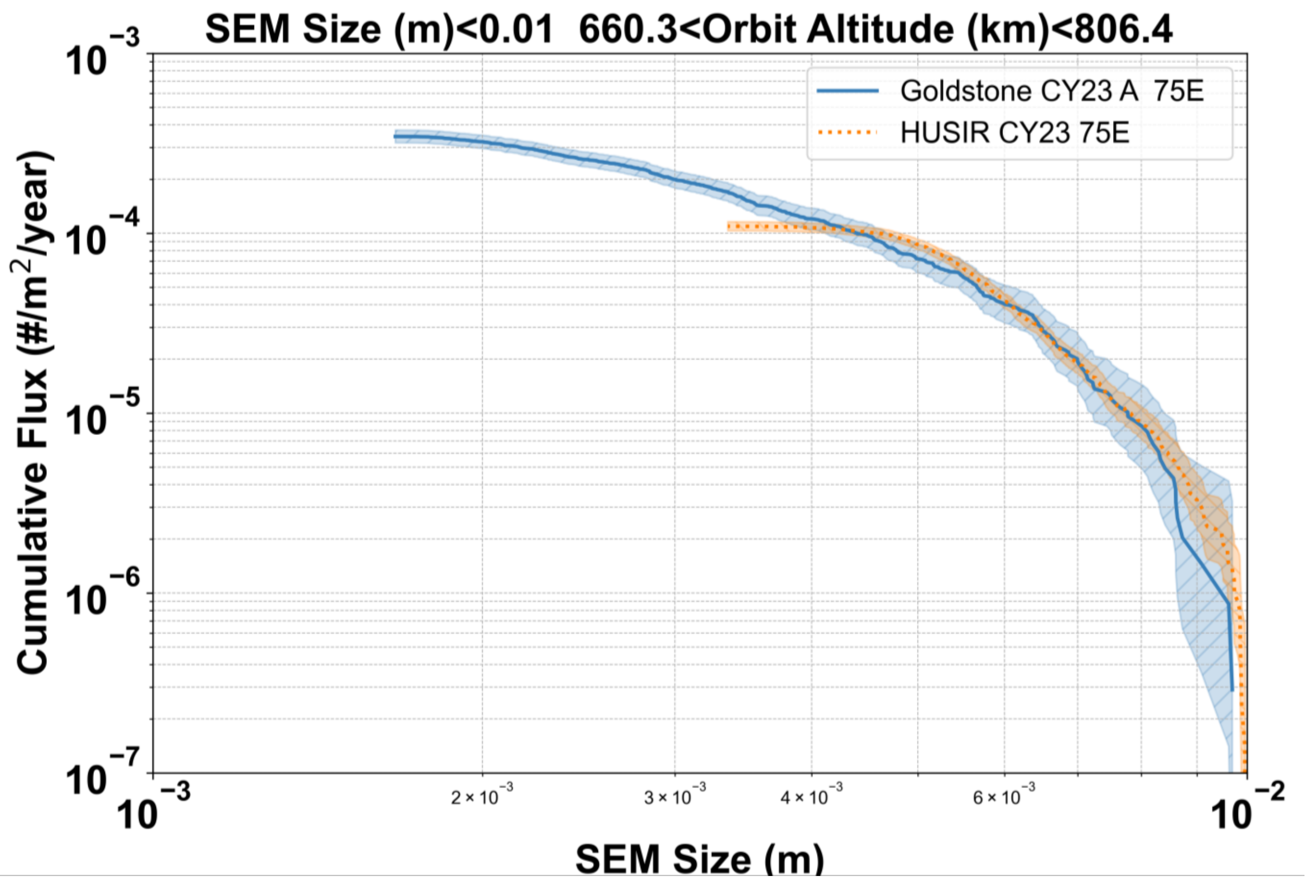
EVOLUTION OF THE OD ENVIRONMENT

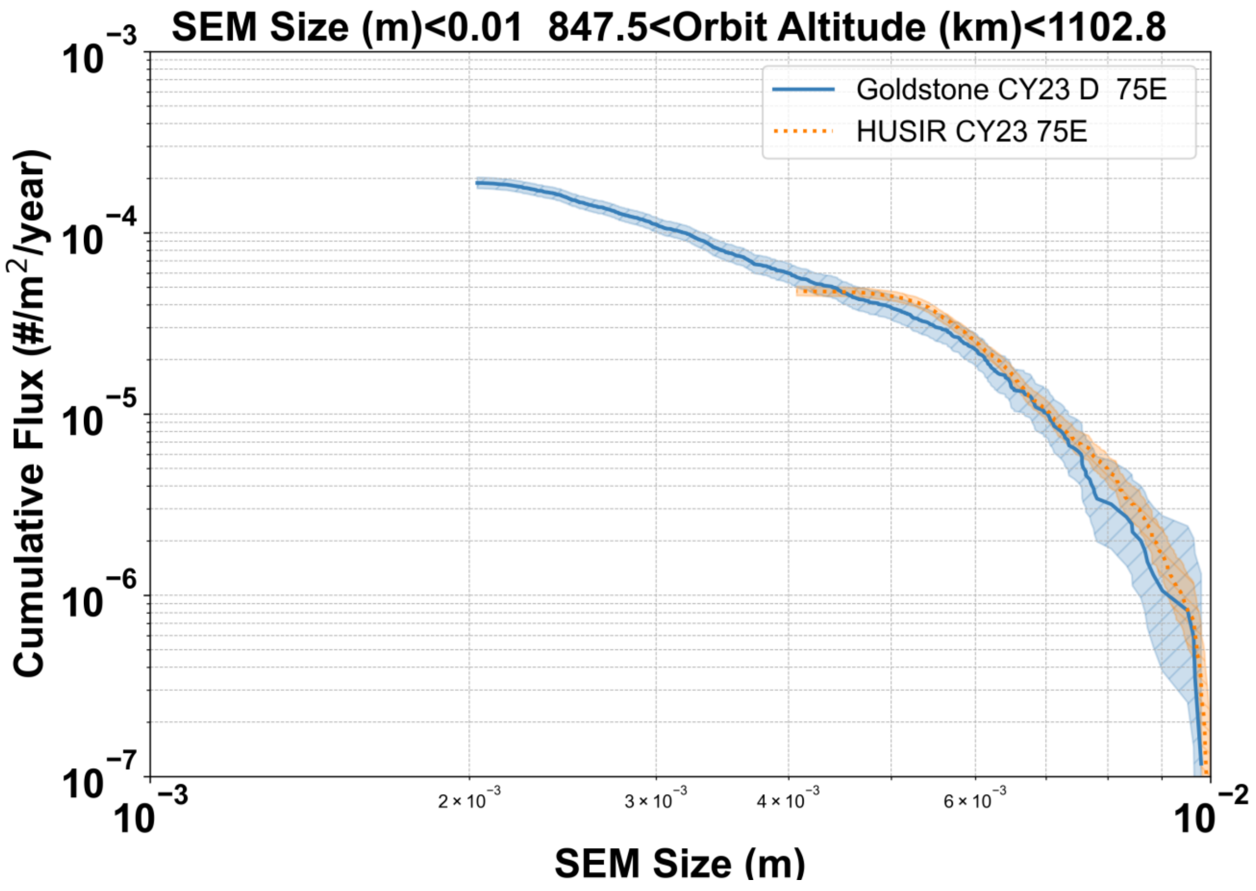
Orbit Altitude vs. Doppler Inclination, 2023



- **Highly concentrated regions of detections correspond to different orbital families**
- **Notable, historic fragmentation events indicated by black circles centered at altitude and inclination of the parent body at the time of the event**
- **Other special populations identified: Starlink, NaK, 82° cloud**

