

# SAFE CONSTRUCTION IN SPACE: USING SWARMS OF SMALL SATELLITES FOR IN-SPACE MANUFACTURING

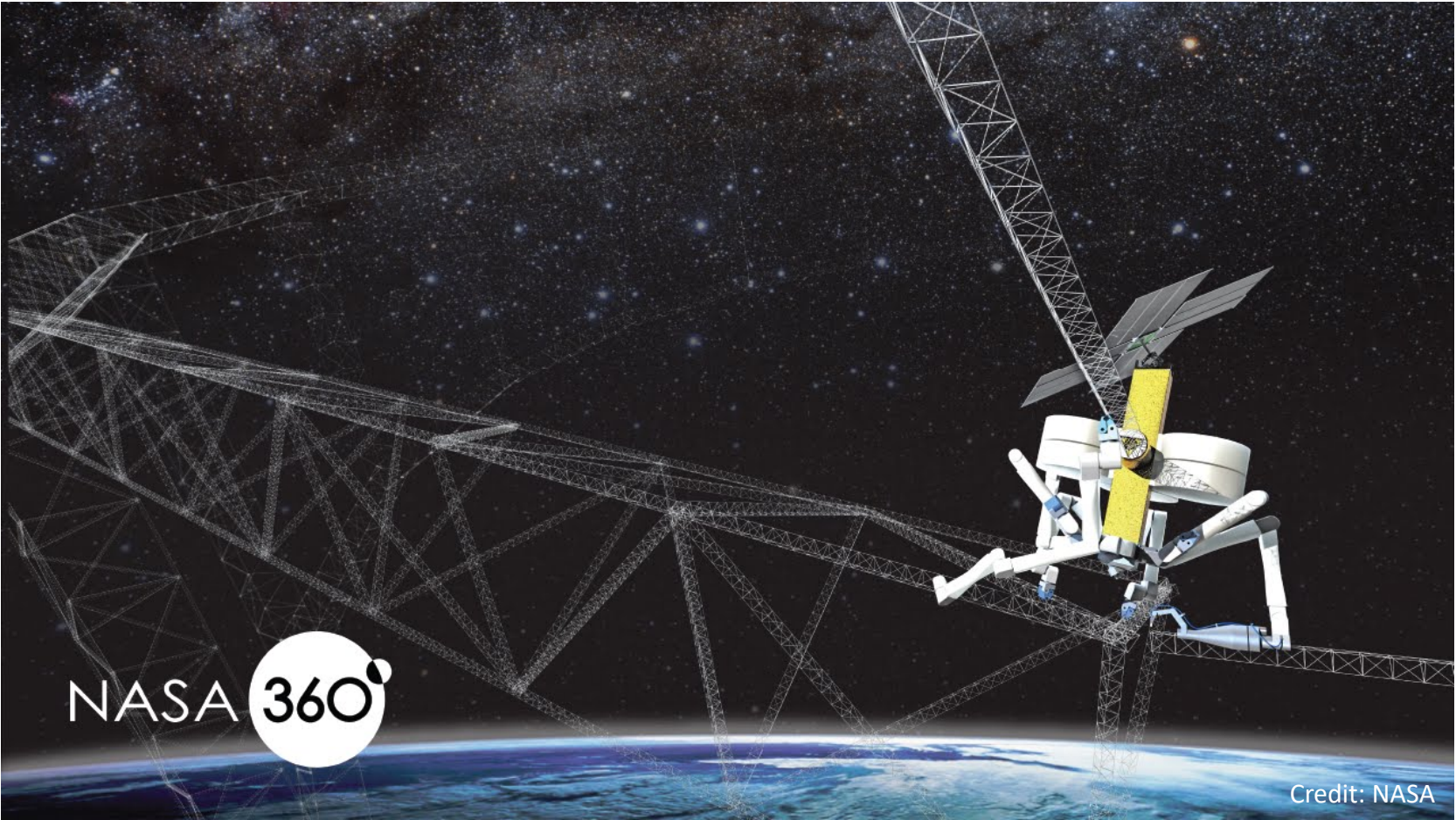
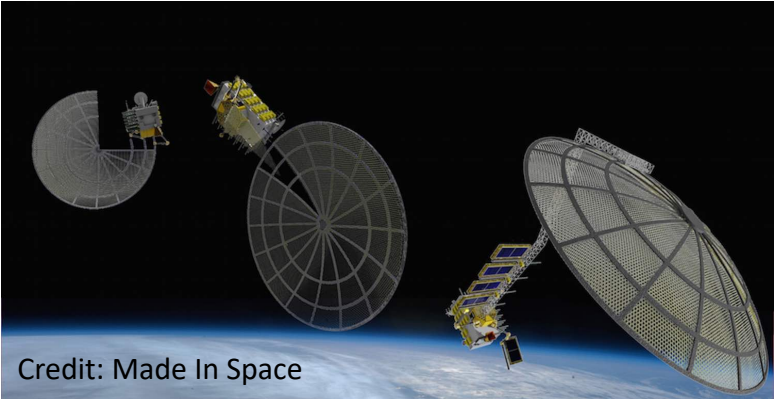
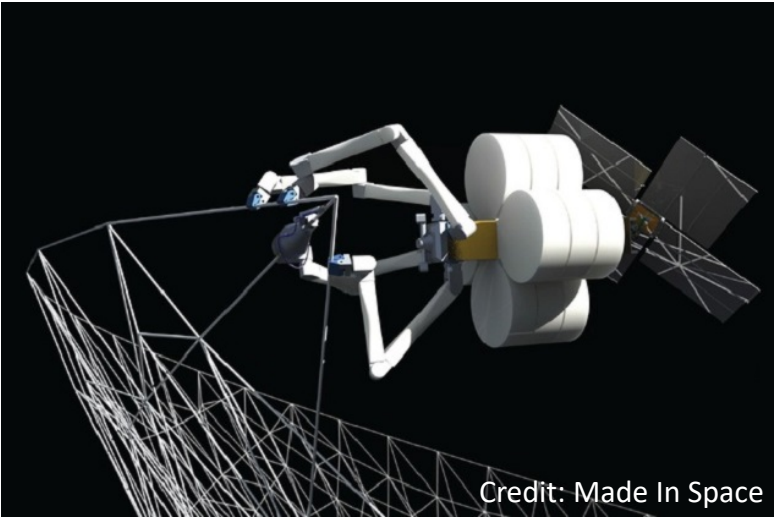
Rahul Rughani, David Barnhart

