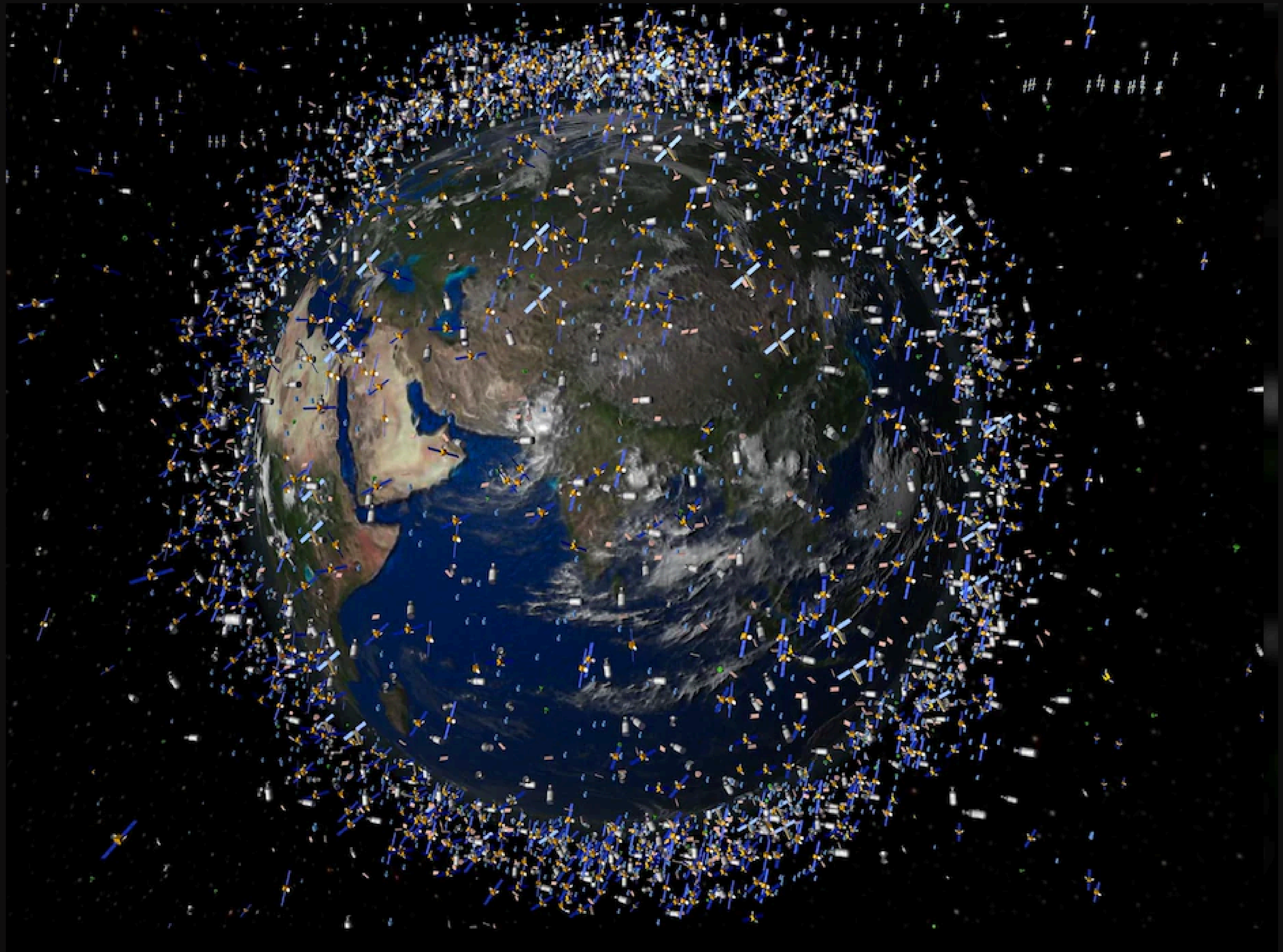
INTELLIGENT DETECTION AND TRACKING OF SPACE DEBRIS IN LOW EARTH ORBIT



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PROBLEM STATEMENT

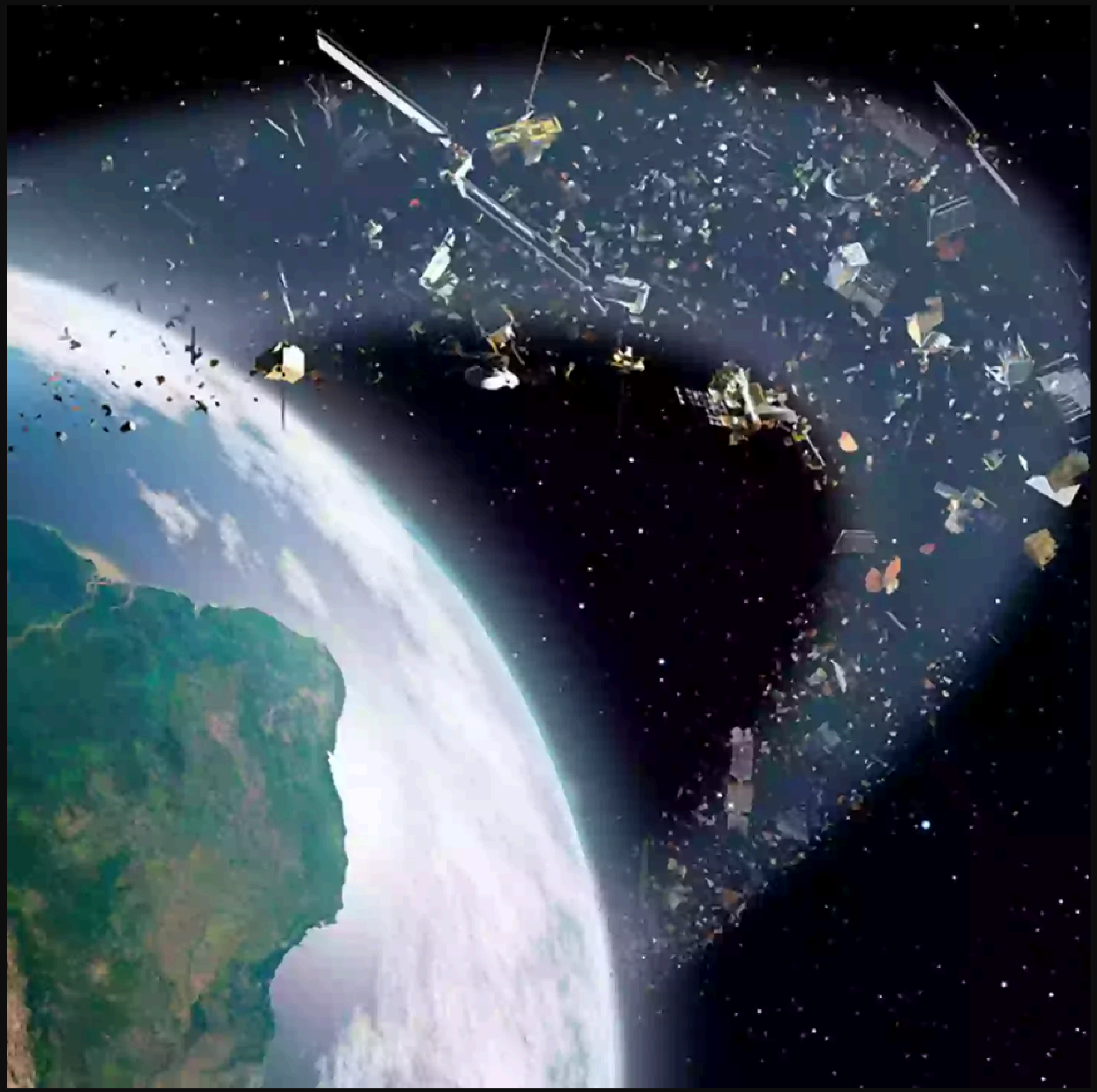
- Over 100 million pieces of debris in LEO
- Risks include:
  - Satellite collisions
  - Kessler Syndrome
  - Damage to space missions

PROJECT OBJECTIVE

To Design an autonomous/mechanized robot to identify small-to-medium sized space debris.

WHY

🛡️ **Prevent collisions** — stop debris from multiplying.
🛰️ **Protect satellites** — keep orbits safe and usable.
♻️ **Enable cleanup** — you can’t remove what you can’t see.
🌐 **Coordinate globally** — smarter space traffic control.
🌍 **Secure the future** — preserve space for generations to come.



SYSTEM OUTPUT

Detection is the First Step to Any Space Debris Solution
You can’t remove what you can’t detect.
All other efforts (removal, avoidance, collision prediction) depend on accurate tracking.

- Removal missions (e.g., Astroscale, ClearSpace) require real-time location data.
- Collision avoidance relies on trajectory prediction and tracking accuracy.
- Insurance companies require debris risk maps to price satellite coverage.

TECHNICAL OUTPUT

Detection pipeline:
- demonstration of accurate object localization and classification

Trajectory and conjunction prediction:
- validated on real or synthetic data

Risk maps:
- visualise high-collision zones and predictive future hotspots

Performance reporting:
- detection precision/recall, position errors, false alarms

SCIENCE

ORBITAL MECHANICS

modeling debris motion under gravity, drag, solar perturbations

ELECTROMAGNETICS

sensing principles: radar reflectivity, LiDAR range resolution, optical imaging sensitivity

KINETICS

impact analysis: energy and momentum of collisions from small objects at ~28,000 km/h

MACHINE LEARNING

object classification and sensor fusion techniques to combine multi-modal observations

CONDITION MODELING

statistical debris population (size, density distribution) per ESA/Space Data Association models

PAST ATTEMPTS

1. **ESA – ClearSpace-1**
   - Status: Not launched yet (planned for 2026).
   - Success: still in development phase.