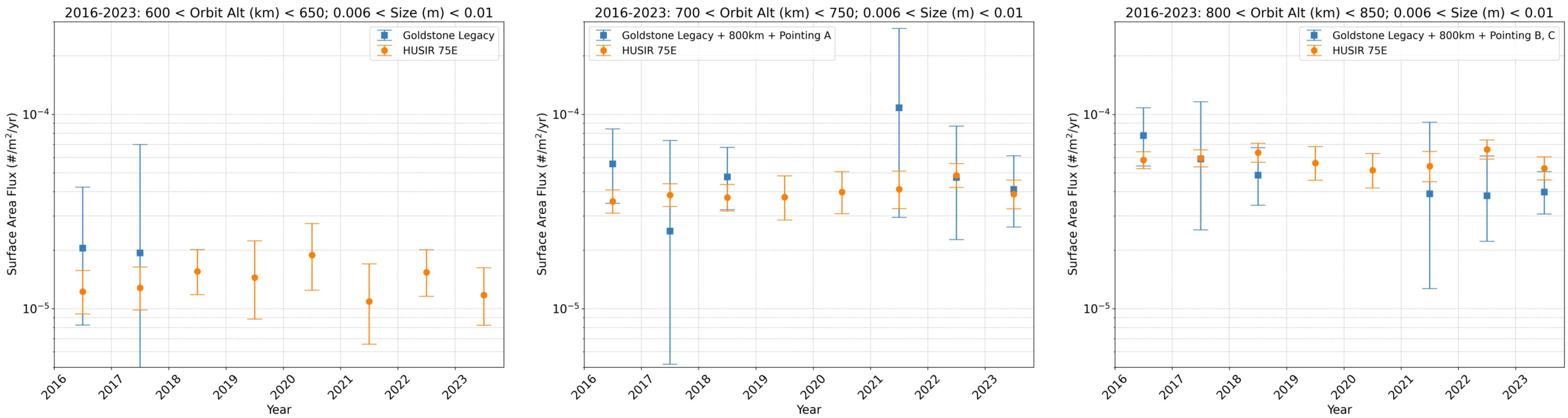
Cumulative Flux vs. Size, HUSIR and Goldstone, 2023





- **Goldstone complements and extends HUSIR coverage to smaller sizes**

Surface Area Flux vs. Time, HUSIR and Goldstone



- **Year-to-year variability as debris decays into and out of altitude bands due to atmospheric drag**
- **Generally good agreement between sensors within respective uncertainties**
  - Excellent agreement for 700-750 km in 2022 and 2023 and for 800-850 km in 2017