34<sup>th</sup> Annual Small Satellite Conference

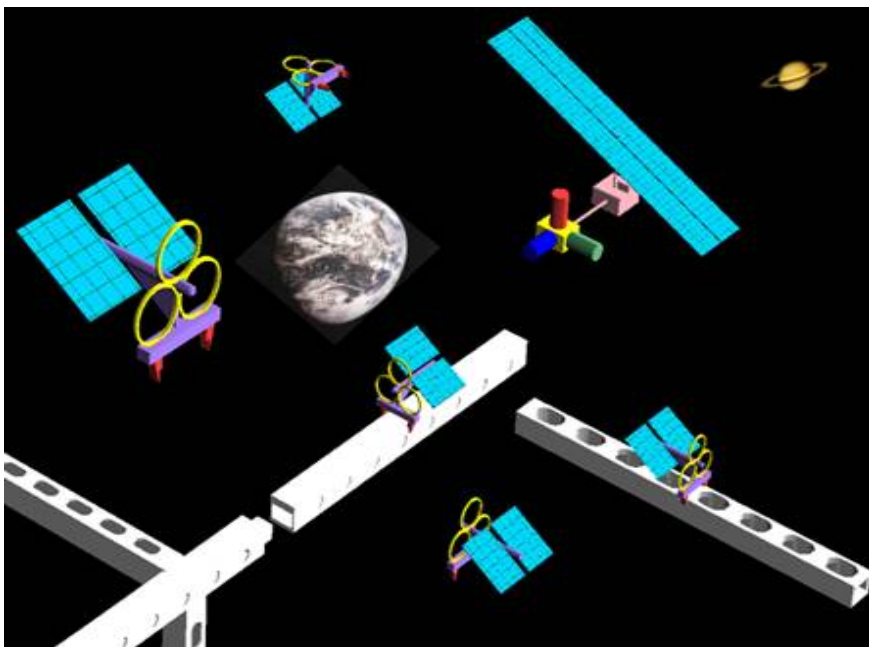
Pre-Conference Workshop (Advanced Concepts), August 2, 2020

Logan, Utah (Virtual)

