Distributed Space Architectures for Mission Assurance

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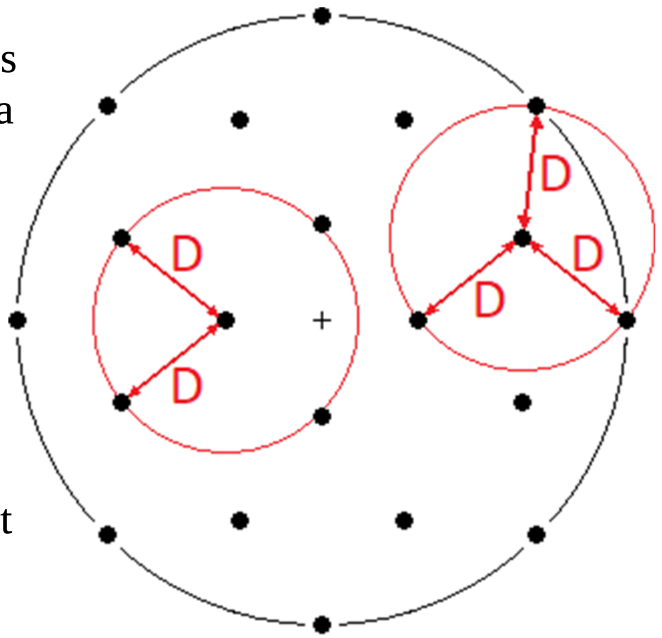
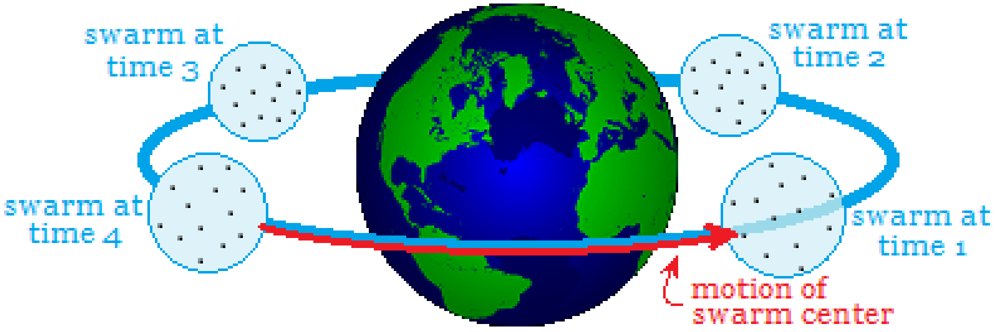
Distributed Space Architectures

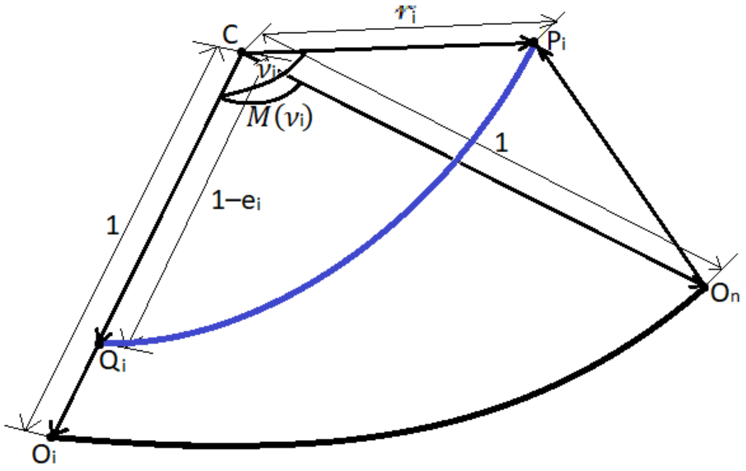
- Operationalize the use of **distributed** space architectures to assure the continued operation of high-value assets in a contested space environment

- Introducing **Swarm Shield**: A system of networked space assets to obfuscate or disaggregate high-valued assets for mission assurance

- **Goals**: Provide a system of redundancy to assure operations of high-valued space assets; obstruct any effort by bad actors to identify and disable US assets; provide warnings to mission controllers of active threats against US space assets







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Motivation

As space becomes an evermore competitive environment for **strategic advantages** against prospective international rivals, opportunities for friction abound

- Russian satellite **Kosmos 2542** "stalks" U.S. spy satellite **USA 245** – 2019/2020
- International testing of kinetic-kill anti-satellite (ASAT) weapons:
  - **Mission Shakti**, India – 2019
  - **PL-19 Nudol** launched by Russia:
    - November, 2015
    - May, 2016
    - December, 2016
    - March, 2018
    - December 2018
  - **Operation Burnt Frost**, USA – 2008
  - **Fengyun-1C** destroyed by China – 2007
- Long-term risks of collision – demonstrated by **Iridium-Kosmos collision** in 2009

Forbes

EDITORS' PICK | 3,998 views | Feb 5, 2020, 10:25am EST

Russian Spacecraft Stalking U.S. Spy Satellite Sparks Espionage Fears

Kate O'Flaherty Senior Contributor ⓘ
Cybersecurity
I'm a cybersecurity journalist.

In a strange twist that could come straight from a movie, it appears a Russian satellite is stalking a U.S. spy satellite in space. [-] GETTY

https://www.forbes.com/sites/kateoflahertyuk/2020/02/05/space-espionage-fears-as-russian-spacecraft-starts-stalking-us-spy-satellite/

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How can Swarm Shield help?

Two primary methods of utilizing Swarm Shield are being considered:

1. A swarm of decoys is placed around an existing **high-valued asset** (HVA) – hiding a “needle in a haystack” by constructing the “haystack” (the swarm) around the “needle” (the high-value asset)
   - Has the advantage of allowing **integration** of Swarm Shield into the current mission landscape without the need to replace or relocate the existing HVA
   - Has the disadvantage of requiring decoys with **similar physical characteristics** to avoid identification of the true HVA
   - Recommended for situations where the priority objective for the Swarm Shield is **situational awareness** of the surrounding environment
2. HVA is **disaggregated** into a swarm of satellites which actively work together to perform the role previously held by the singular unit
   - Introduces **redundancy** to allow a swarm of satellites to continue to execute its mission, even if some members of the swarm are disabled
   - Some elements of the swarm **are still specialized** to perform unique roles

Case study: LISA (2034)

The **Laser Interferometer Space Antenna (LISA)** – to detect gravitational waves with an effective interferometry arm length multiple orders of magnitude greater than Earth's radius

- Consists of three satellites placed in orbits around the sun
- Orbits are such that the distance between any two satellites is approximately constant over time, and identical for all three pairs of satellites
- Lessons from LISA:
  1. **Metrics used to assess the geometry** of the formation
  2. Impact and significance of **disturbance forces** on the formation
  3. **Communication and processing** between linked satellites in a network