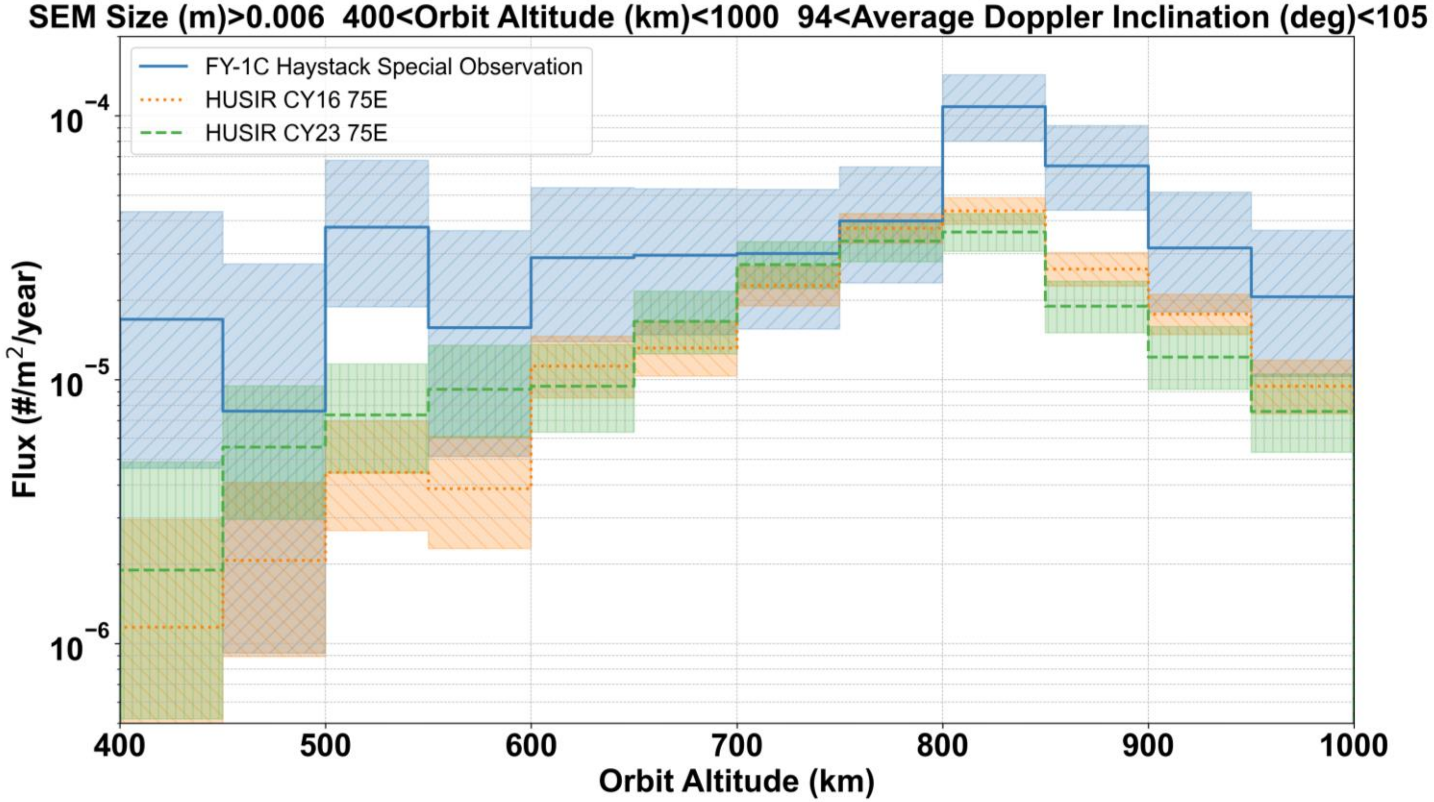
SIGNIFICANT DEBRIS-GENERATING EVENTS

Fengyun 1C

					Breakup Debris		Parent Body			
Satellite Name	International Designator	SSN Number	Launch Date	Breakup Date	Cataloged to Date*	On Orbit*	Apogee (km)	Perigee (km)	Inclination (deg)	Breakup Type
FY-1C	1999-025A	25730	10-May-99	11-Jan-07	3532	2557	865	845	98.6	Collision

*Per SSN catalog as of 3 January 2025

- **Largest breakup in the history of spaceflight**
  - 72% of cataloged fragments remain on orbit as of 3 Jan 2025
- **Special data collects using Haystack soon after event**
- **2016 and 2023 flux similar to levels from special observations at 750-800 km altitude, slightly lower at 700-750 km**
  - Breakup still a major contributor to OD environment at these altitudes



Iridium 33 / Cosmos 2251 Accidental Collision

					Breakup Debris		Parent Body			
Satellite Name	International Designator	SSN Number	Launch Date	Breakup Date	Cataloged to Date*	On Orbit*	Apogee (km)	Perigee (km)	Inclination (deg)	Breakup Type
Cosmos 2251	1993-036A	22675	16-Jun-93	10-Feb-09	1715	811	800	775	74.0	Collision
Iridium 33	1997-051C	24946	14-Sep-97	10-Feb-09	657	165	780	775	86.4	Collision