2. **NASA**
   - Status: Focused more on debris monitoring and passive mitigation, rather than active removal.
   - Success?: Very **successful in tracking** and modeling debris.

3. **JAXA** – Kounotori Integrated Tether Experiment (KITE)
   - Status: **Failed**

4. **Astroscale – ELSA-d**
   - Status: **Partially successful**
   - Successfully demonstrated magnetic capture of a small satellite in orbit (2021).

LITERATURE SURVEY

1. **Deep learning-based space debris detection for space situational awareness: A feasibility study applied to the radar processing**
Federica Massimi, Pasquale Ferrara, Roberto Petrucci, Francesco Benedetto

2. **NASA Seeks Solutions to Detect, Track, Clean Up Small Space Debris -** link

3. **ESA - Detecting, Tracking and Imaging Space Debris**
D. Mehrholz, L. Leushacke

4. **Space Surveillance payload camera breadboard: Star tracking and debris detection algorithms -** J Filho, P M R Duarte, P Gordo

5. **Detecting Space Debris using Deep Learning Algorithms: A Survey**
Publisher: IEEE

WHAT CAN BE IMPROVED?

1. **Develop a Domain-Tailored AI Model**

Generic object detection models (YOLO, etc.) aren't optimized for space debris conditions.

- Designing a custom CNN or Transformer model trained on space-domain-specific features (e.g., orbital motion blur, radiometric noise).
- Using physics-aware AI, where you integrate orbital dynamics into your model.

2. **End-to-End Pipeline**

R**aw sensor data → Detection → Tracking → Threat classification**

- Preprocessing for noise/artifact reduction
- Detection using a CNN or YOLOv8
- Object classification (e.g., known satellite vs. debris)
- Estimating orbital trajectory
- Risk score calculation (collision likelihood)

USING THE ADVANTAGES

1. **Real-World Data Sources**
   - NASA Space-Track / CelesTrak – Orbital data (TLE) for debris tracking
   - ESA MASTER / NASA ORDEM – Models for debris environment & flux estimation
   - DISCOS Database (ESA) – Catalog of known space objects

2. **Simulation & Analysis Tools**
   - AGI STK / GMAT – Orbit & sensor simulation platforms
   - DRAGONS (NASA) – Debris risk assessment tool

3. **AI & Synthetic Data Tools**
   - YOLOv8 / Detectron2 – SOTA object detection frameworks
   - Blender / NVIDIA Replicator – Generate synthetic training data for ML models

ENGINEERING PRINCIPLES

SENSOR DESIGN

Designing sensor: radar vs LiDAR vs optical, based on detection thresholds, power, weight