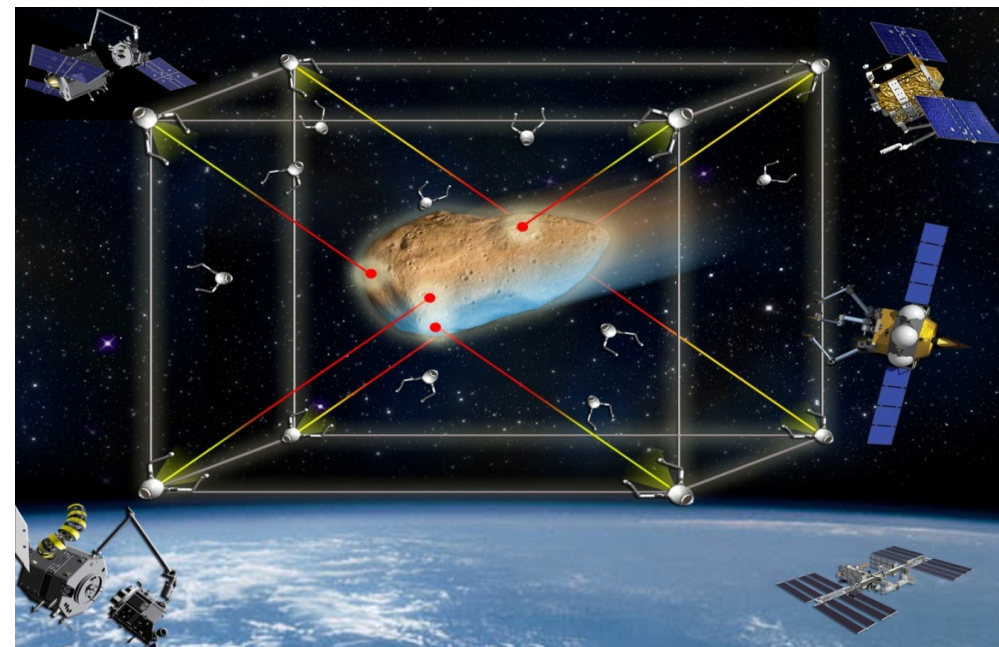
# On-Orbit Construction



# Swarm Operations in Orbit



On-orbit assembly

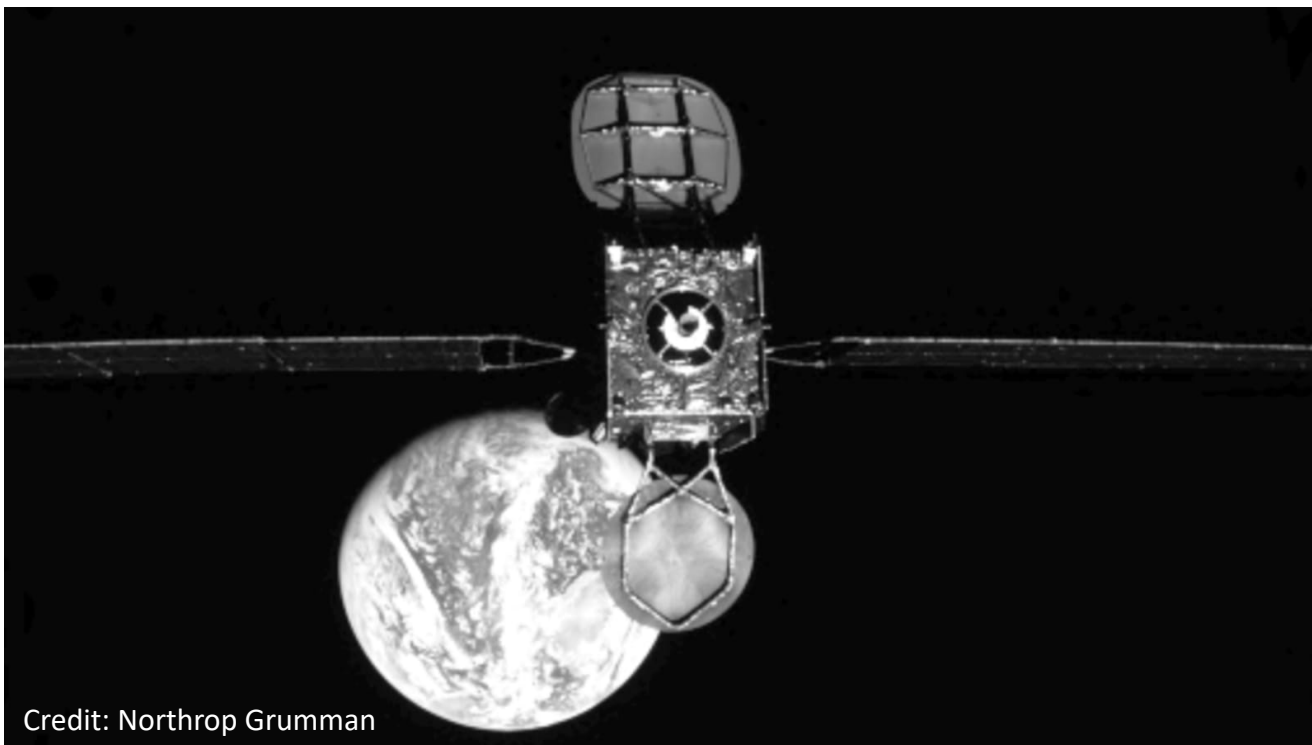


Cooperative Proximity Operations

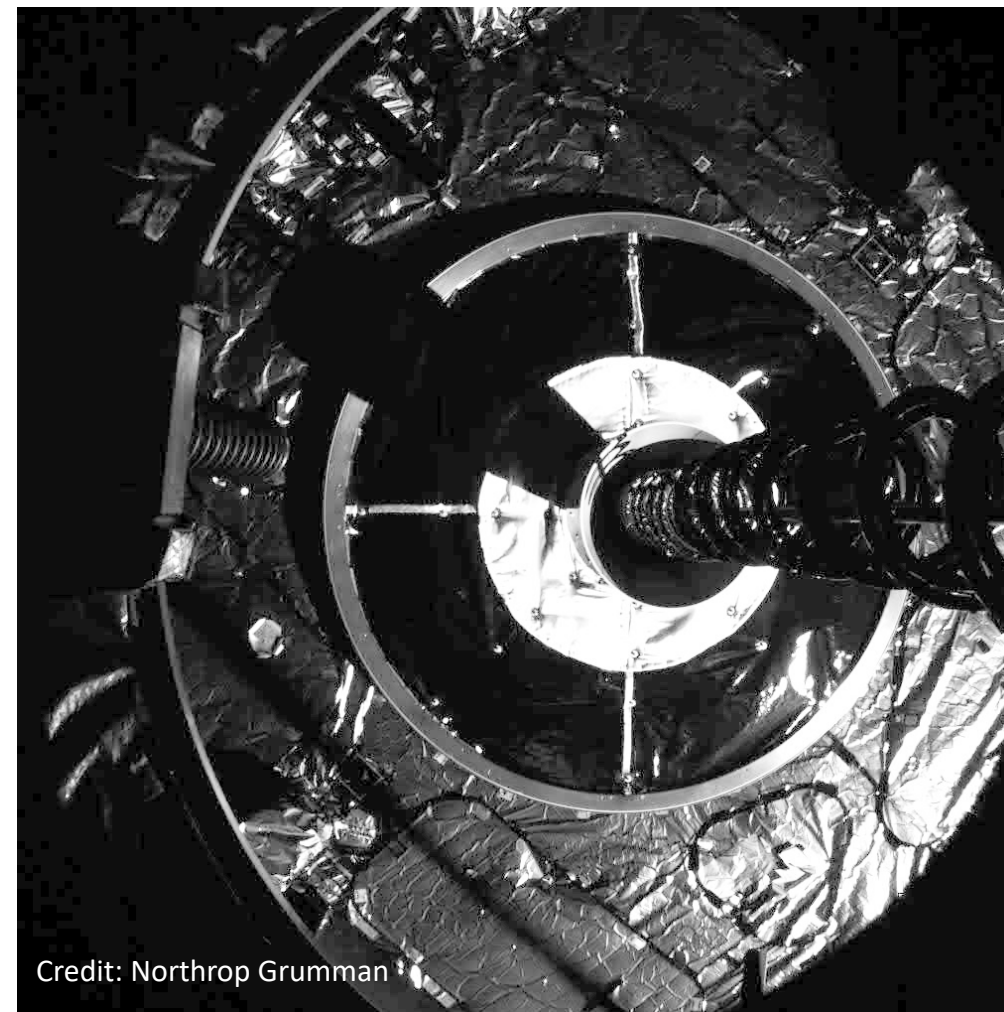
- Enables construction of complex orbital assets, and repair of existing assets.

- Redundant nature of swarm and large number of spacecraft allow for higher autonomy and reliability