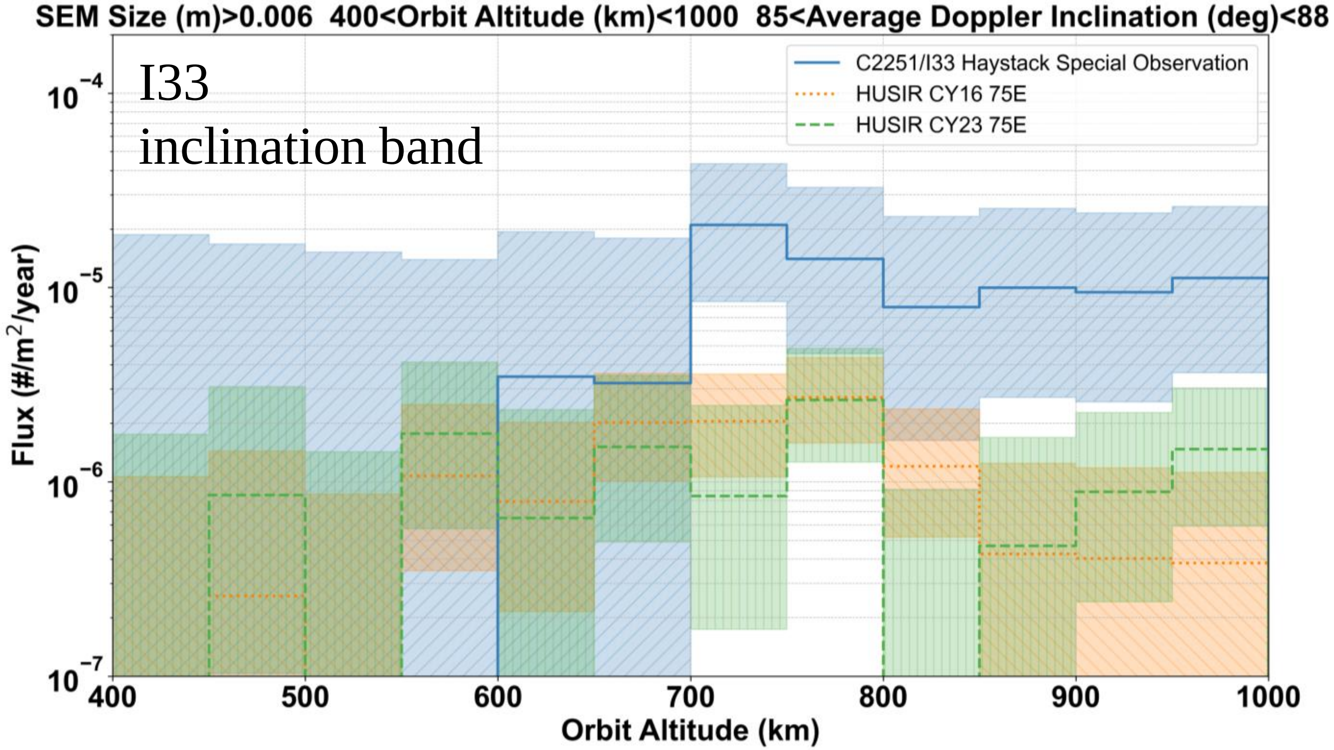
*Per SSN catalog as of 3 January 2025

- **First known accidental collision of an inoperable spacecraft with a functional spacecraft**
- **Special data collects using Haystack soon after event**
- **C2251 was an older satellite while I33 was relatively modern, constructed extensively of lightweight composite materials**
  - Differences seen in evolution of the breakup clouds