ROBOT ARCHITECTURE

Creating a robot: possibly CubeSat-based or high-fidelity simulation environment

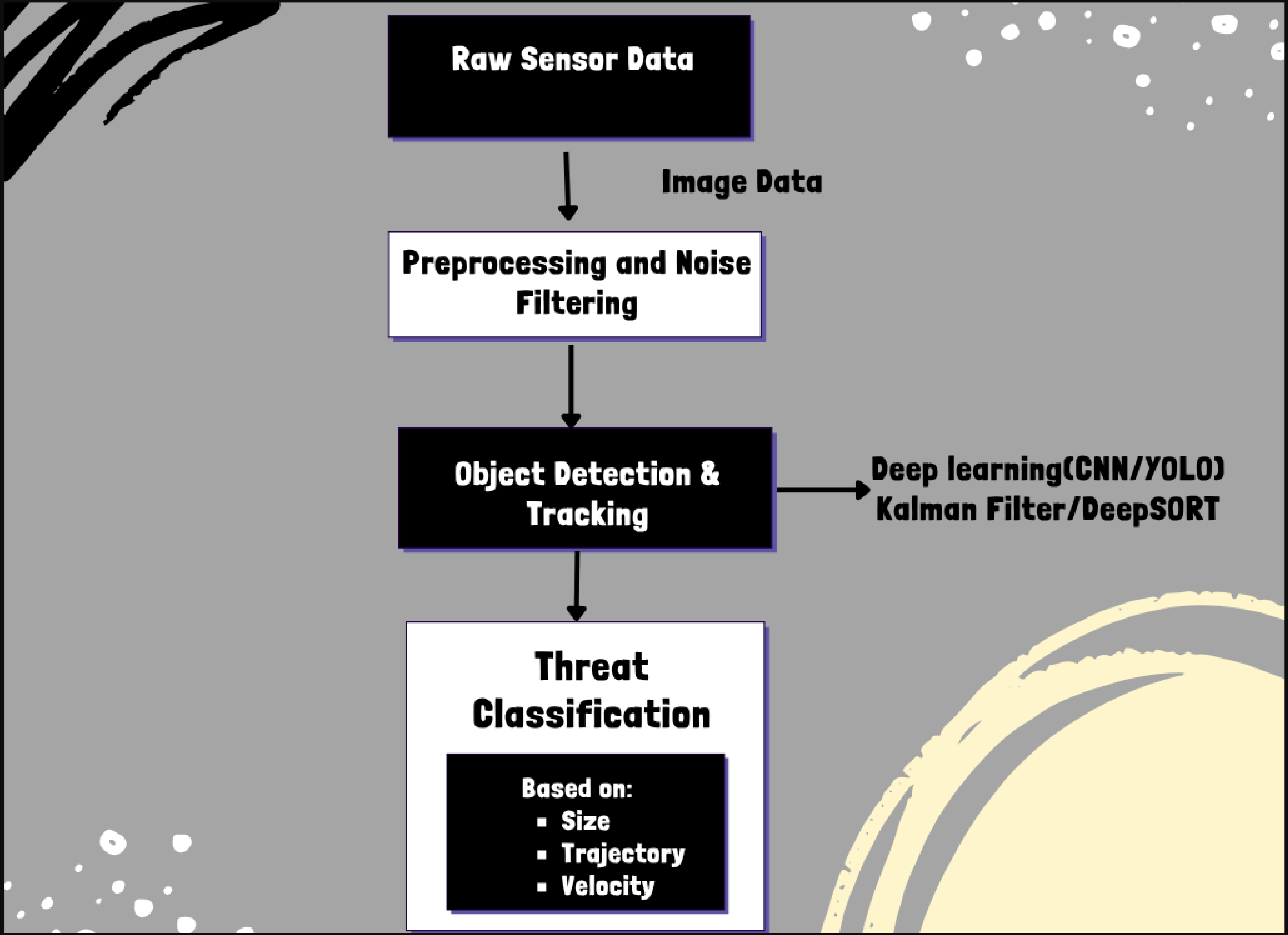
AI PIPELINE

AI Engineering: dataset generation, labeling, augmentation, real-time model execution

PREDICTION ENGINE

Implementing a prediction engine using orbital filters and collision probability metrics

PROJECT WORKFLOW



OPERATING MECHANISM

1. **Raw Sensor Data Acquisition**
    - Space-based sensors (if simulated)
    - Public datasets like Space-Track, ESA DRAMA, NORAD Two-Line Elements (TLE)
2. **Data Preprocessing**
   - Convert raw sensor feeds into usable formats
3. **Space Debris Detection**
    - YOLOv5/YOLOv8 for fast object detection
    - RetinaNet or EfficientDet for better accuracy
4. **Threat Classification**
   - Based on:
      - Size (from bounding box)
      - Velocity and direction (from tracker)
      - Proximity to satellite paths (optional)