# Current State-of-the-Art



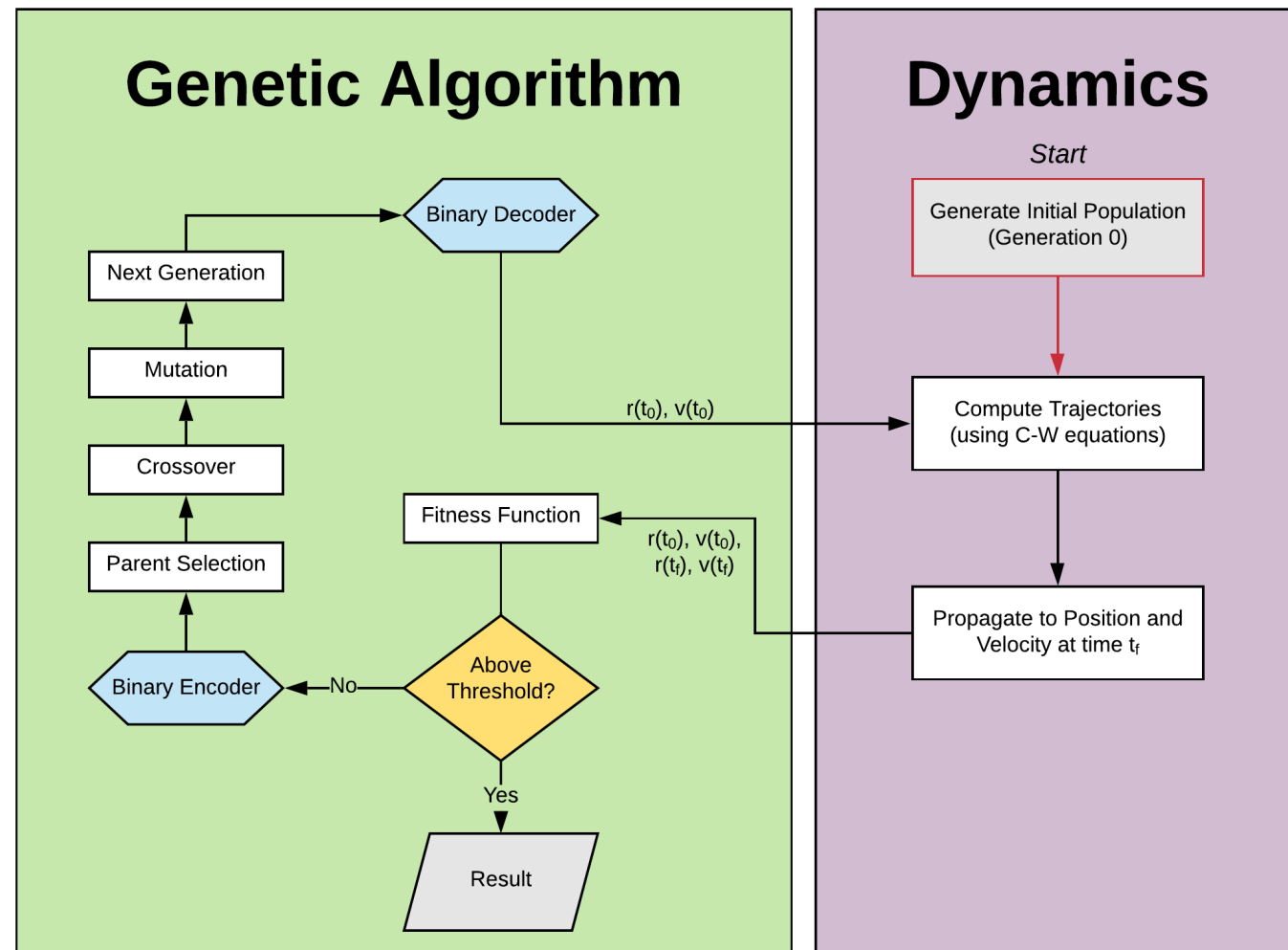
- MEV-1 successfully docked to a retired GEO spacecraft to provide mission extension services [1]