Iridium 33 / Cosmos 2251

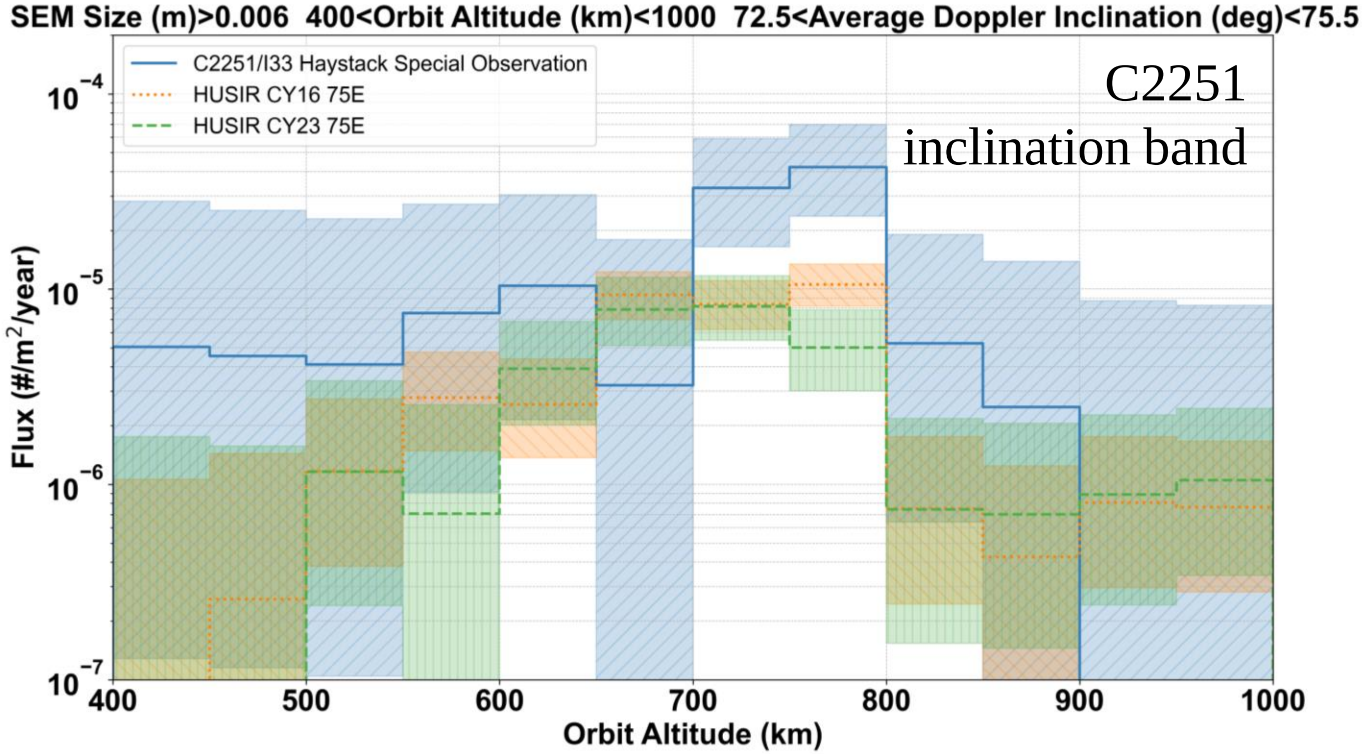
I33

- By 2023, broad distribution of flux with no clear indication of a significant contribution from the original breakup cloud



C2251

- 2016 and 2023 fluxes at 650-700 km altitude are higher than the special observations by a factor of 3
  - Likely due to debris decaying from higher altitudes

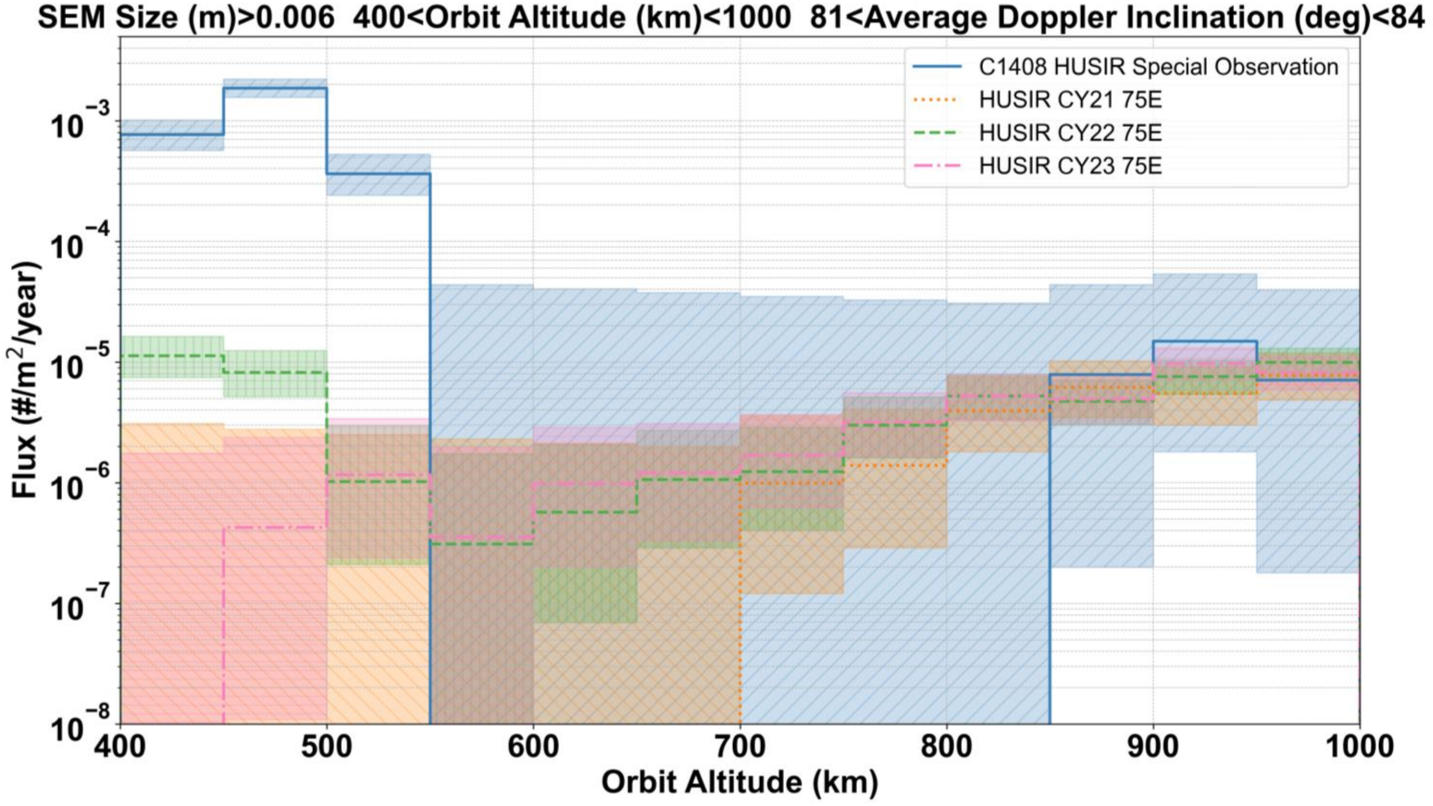


Cosmos 1408

					Breakup Debris		Parent Body			
Satellite Name	International Designator	SSN Number	Launch Date	Breakup Date	Cataloged to Date*	On Orbit*	Apogee (km)	Perigee (km)	Inclination (deg)	Breakup Type
Cosmos 1408	1982-092A	13552	16-Sep-82	15-Nov-21	1807	14	490	465	82.6	Collision