DESIGN & COMPONENTS

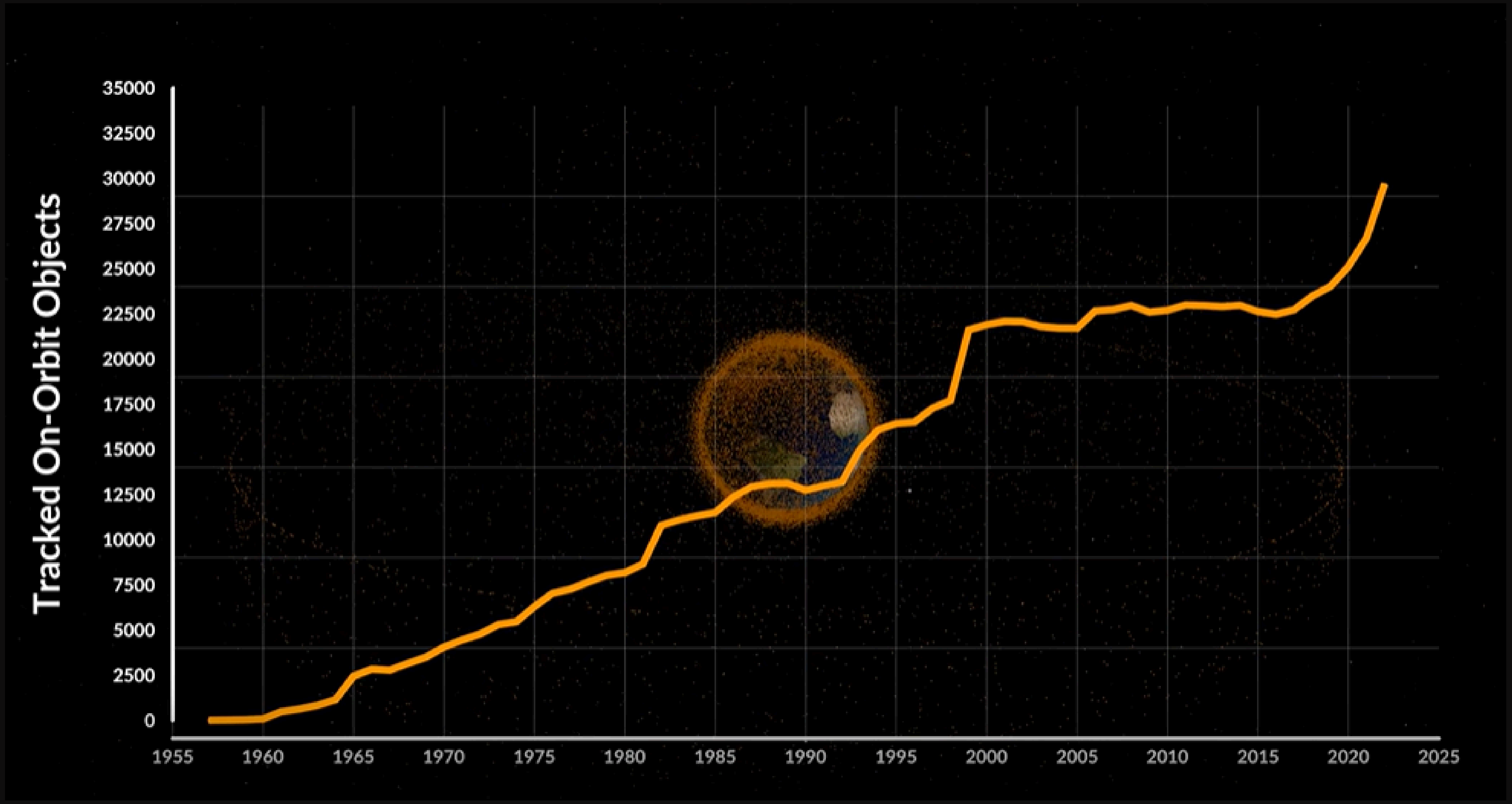
Module	Design/Spec
Chassis	CubeSat Form (6U) or $1m^3$
Propulsion	Ion Thrusters / Cold Gas
Sensors	Lidar + Optical Cameras
AI Unit	Prediction Engine

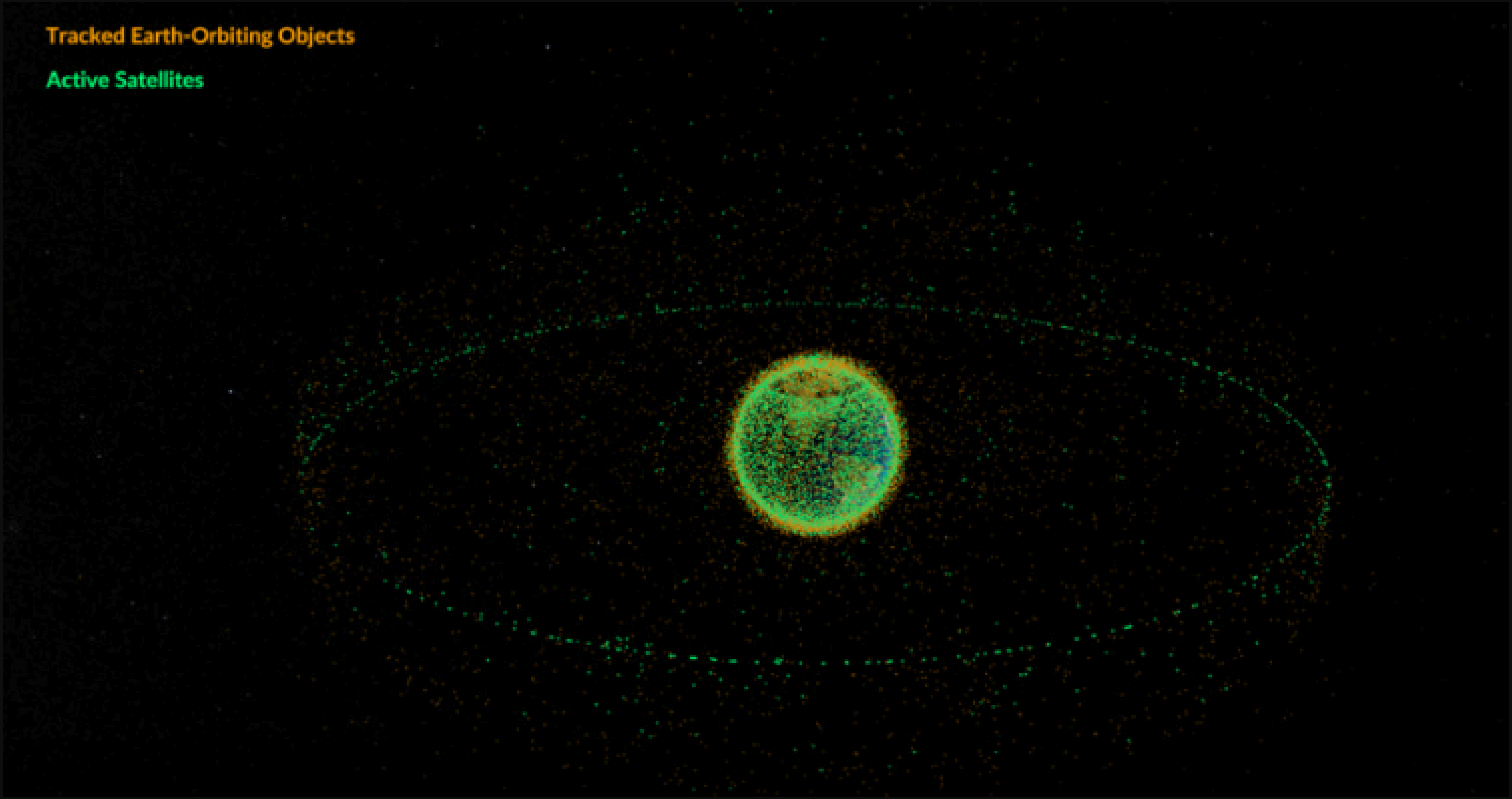
HOW FAR HAVE WE PROGRESSED?