MEV-1 docks with Intelsat-901

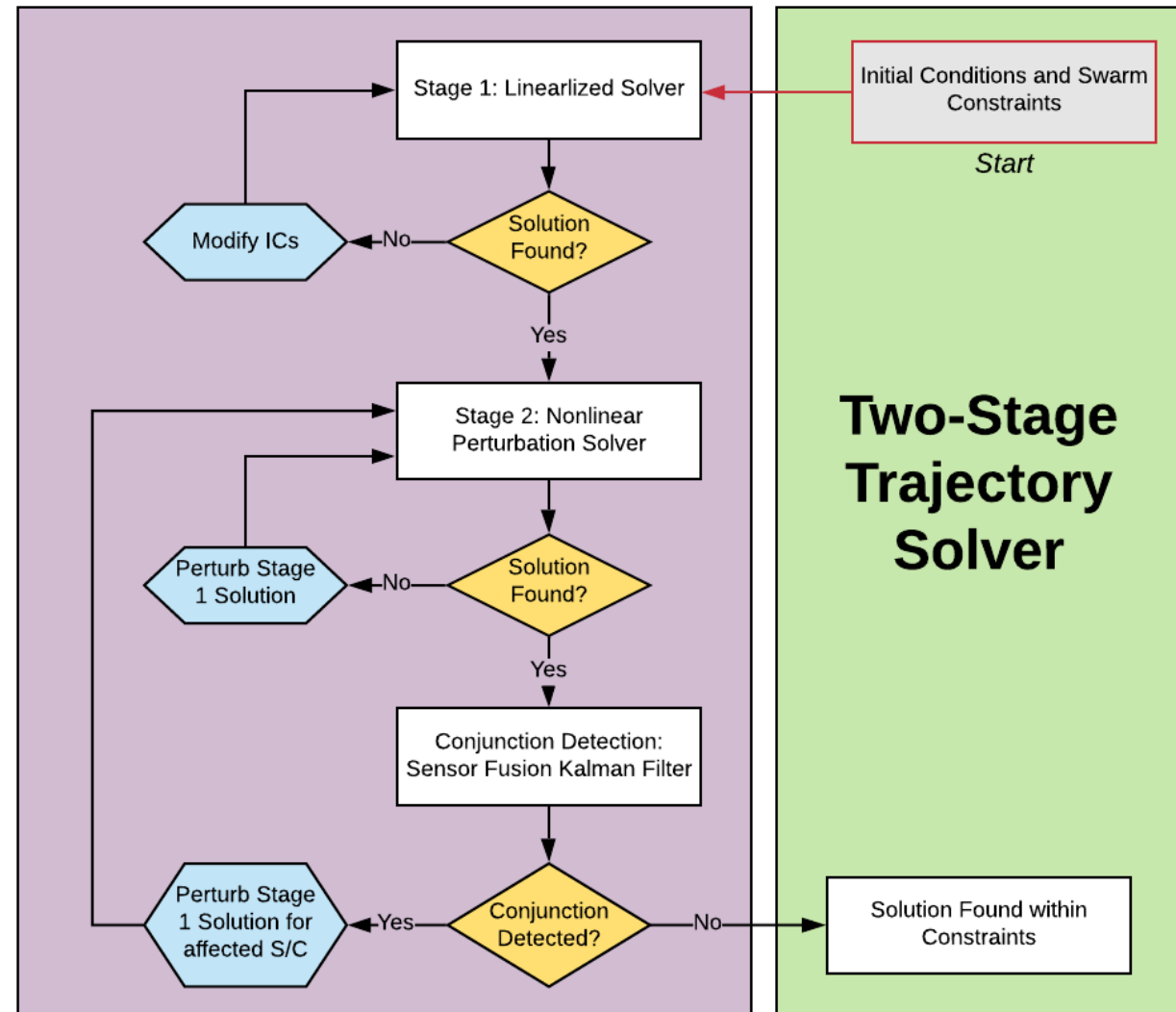
# Trajectory Generation

- Free-flight trajectories, combined with conjunction analysis, used to build safe swarms
- Optimization performed using genetic algorithms to find solutions satisfying a set of criteria [2,3]
  - Minimize insertion  $\Delta v$
  - Trajectories with no collision risk for at least 24h



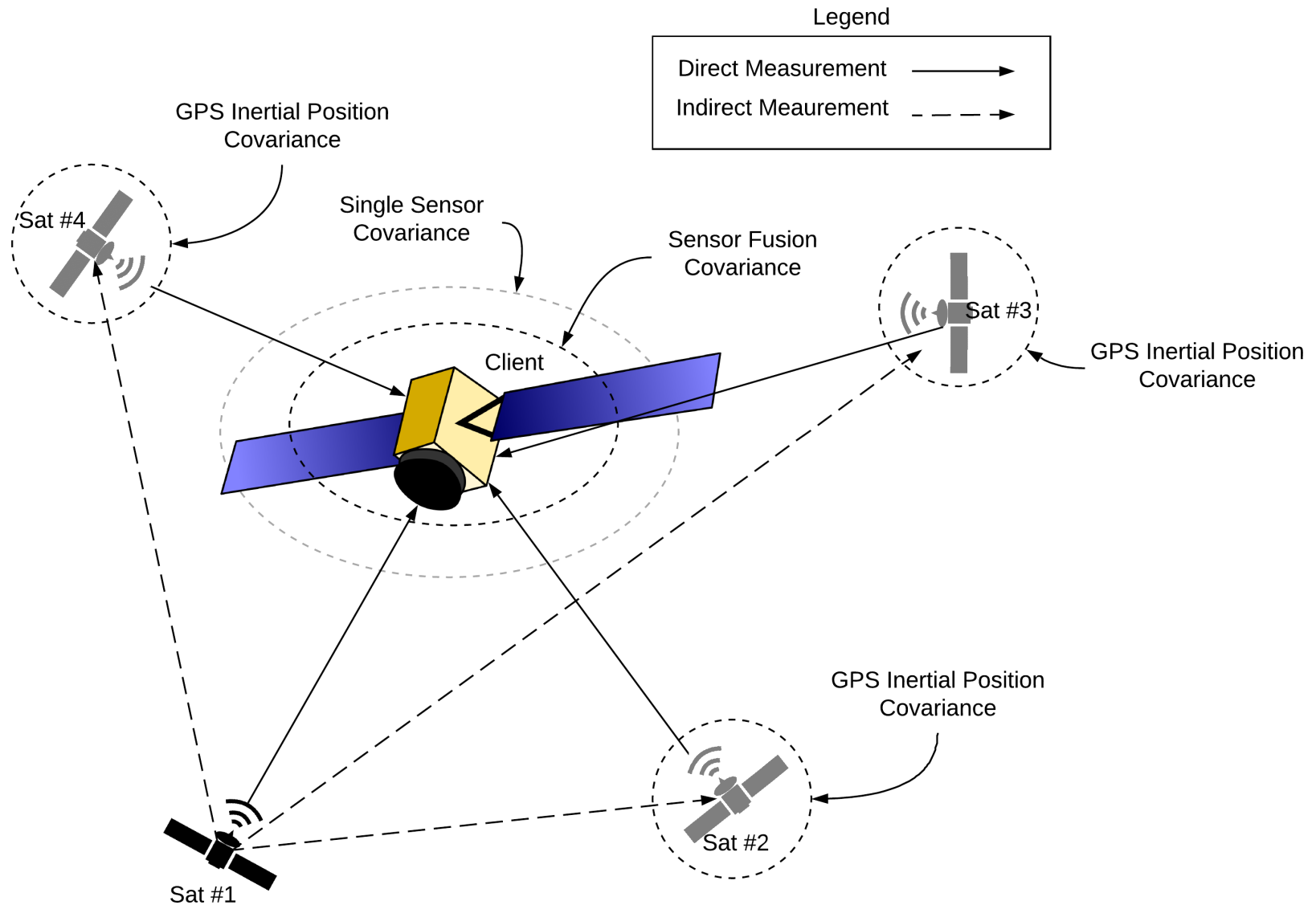
# Two-Stage Iterative Solver

- Two-stage process allows for efficient solutions, with high-fidelity perturbation models
  - J2 gravitational perturbations (extended to 4<sup>th</sup> order spherical harmonics for GEO [4])
  - Solar Radiation Pressure (GEO)
  - Sun-Moon Perturbations (GEO)