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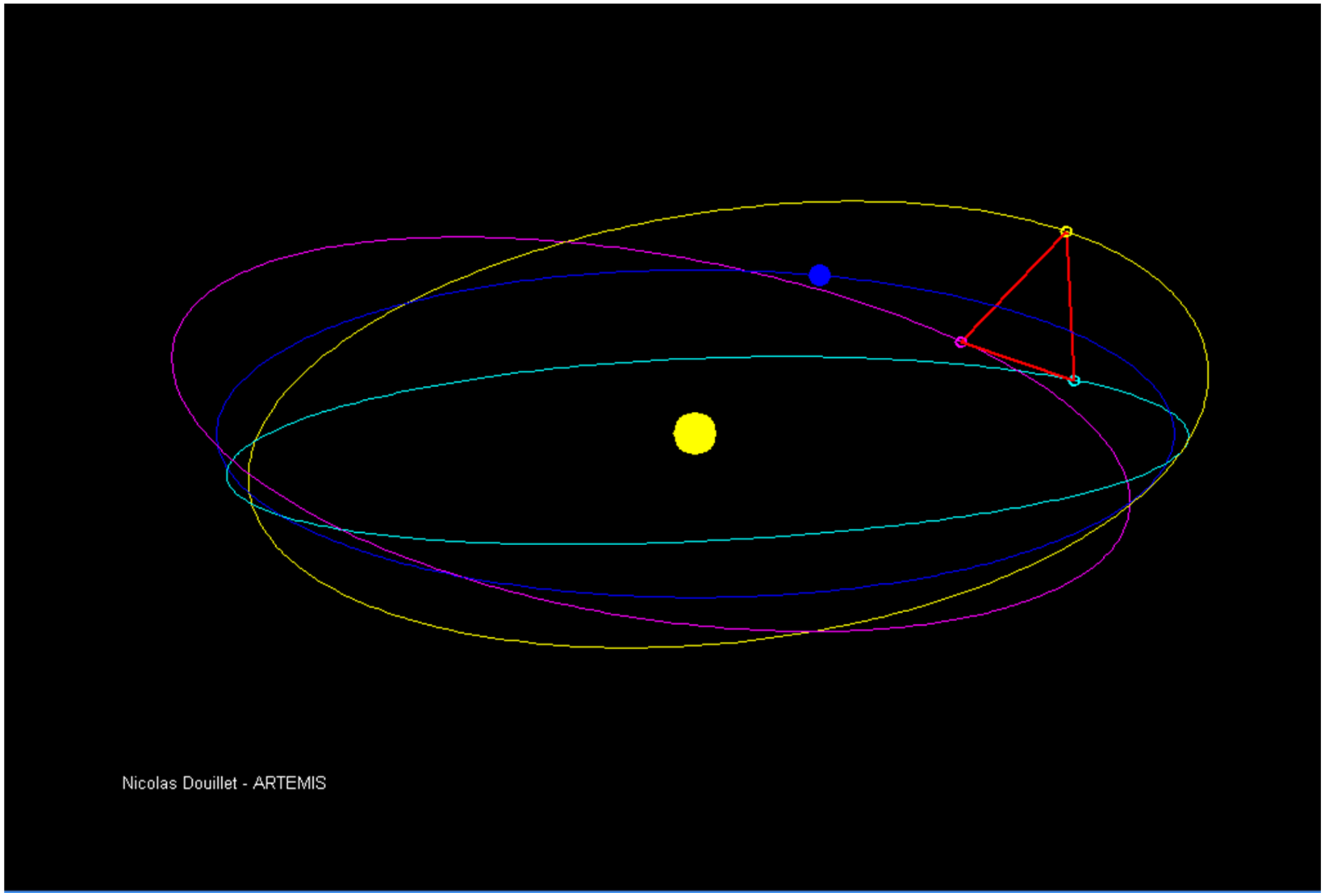
Case study: LISA (2034)

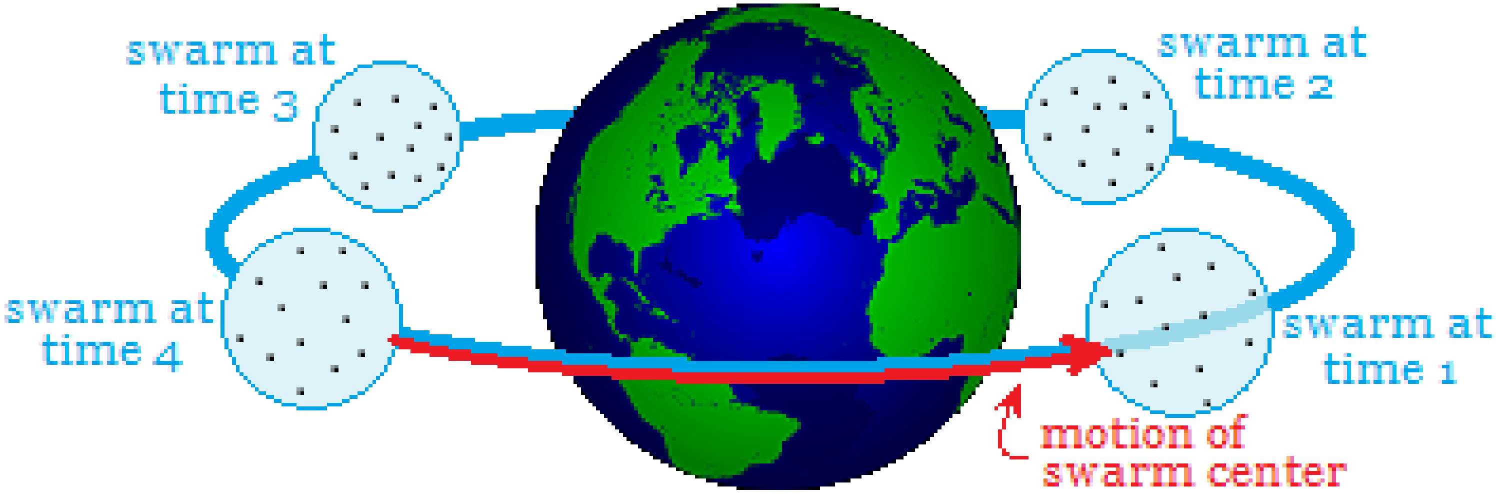


LISA Orbits (Wikipedia)

Quantifying Swarm Geometry

Start with a high-level description of the swarm, then codify this description using the rules of vector geometry to build a **swarm cost functional**

- At any given moment in time, we seek to arrange the satellites of the swarm such that they are **homogeneously distributed** throughout a **spherical region** of space
- As time evolves, we wish to **minimize the deviation** from a spherical envelope containing the swarm, as well as the deviation from homogeneity



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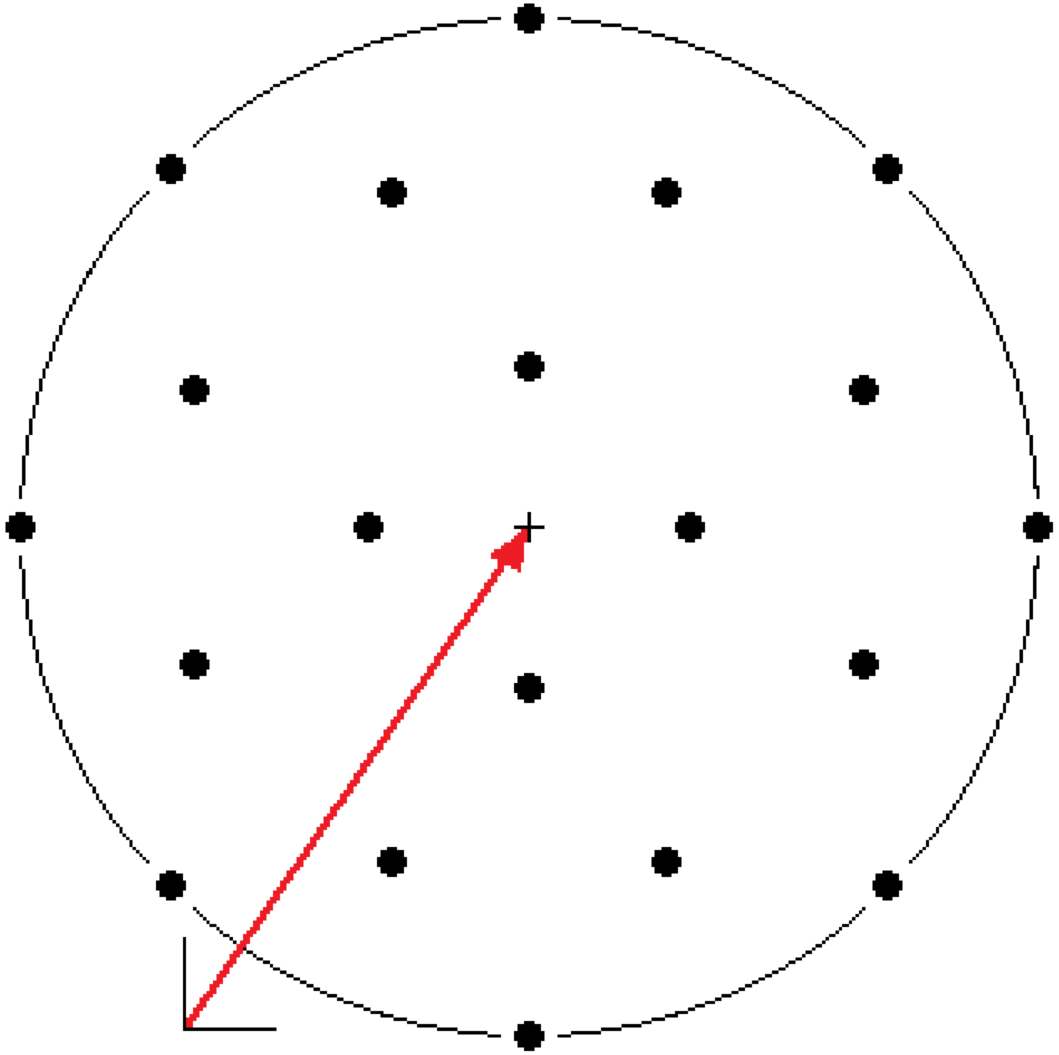
Quantifying Swarm Geometry