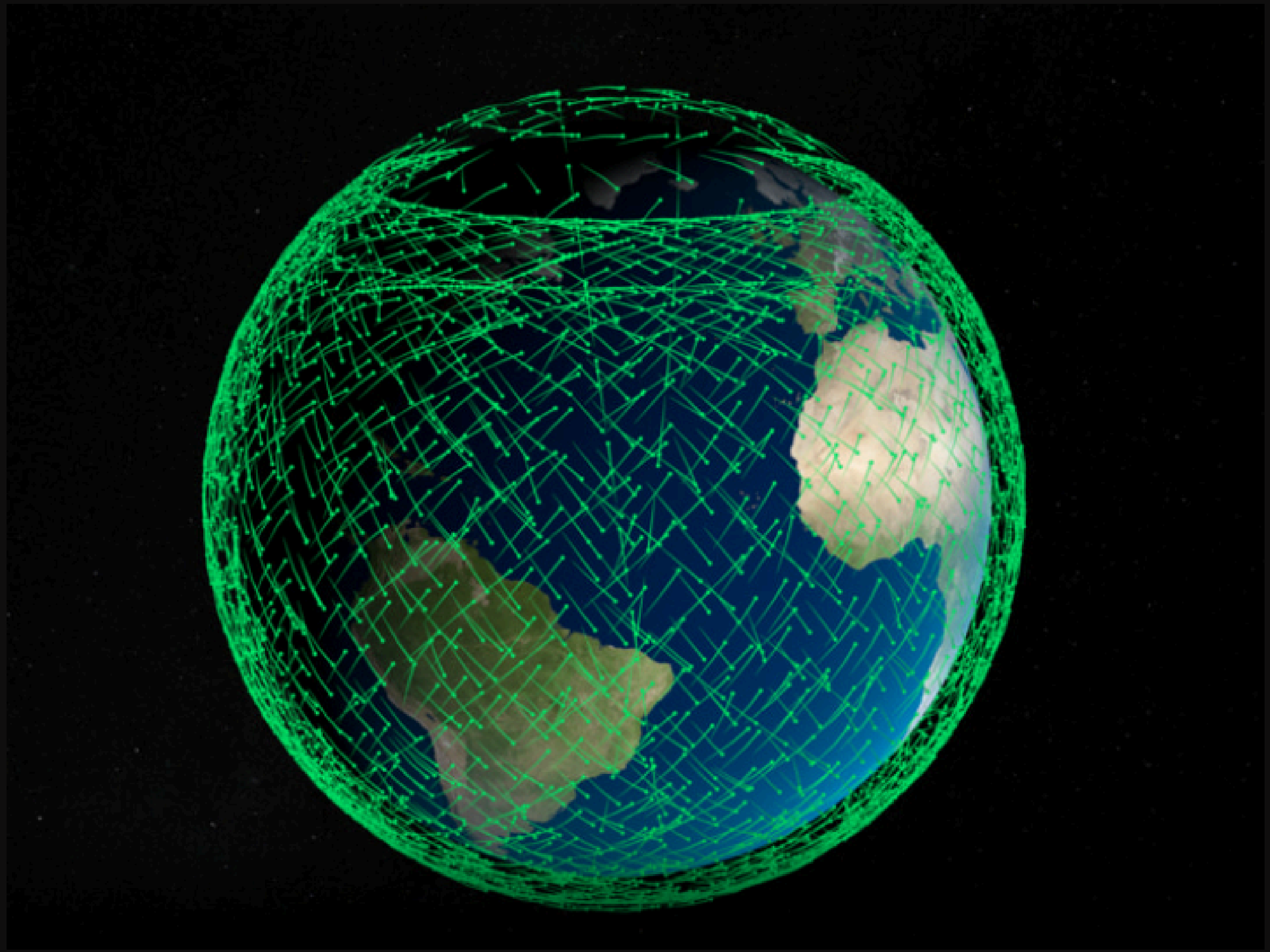
Exploring the Publicly available NASA's Dataset