*Per SSN catalog as of 3 January 2025

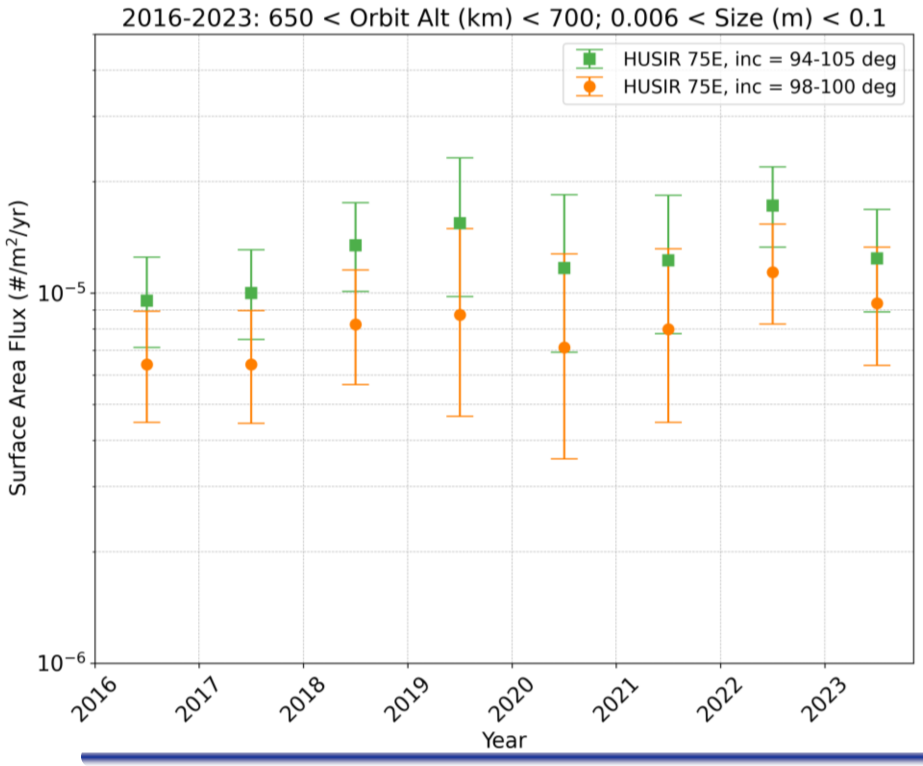
- **Special HUSIR observations soon after breakup led to a rapid update to ORDEM**
  - ORDEM 3.2 released only a few months after the event
- **Significant effect on fluxes below 600 km altitude**
- **Fluxes below 500 km near pre-breakup levels by 2023**

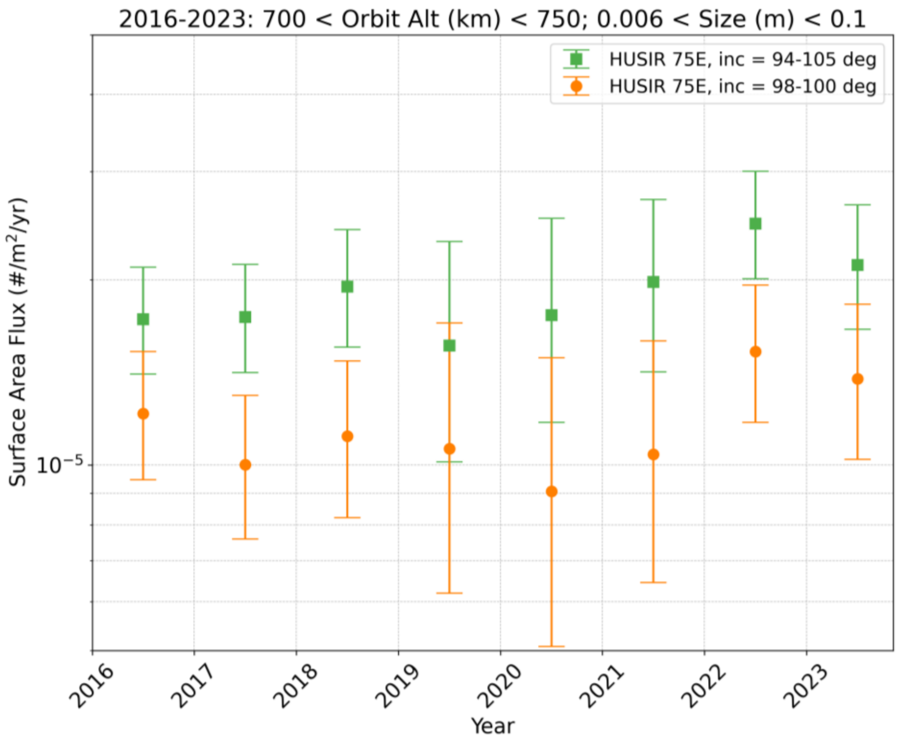


NOAA 16 and CZ-6A

					Breakup Debris		Parent Body			
Satellite Name	International Designator	SSN Number	Launch Date	Breakup Date	Cataloged to Date*	On Orbit*	Apogee (km)	Perigee (km)	Inclination (deg)	Breakup Type
NOAA 16	2000-055A	26536	21-Sep-00	25-Nov-15	459	413	858	842	98.9	Explosion
CZ-6A R/B	2022-151B	54236	11-Nov-22	12-Nov-22	794	677	847	813	98.8	Explosion