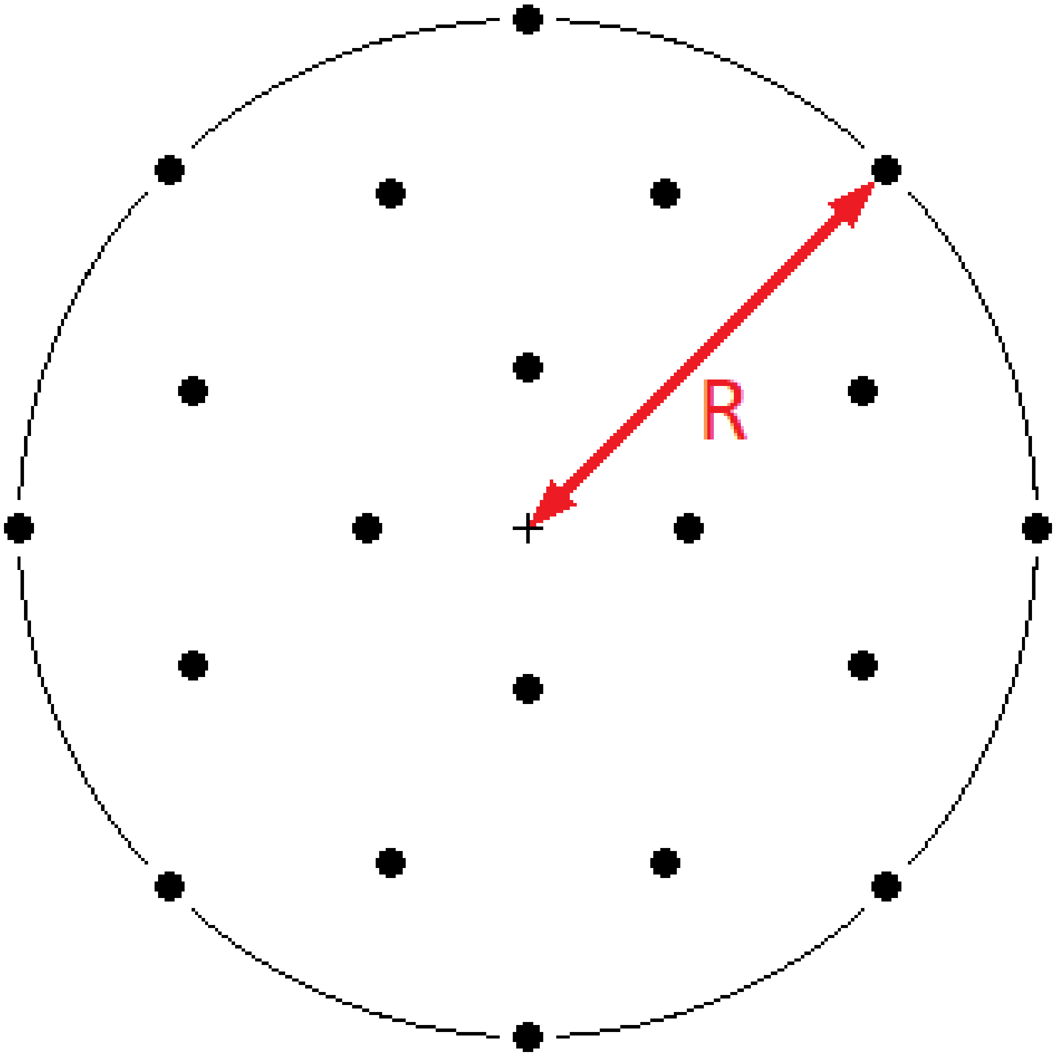
Currently there are **5 constraints** – each with its own cost function:

1. Adjusts the swarm's **geometric center** to track a desired trajectory
    - Ensures the swarm remains aligned with its reference plane
2. Sets the **maximum distance** between the swarm center and any one satellite (i.e., defines **the radius of the swarm**)
    - Prevents the swarm from collapsing to a single point during optimizing
3. Equalizes the **shortest distance** between any two adjacent satellites (**the clearance**) for all pairs of satellites within the swarm
    - Promotes homogeneity and discourages collisions between satellites
4. Sets the **distance between each satellite and the center** of the swarm in terms of the satellite's orbital parameters
    - Promotes homogeneity and uniformity of the swarm envelope over time
5. Maximizes the **volume efficiency** of the swarm
    - Promotes homogeneity and discourages collisions between satellites
    - Complements constraints 3 and 4 to homogenize the swarm