Name: Space-Track TLE (Space-Track Two-Line Elements) **Type**: Ephemeris

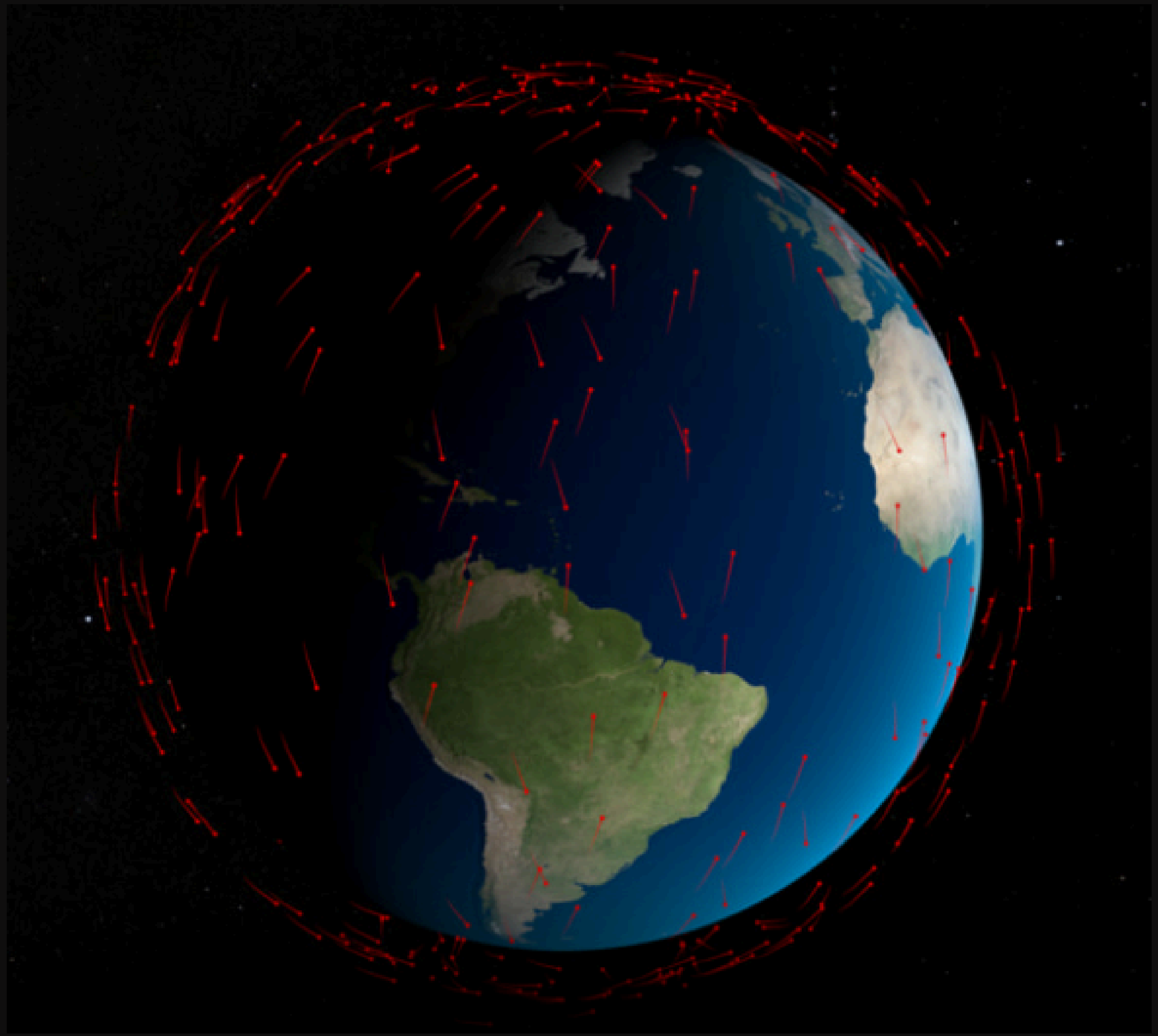
Collected by: NORAD Satellite ephemerides. Publicly available at http://Space-Track.org




Tracked Earth-Orbiting Objects
Active Satellites



Active Starlink satellites as of February 2024 (approximately 5,410 satellites).