*Per SSN catalog as of 3 January 2025

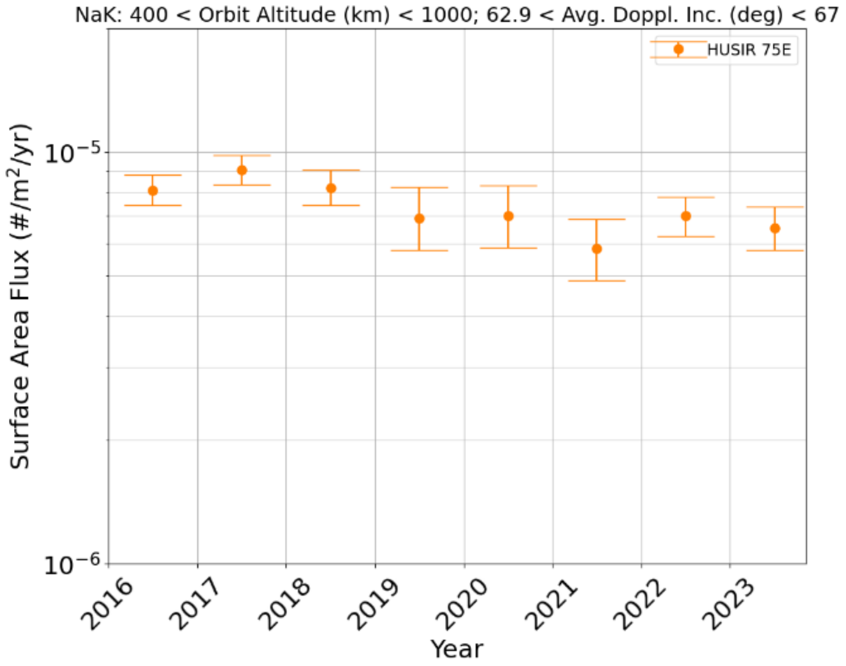


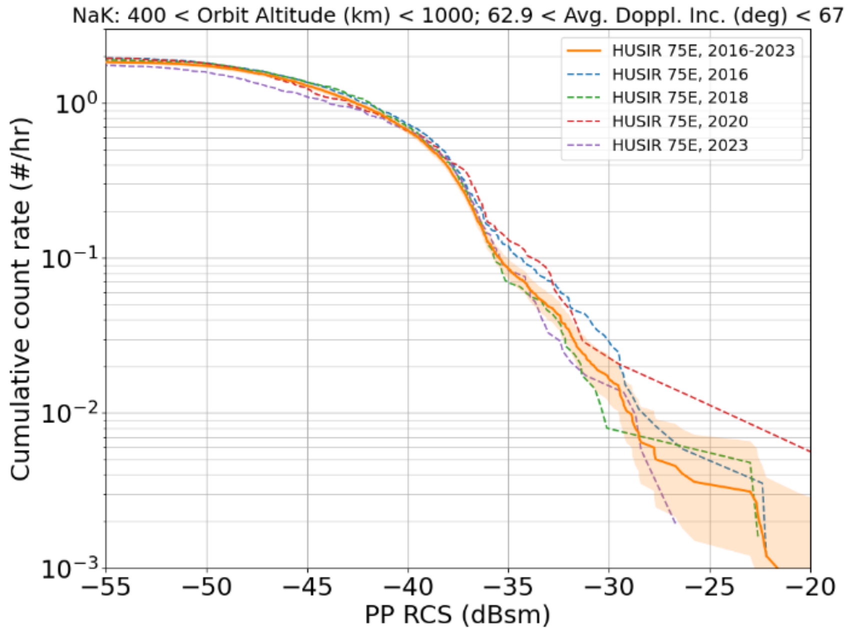


- **Similar orbits of NOAA-16, CZ-6A, and FY-1C at their breakup times introduce challenges to analysis**
  - Narrower inclination band for NOAA-16/CZ-6A (98°-100°) than FY-1C (94°-105°)
- **Flux in NOAA-16/CZ-6A inclination band is at least half of the flux from the FY-1C inclination band**
  - More significant in later years for 650-700 km