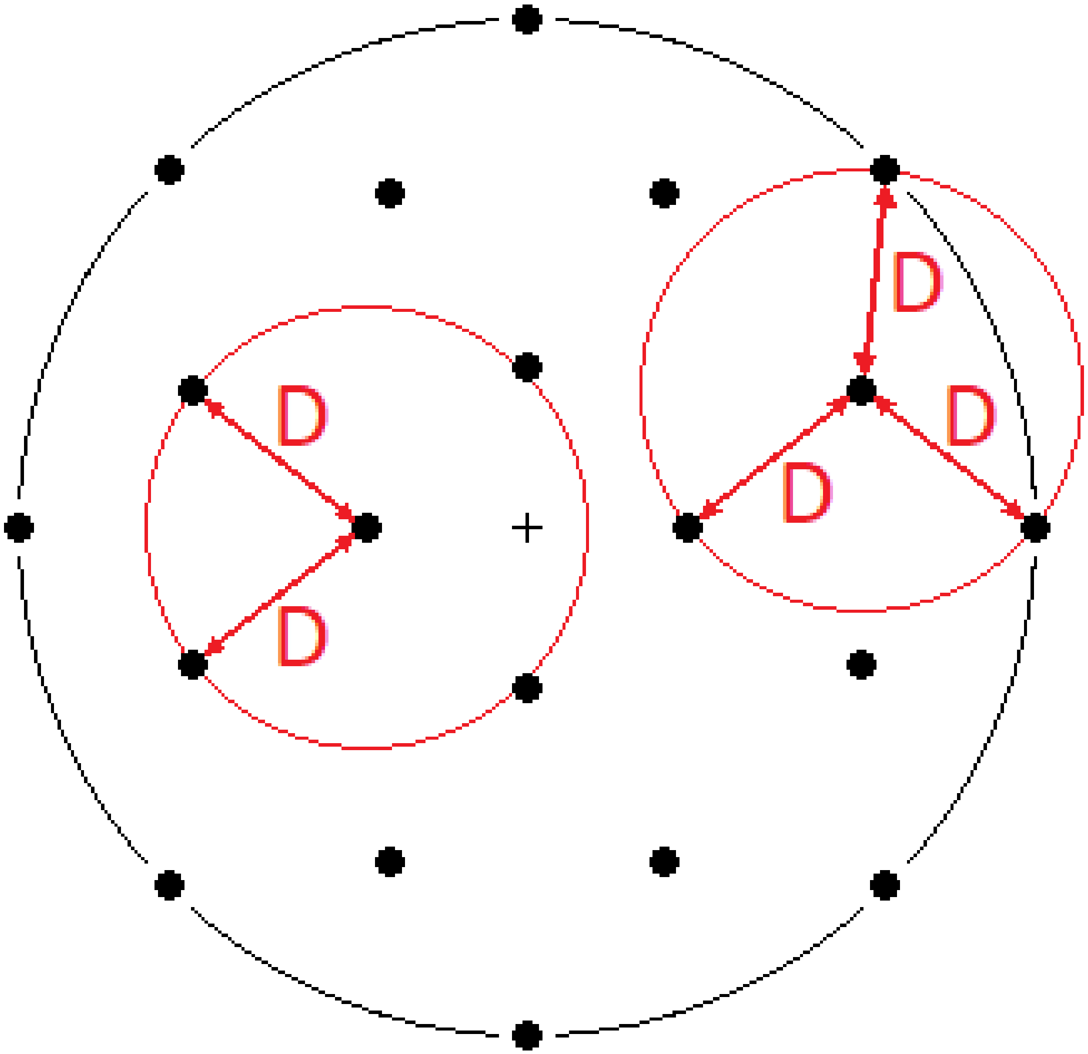
Quantifying Swarm Geometry



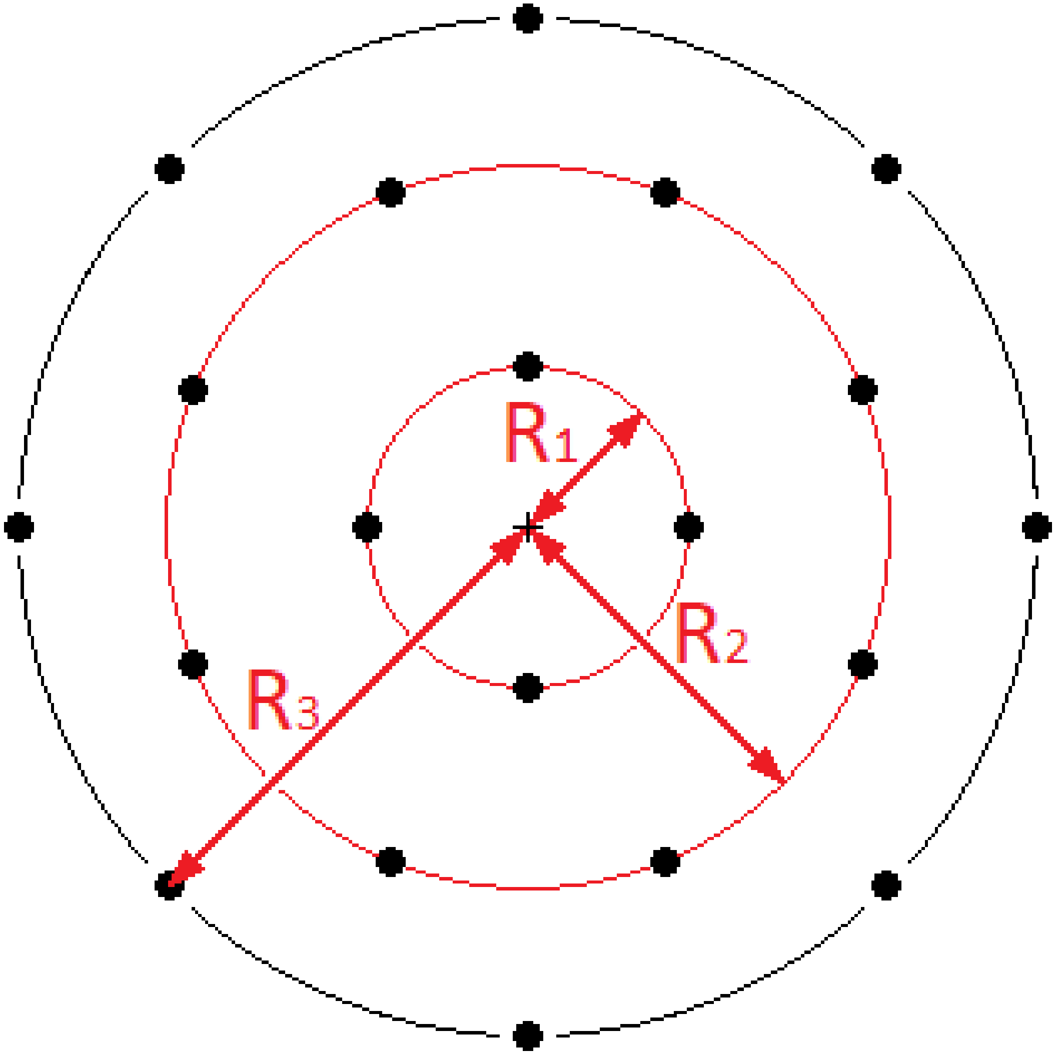
Quantifying Swarm Geometry



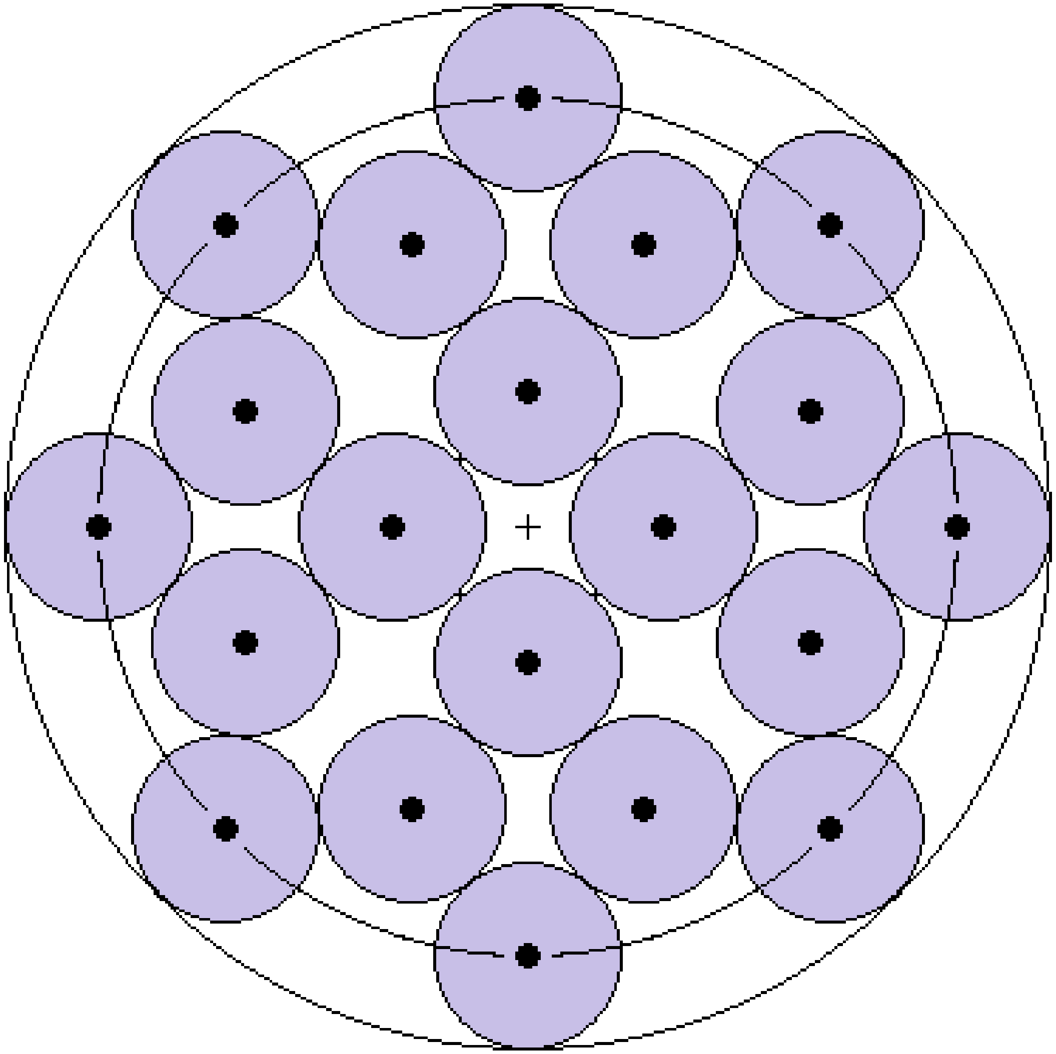
Quantifying Swarm Geometry



Quantifying Swarm Geometry



Quantifying Swarm Geometry



Quantifying Swarm Geometry

Each constraint is codified within the swarm cost functional:

$$\mathcal{J} = w_1\mathcal{J}_1 + w_2\mathcal{J}_2 + w_3\mathcal{J}_3 + w_4\mathcal{J}_4 + w_5\mathcal{J}_5.$$