A view of leftover debris from the 2009 collision between Cosmos 2251 and Iridium 33, still in orbit as of February 2024 (~500 trackable objects).

WORKING WITH DETECTRON2

Detectron2 is a popular open-source object detection and segmentation library developed by Facebook AI Research (FAIR). It is written in Python and built on PyTorch, making it flexible, fast, and modular for computer vision tasks.

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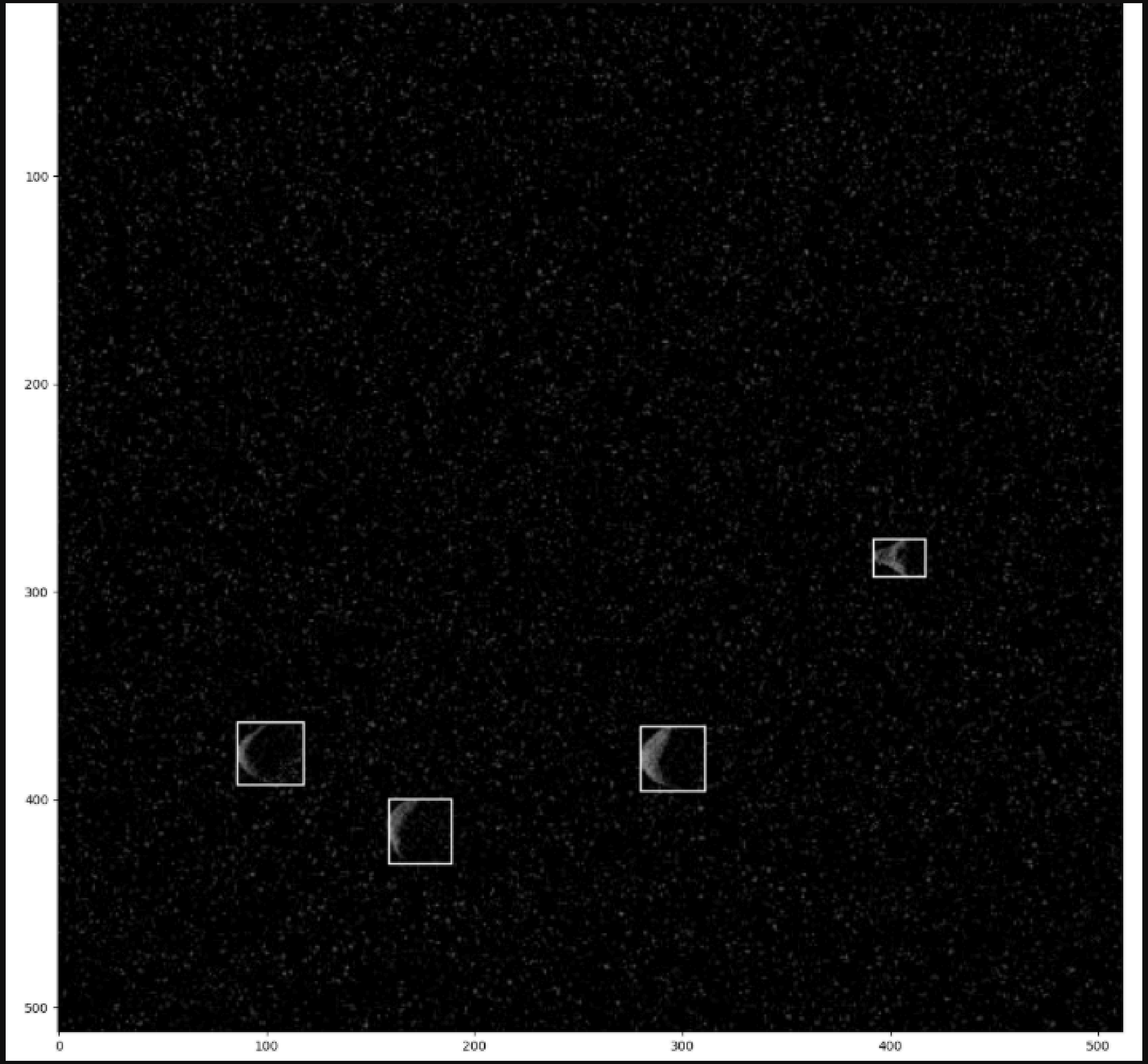

MANAGEMENT

STAKEHOLDERS

- Satellite operators (SpaceX/Starlink, ESA, ISRO)
- Insurance industry (anti-collision risk modeling)
- Space agencies tracking debris (ESA, NASA ODPO, ISRO)
- Startups offering debris services (Astroscale, LeoLabs)

ECONOMIC RELEVANCE

Preventing Satellite Collisions = Saving Billions

- Current Value of Satellites in Orbit: Over $570 billion worth of satellites are operational today.
- Improved detection leads to earlier evasive maneuvers, reducing the likelihood of damage or total loss.


THANK YOU!