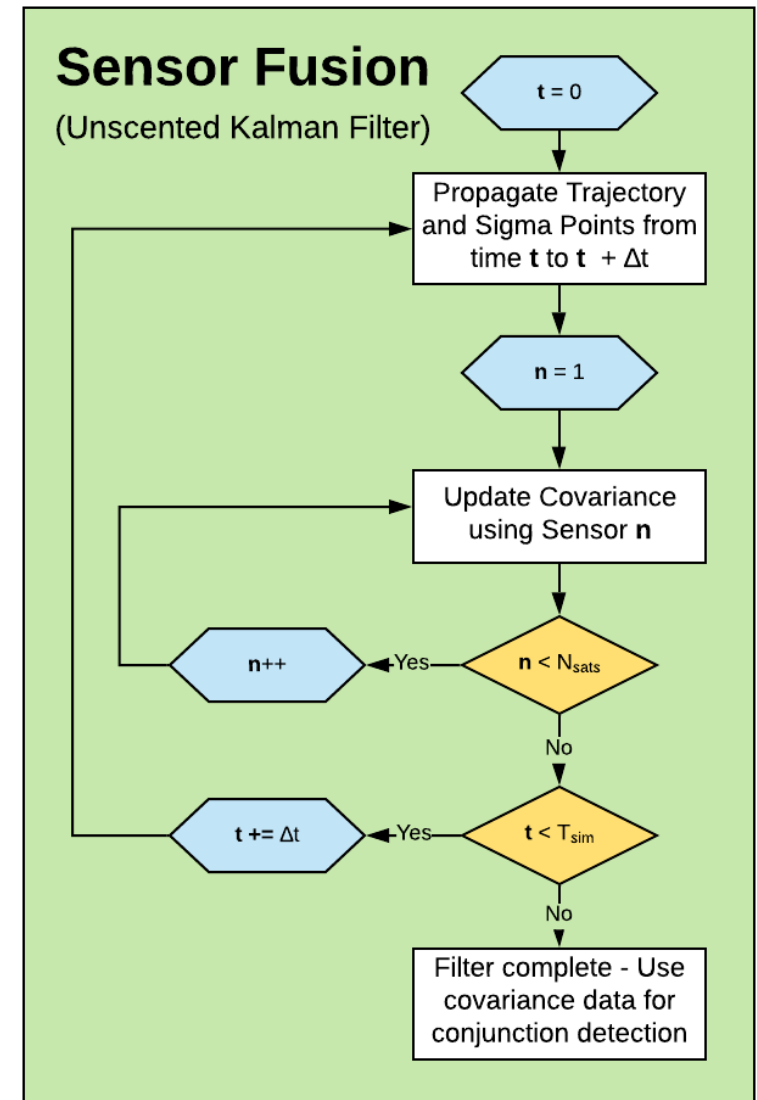
# Swarm Sensor Fusion

- Sensor Fusion combines inputs from multiple sensors, spread across the swarm
- Using a Kalman filter, this shared data can be used to pinpoint the relative positions of each spacecraft more accurately, reducing their covariances



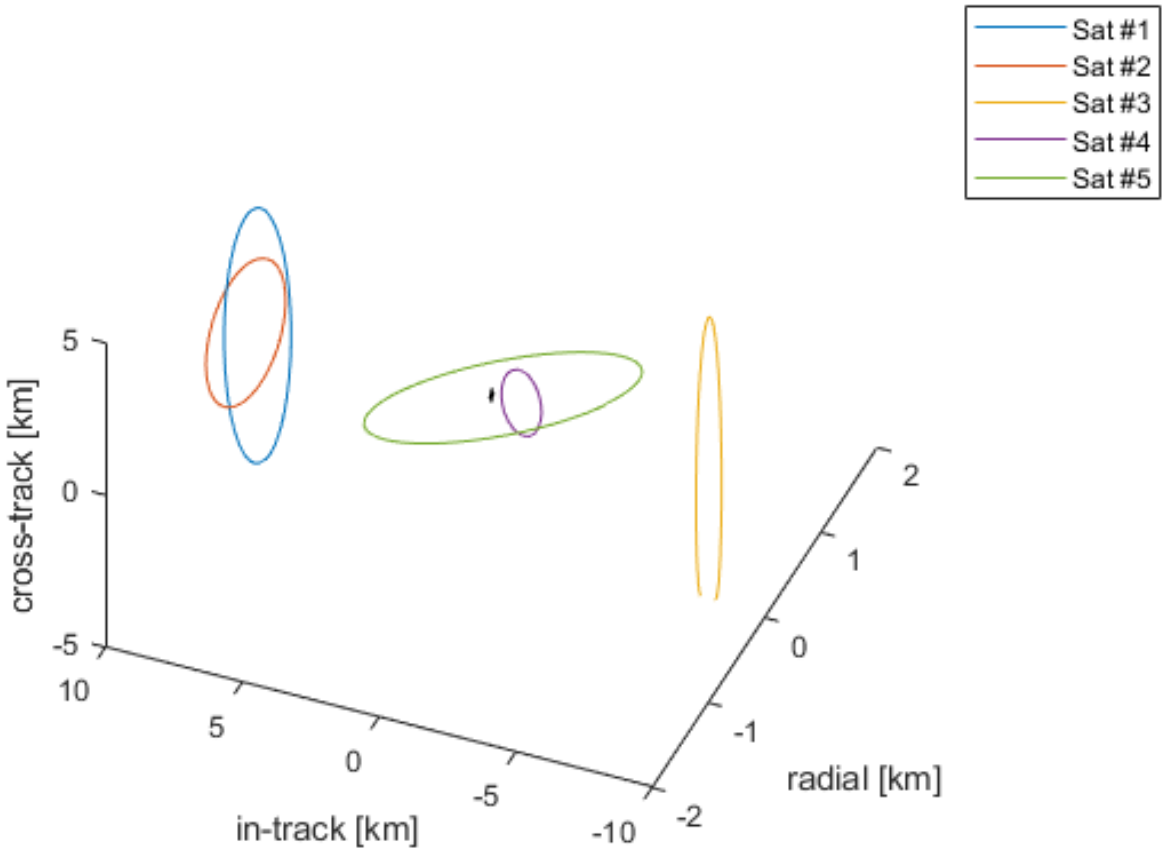
# Sensor-Fusion Kalman Filtering

- Sensor fusion can be applied to Kalman filters
  - Simulation uses the Unscented Kalman Filter since the perturbed 2-body problem is a non-linear problem
- Similar to a standard Kalman filter, except the update step is repeated for each sensor in the shared swarm sensor net
  - Adds very little computational overhead, as most of the wall-time is spent on the propagation step of the UKF