- Weights w_1 through w_5 currently determined through trial and error
- Modular form facilitates additional terms (if necessary)
- A swarm with n satellites contains n crossings of the reference plane; define ${}^{i}\mathcal{J}$ to be the value of $\mathcal{J}$ when the i^{th} satellite is at periapse (ω=0)
- Define:

$$\bar{\mathcal{J}} = \frac{1}{n}\sum_{i=1}^{n} {}^{i}\mathcal{J}\,; \quad \sigma_{\mathcal{J}}^2 = \frac{1}{n}\sum_{i=1}^{n}\left({}^{i}\mathcal{J} - \bar{\mathcal{J}}\right)^2$$

- Goal: to minimize $\mathcal{V} = w_{\bar{\mathcal{J}}}\bar{\mathcal{J}} + w_{\sigma_{\mathcal{J}}}\sigma_{\mathcal{J}}$ for “appropriate” weights $w_{\bar{\mathcal{J}}}$ and $w_{\sigma_{\mathcal{J}}}$
  - Define $w_{\bar{\mathcal{J}}} = 1/(K_\sigma + 1)\,;\ w_{\sigma_{\mathcal{J}}} = K_\sigma/(K_\sigma + 1)$ where $K_\sigma \in [0, \infty]$ ($K_\sigma = \infty$ permitted)

Quantifying Swarm Geometry

Requires a swarm to hold its form within a spherical envelope; the orbits of each satellite are therefore designed with the following requirements:

1. All satellites have the **same orbital period** (constrains a)
2. An inertial **swarm reference plane** exists in which the geometric center of the swarm follows a circular path at a constant angular rate
    - This reference plane is distinct from other commonly used reference planes (also not the orbit plane of the monolithic HVA)
3. Each satellite in the swarm has a **non-zero inclination** relative to the reference plane, forming a **line of nodes**
4. This line of nodes is **coincident** with the **line of apsides** for each orbit
5. A **minimum and maximum altitude** are specified to constrain the size of the swarm

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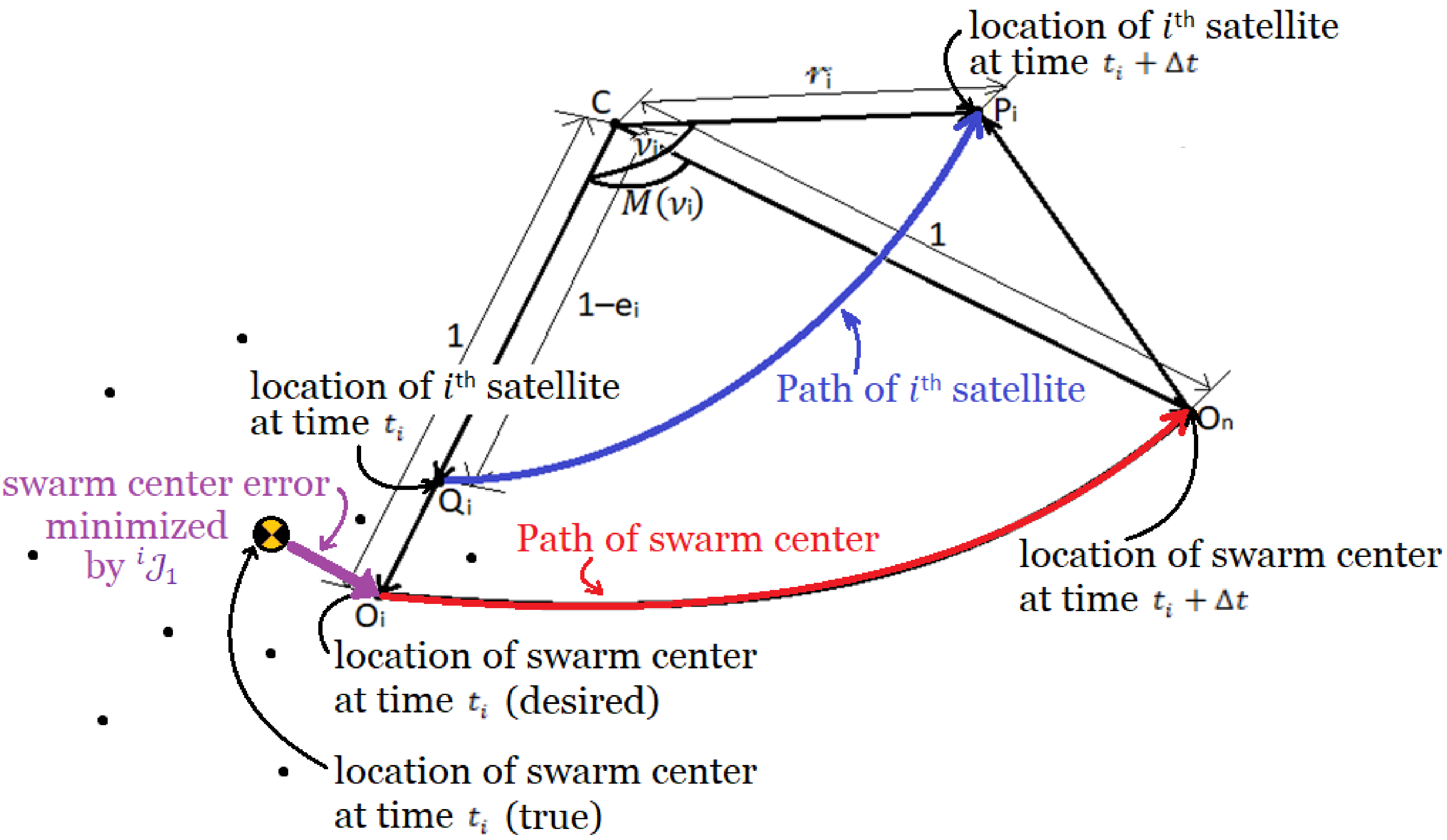
Quantifying Swarm Geometry



location of i^{th} satellite
at time $t_i + \Delta t$

location of i^{th} satellite
at time t_i

Path of i^{th} satellite

swarm center error
minimized
by ${}^{i}\mathcal{J}_1$

Path of swarm center

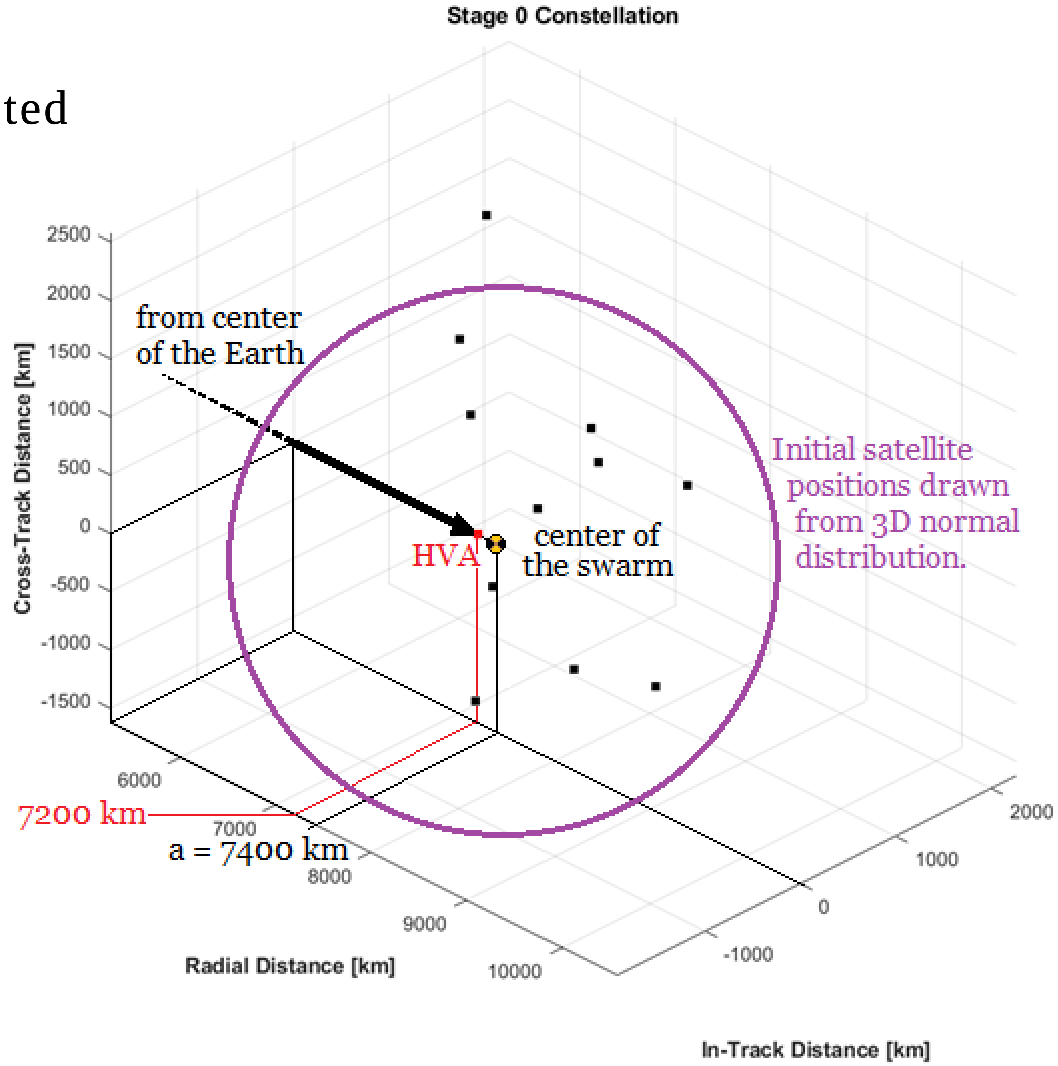
location of swarm center
at time $t_i + \Delta t$