NaK

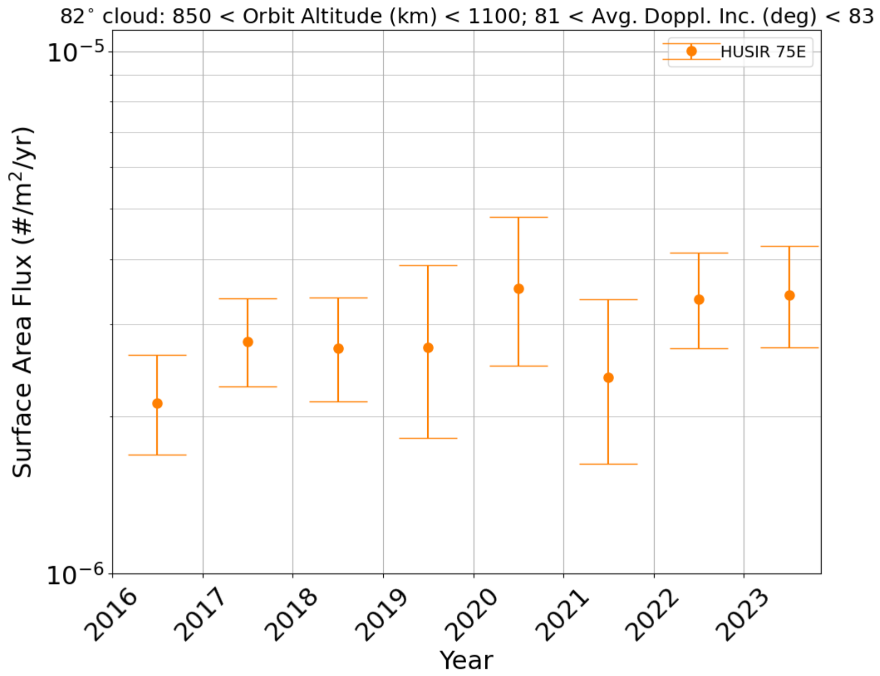
- **First identified in Goldstone and Haystack radar data**
  - Population of electrically conducting spheres from a few millimeters to a few centimeters in size with near-circular orbits around 65° inclination, 850-1000 km altitude
  - Associated with NaK liquid metal coolant used in the Soviet Radar Ocean Reconnaissance Satellite (RORSAT) reactors
- **Analysis indicates relatively steady state population**
  - Possible ongoing production at higher altitudes decaying to lower altitudes

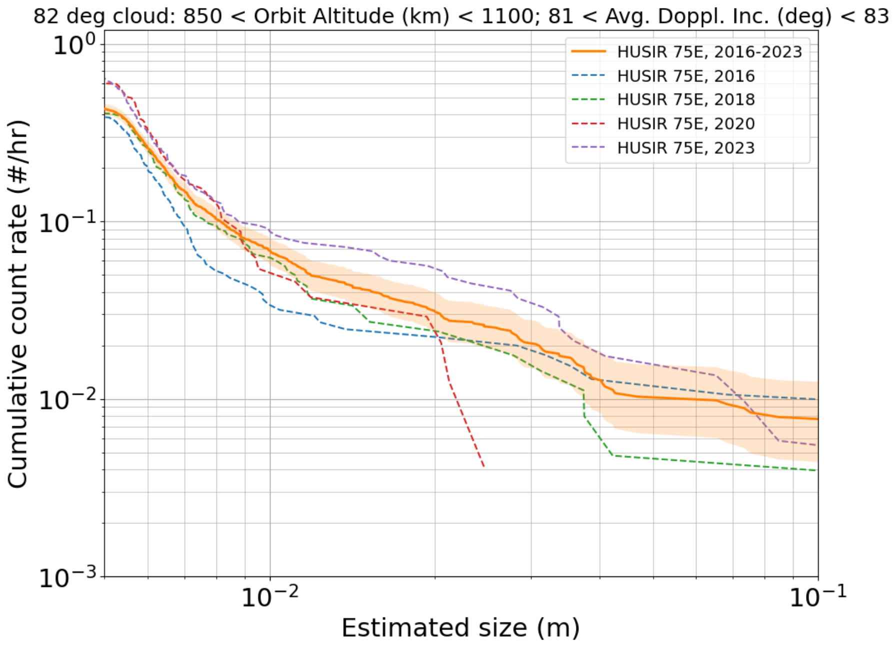




82° Cloud

- **Persistent anomalous debris cloud identified in HUSIR data**
  - Near 82° inclination, below 1200 km in altitude
  - No identified parent body or source mechanism, but observations suggest production by one or more low debris mass, low velocity, non-energetic events
- **Evidence of slight increase in sub-centimeter objects over time**
  - Possible ongoing low-velocity production mechanism





CONCLUSION

Findings and Conclusions

- **Findings from temporal analysis of major debris-producing events:**
  - The FY-1C breakup continues to contribute to the flux of debris less than 1 cm, particularly from 700-800 km altitude
  - C2251 fragments still contribute non-negligibly around 700 km altitude
  - I33 fragments no longer have a significant influence on the fluxes within the I33 inclination band
  - The C1408 breakup cloud has mostly disappeared from the radar data as of 2023 observations
  - Evidence of an increasing influence from decaying NOAA-16 breakup fragments over 650-750 km altitude
  - NaK population appears to be relatively stable
  - 82° cloud has increased within a factor of 2 from 2016 to 2023, suggesting an ongoing production mechanism
- **Continued regular observations from HUSIR and Goldstone will offer insight on the behavior of these and other events and provide necessary data to update OD models**

Thank you for your time and attention!

Questions?