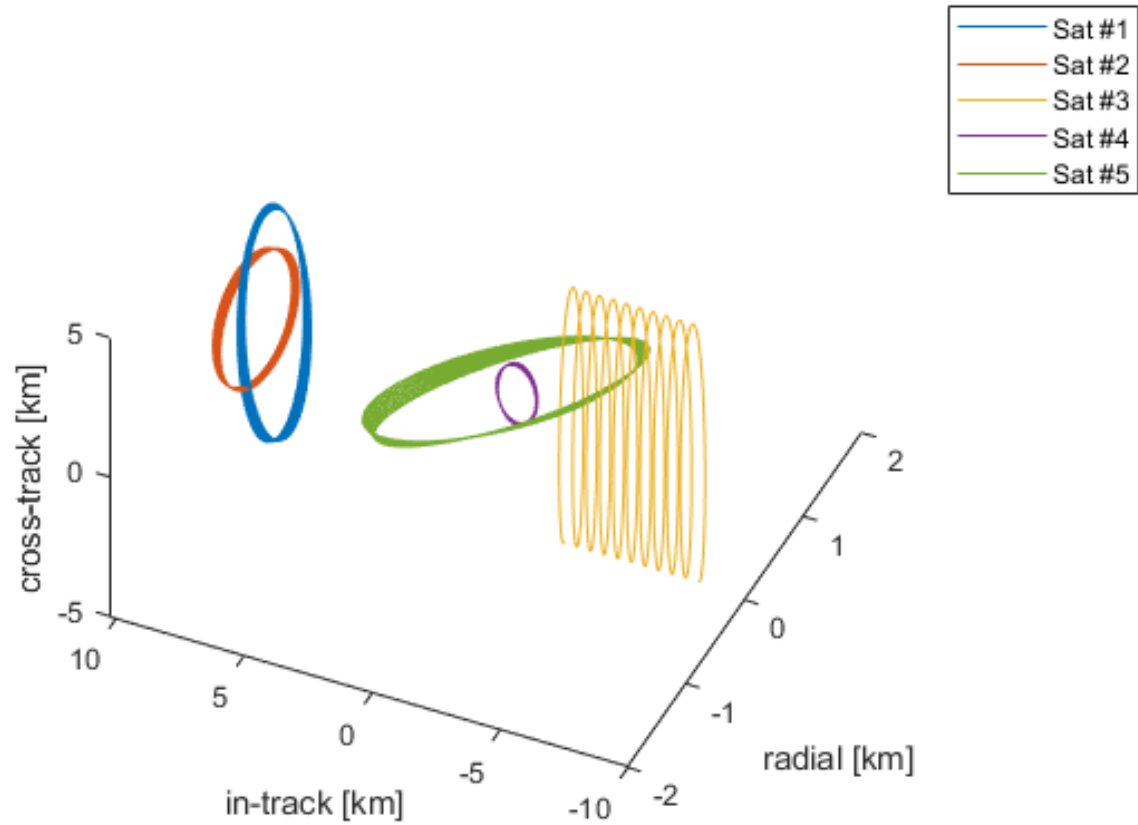


# Trajectory Example

Optimized Trajectories

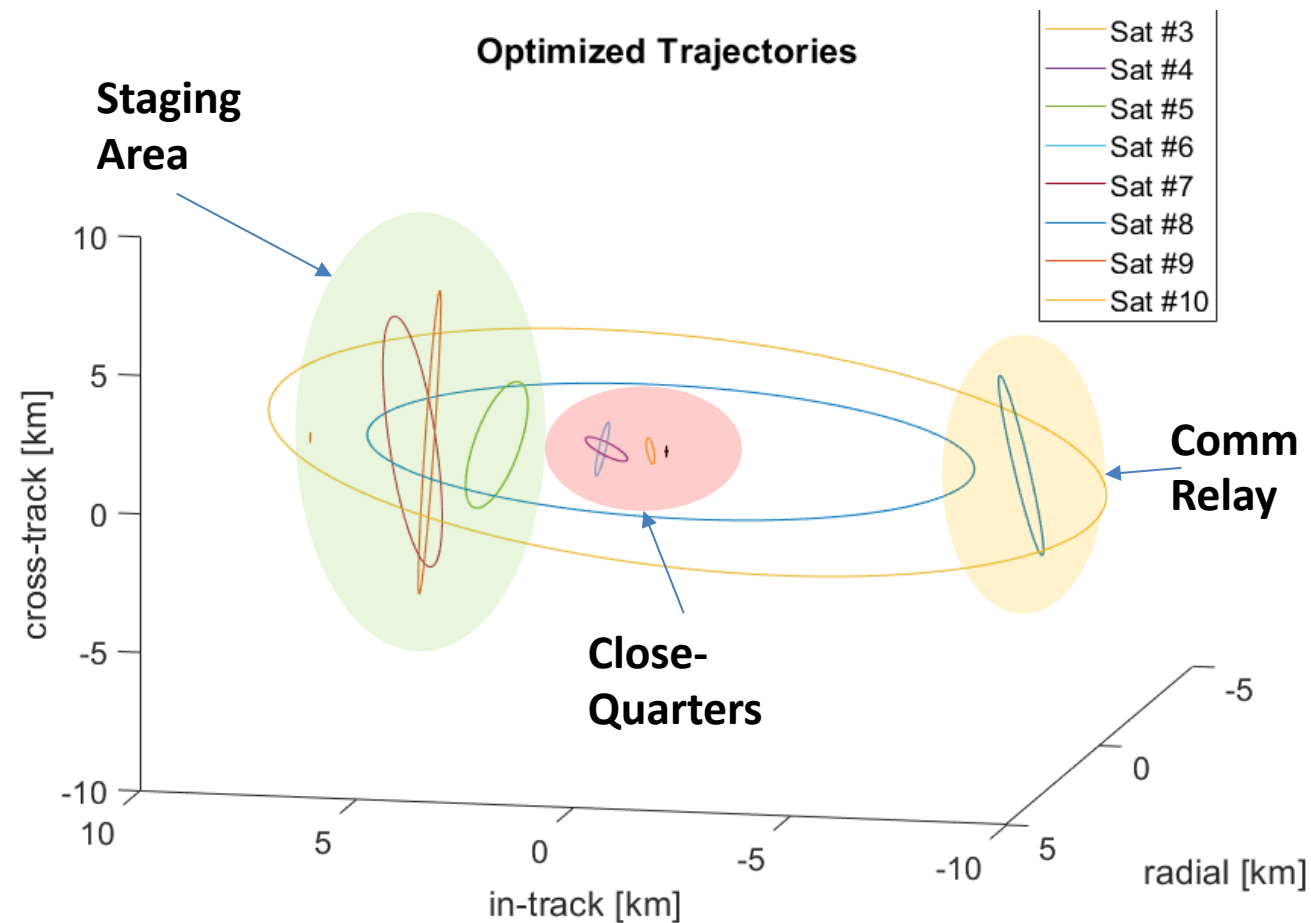


Extended Trajectories



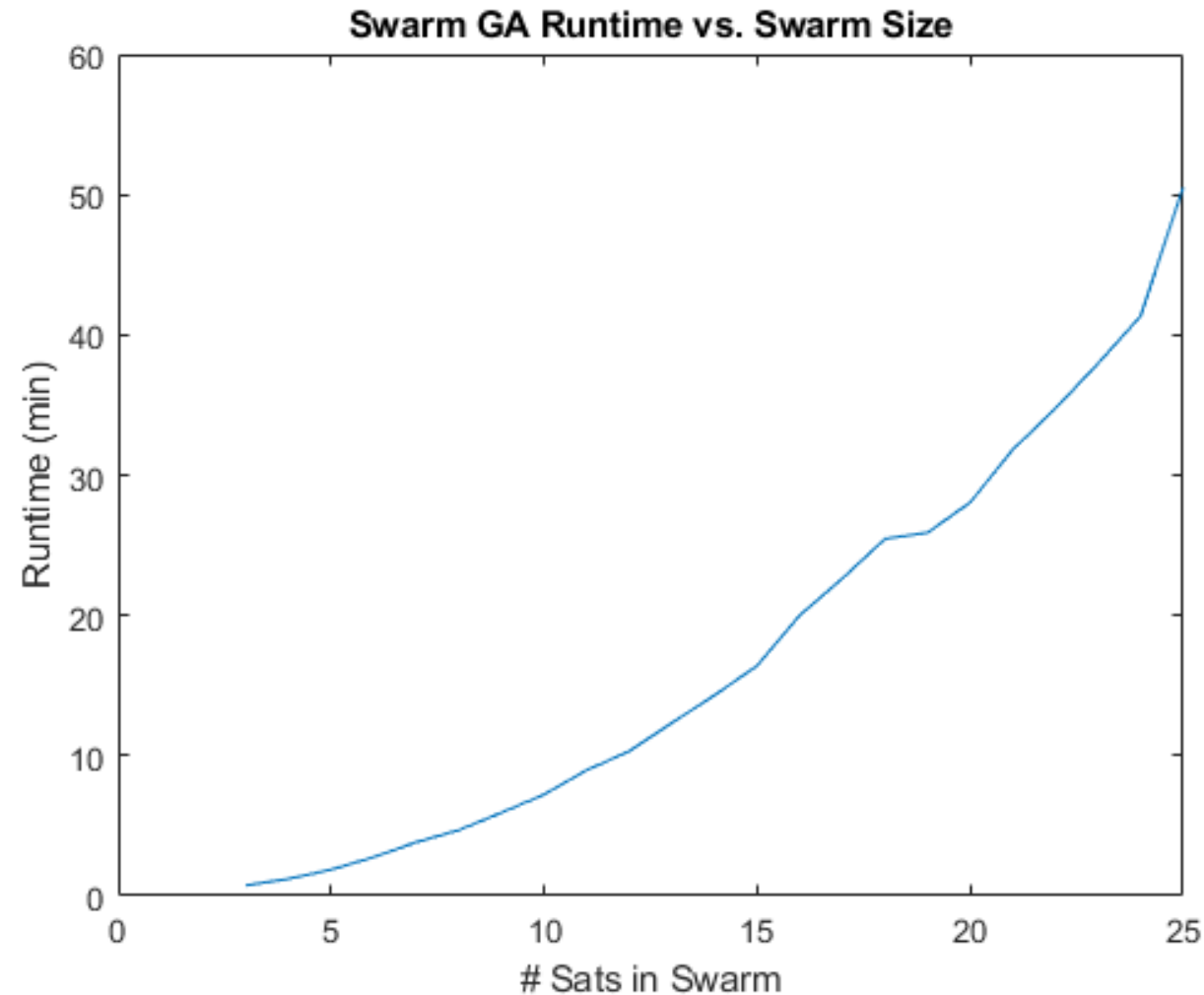
# In-Space Manufacturing

- Trajectory on right shows example of 10-spacecraft swarm for in-space manufacturing
- Swarm roles split up into the staging area, a comm relay, and close-quarters robotic operations



# Scaling with Number of Spacecraft

- Conjunction de-confliction takes the most wall-time
- Scales as  $O(n^2)$
- Runtime also depends on pseudo-random initial conditions
  - Test cases use averages over 100 trial runs for each swarm size



# Conclusion

- Although in the near term, this system will require ground intervention when the swarm deviates from its planned trajectories due to an anomaly, the long term goal is to develop an autonomous system that can accept and remediate failures of one or more of its members in real-time
- While not possible at the moment, real-time generation of trajectories for  $N$  spacecraft may be possible with further optimization and machine learning techniques in software.

- [1] Caleb Henry. Northrop Grumman's MEV-1 servicer docks with Intelsat satellite. SpaceNews, Feb 2020.  
<https://spacenews.com/northropgrummans-mev-1-servicer-docks-withintelsat-satellite/>
- [2] Rughani, R., Barnhart, D.A., *Using Genetic Algorithms for Safe Swarm Trajectory Optimization*. 30<sup>th</sup> AIAA/AAS Space Flight Mechanics Meeting. Orlando, FL, USA, 6-10 January, 2020.
- [3] Goldberg, D. E., *Genetic Algorithms in Search, Optimization and Machine Learning*, 1<sup>st</sup> ed., Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA, 1989.
- [4] Vallado, David A. *Fundamentals of Astrodynamics and Applications*. Vol. 12. Springer Science & Business Media, 2001.