location of swarm center
at time t_i (desired)

location of swarm center
at time t_i (true)

Preliminary Results

Swarm populated



from center of the Earth

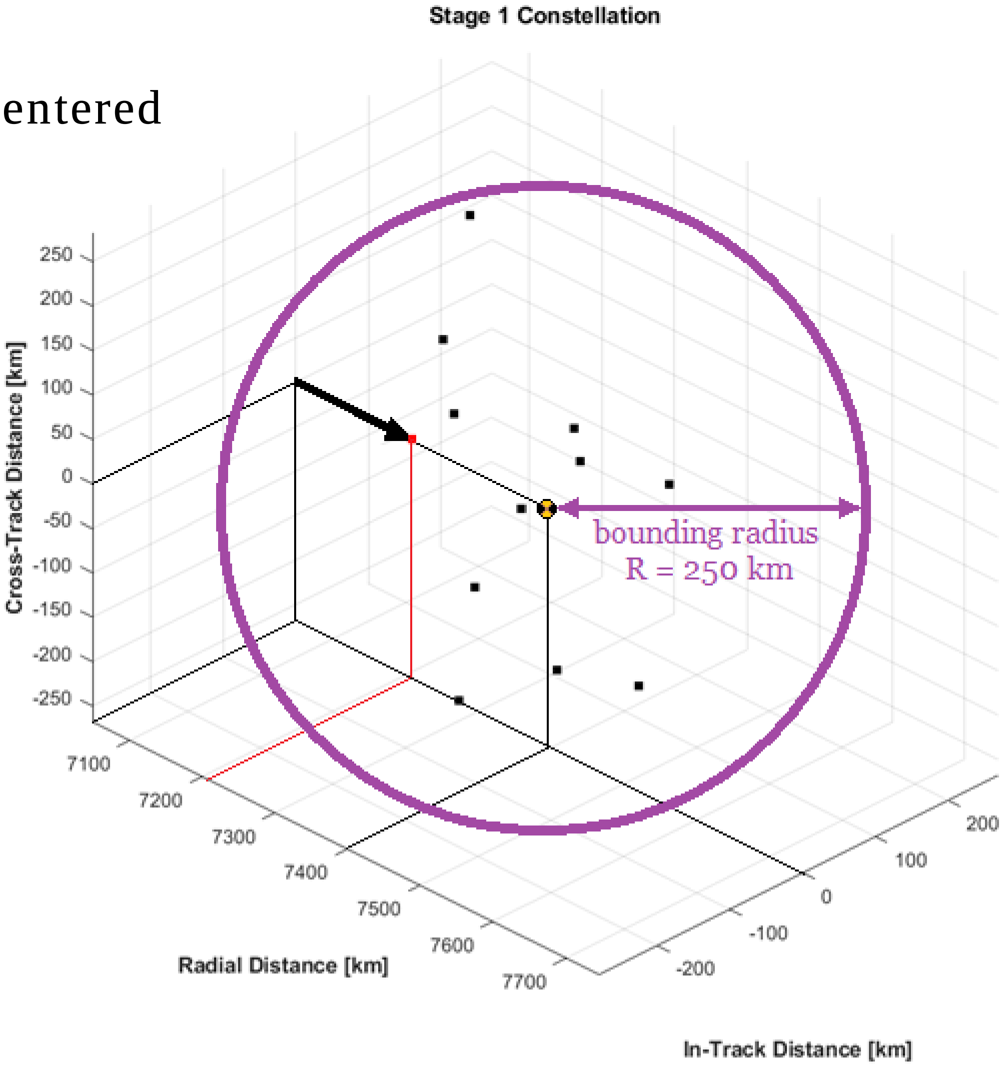
center of the swarm

a = 7400 km

Initial satellite positions drawn from 3D normal distribution.

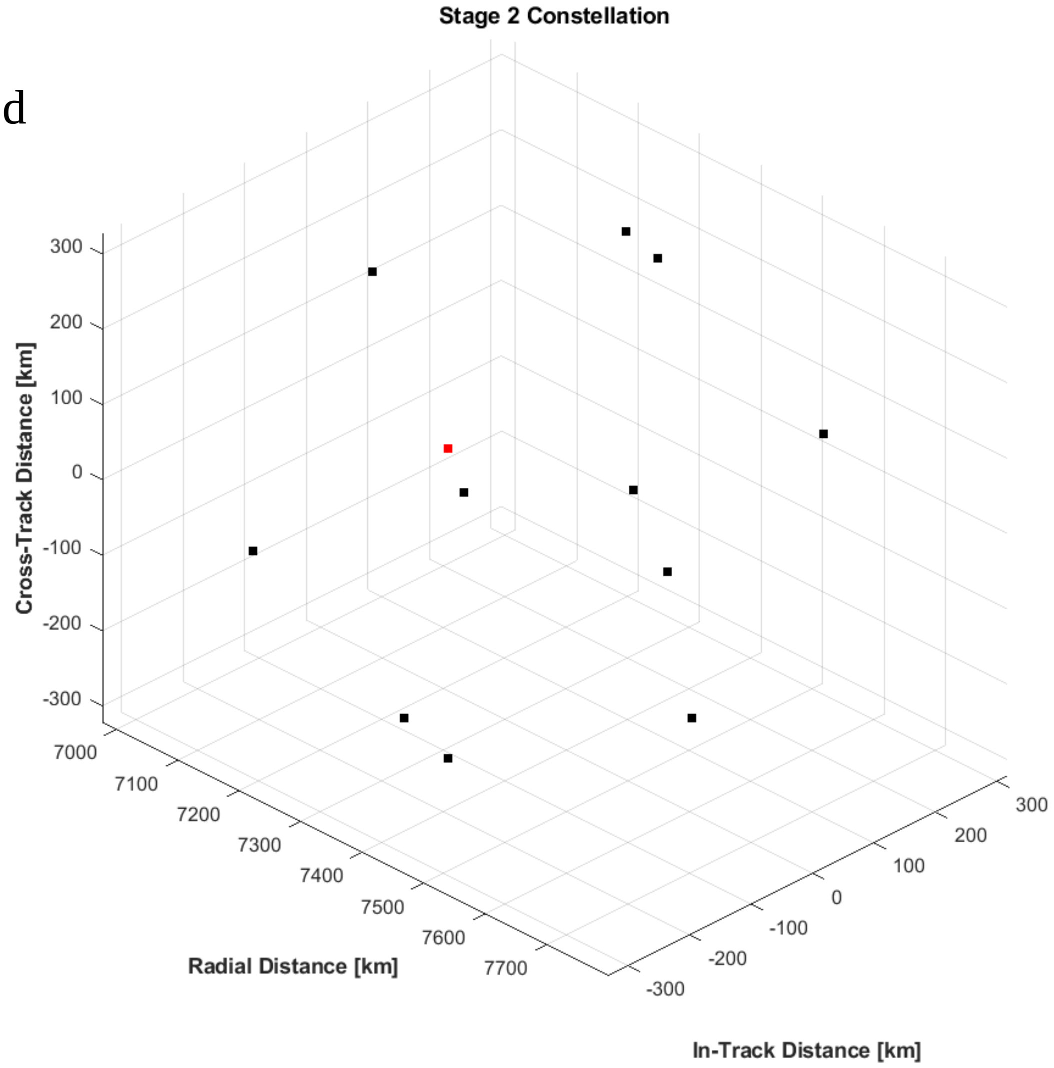
Preliminary Results

Scaled and re-centered



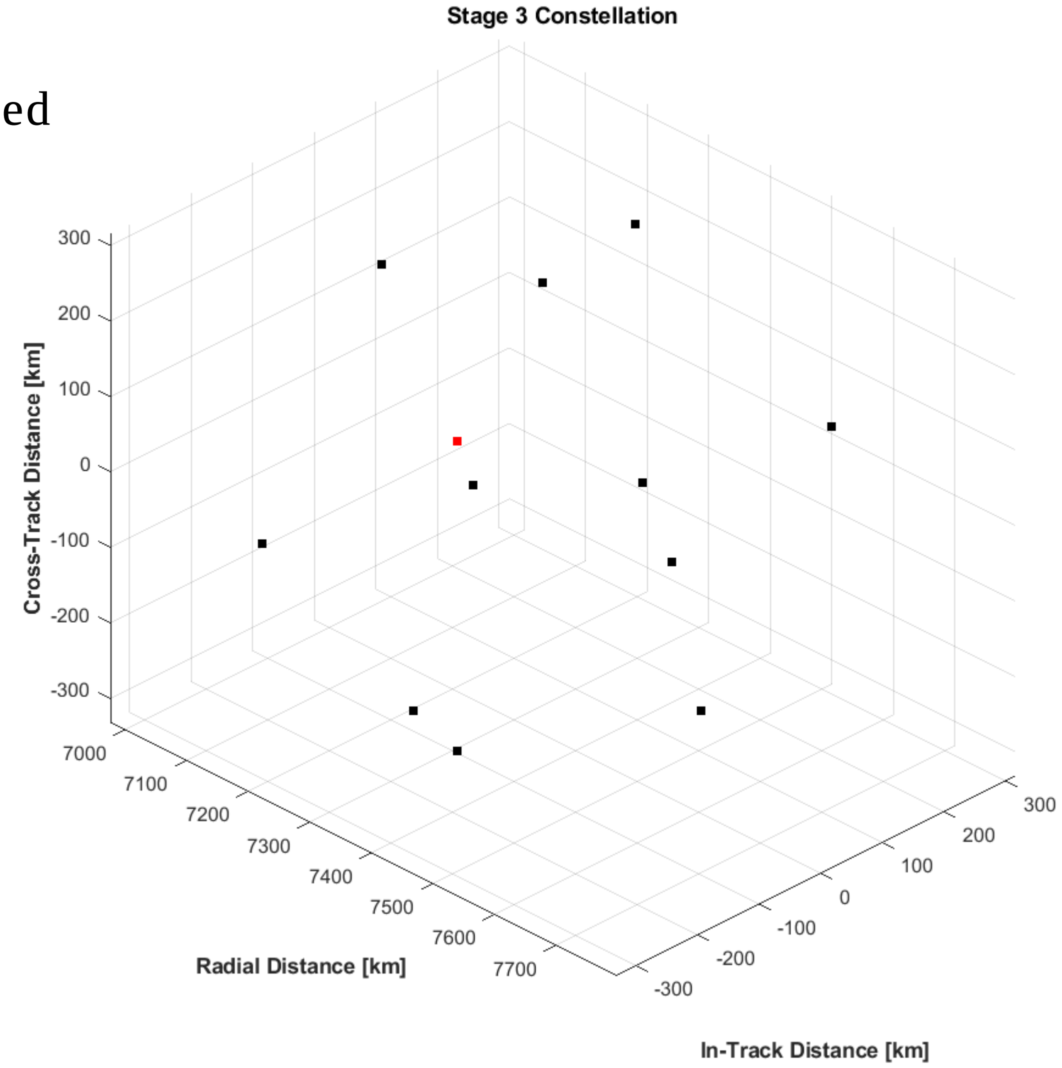
Preliminary Results

${}^{n}\mathcal{J}$ is minimized



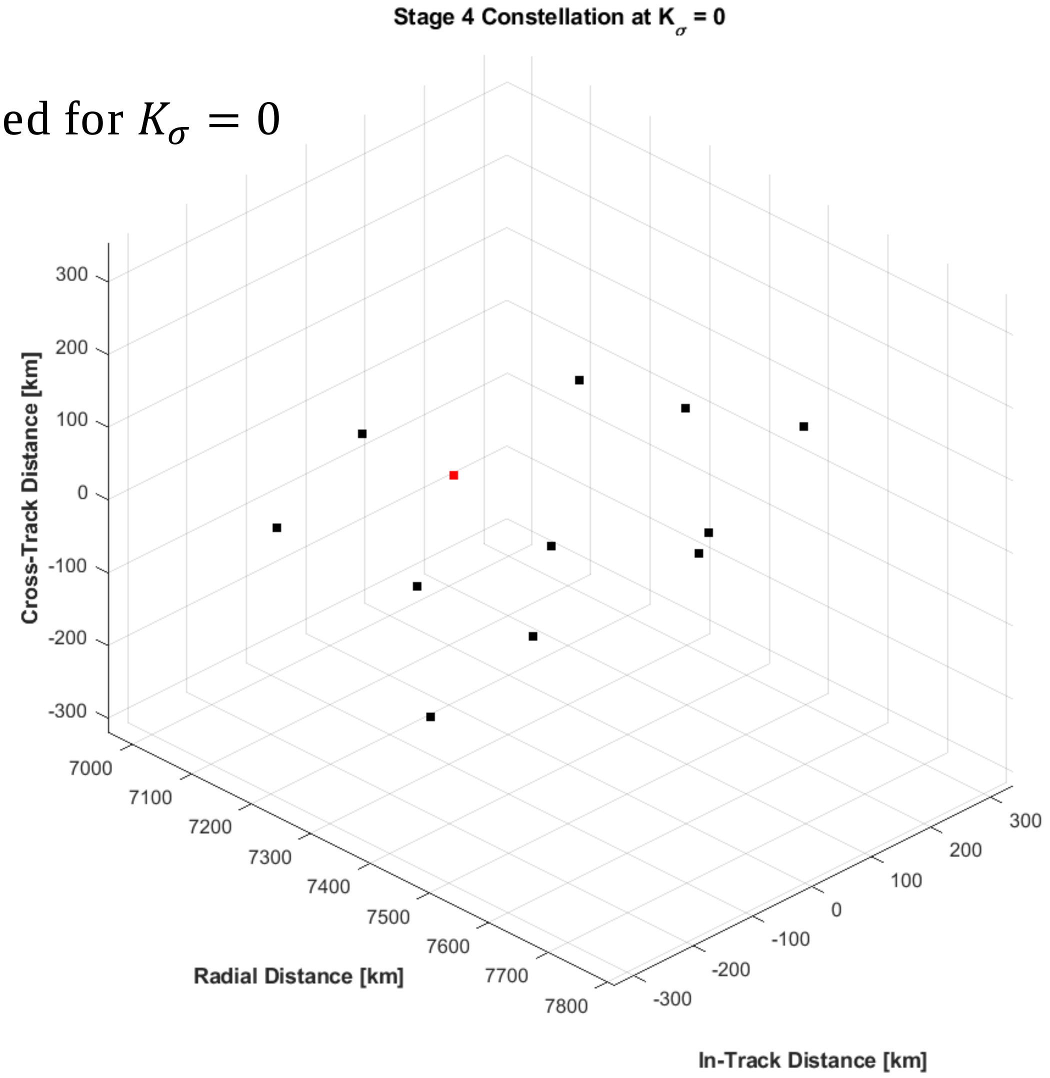
Preliminary Results

Orbits initialized



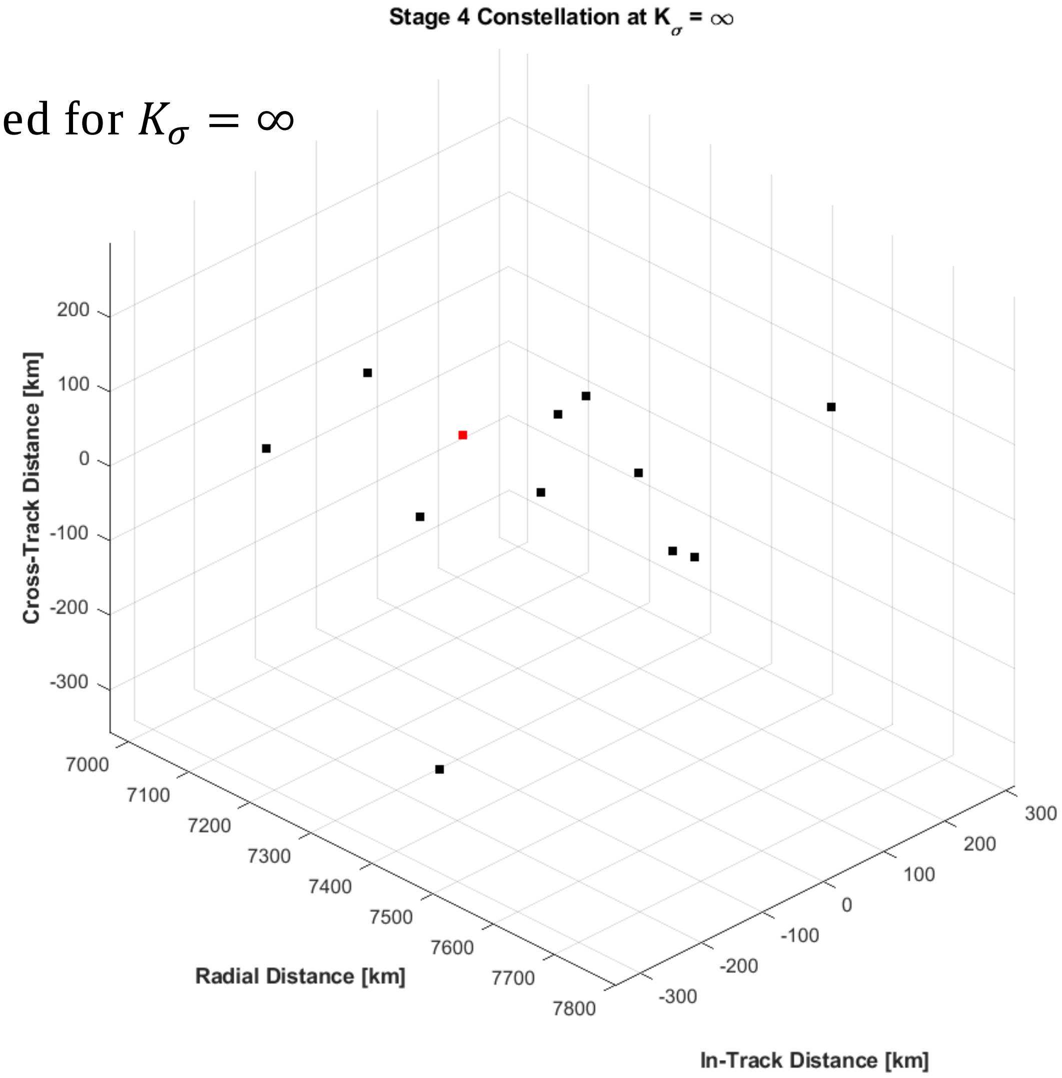
Preliminary Results

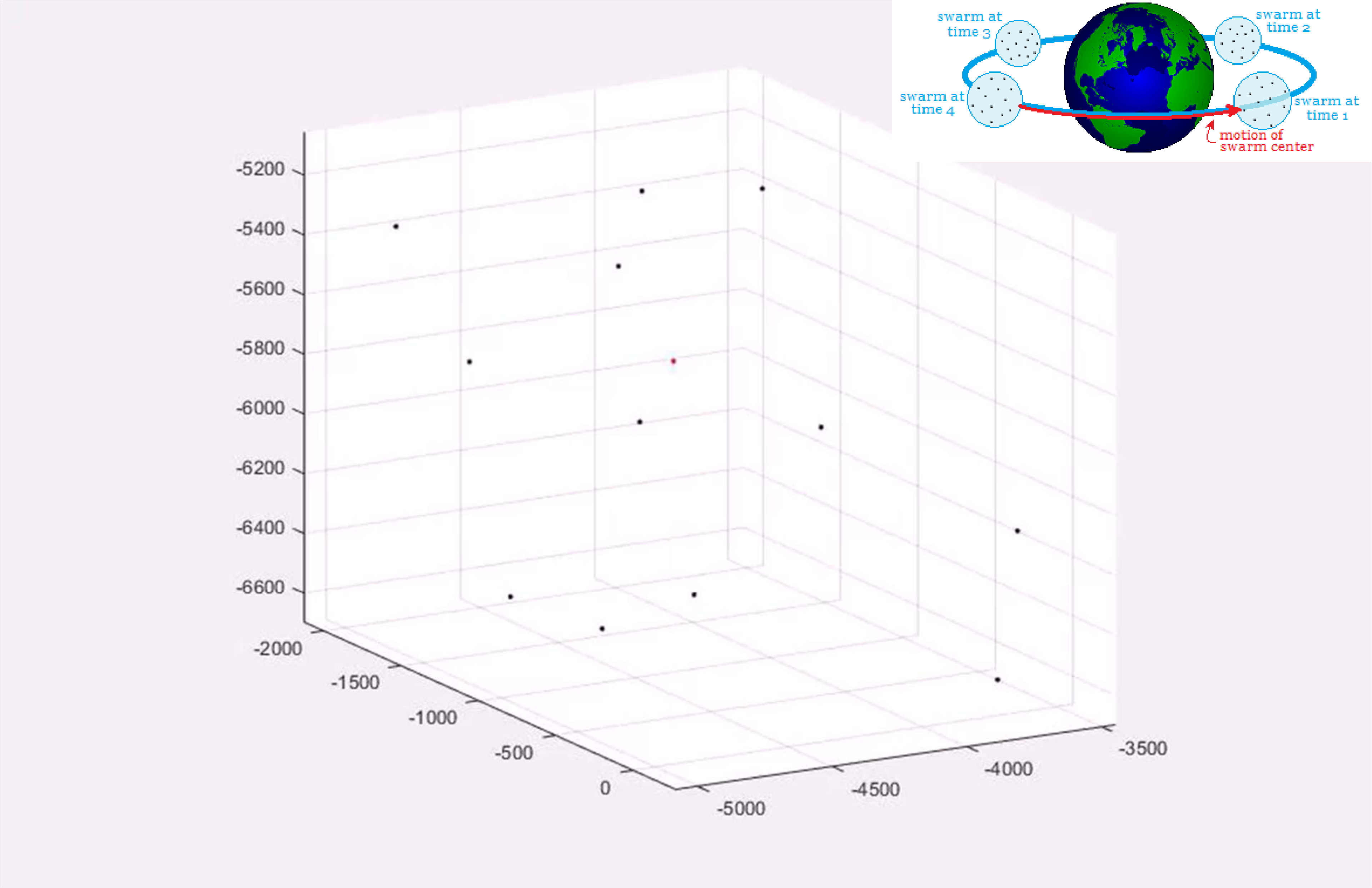
Orbits optimized for $K_\sigma = 0$



Preliminary Results

Orbits optimized for $K_\sigma = \infty$





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Next Steps

- Formulating adaptive cost functional weights
- Exploring optimization approaches
  - Implementing results from RT2
- Assessing the effects of realistic perturbations
  - Effect of Earth oblateness (J2)
  - Solar / Lunar gravity
  - Atmospheric drag / solar wind
  - Etc.
- Implementing network and shared resources
  - Optical base
  - Threat assessment
  - State estimation
  - APF-based stationkeeping