AAS 25-156

HELIO SWARM

THE NATURE OF TURBULENCE IN SPACE PLASMAS

Preliminary Node Separation Orbit Determination Analysis for the HelioSwarm Observatory

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Outline

- HelioSwarm mission overview & concept of operations
- Analysis motivation and setup
- Node tracking data gap study results

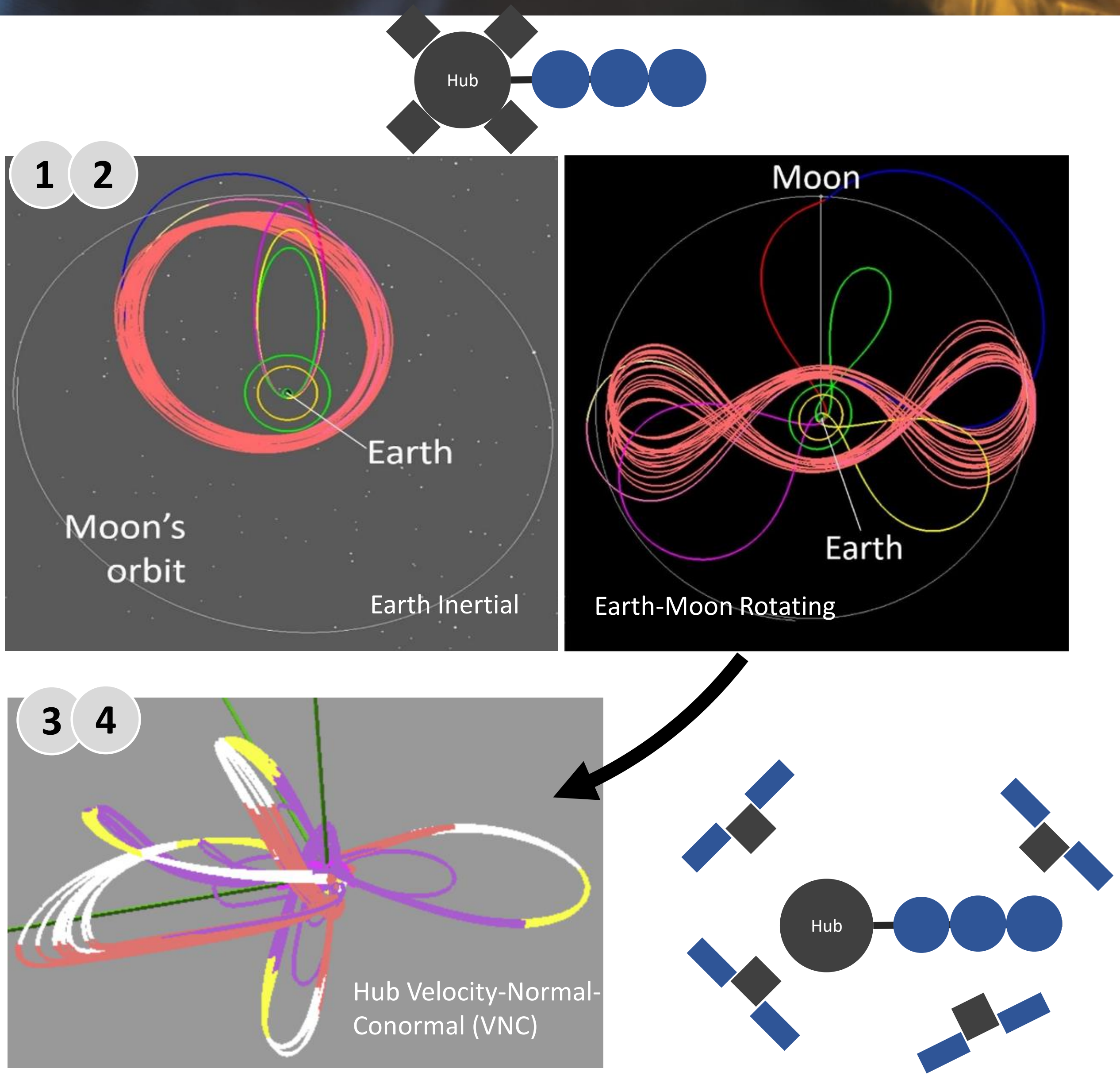
HelioSwarm Overview

HelioSwarm is a NASA Medium-class Explorer (MIDEX) mission expected to launch in 2029 that will study solar wind turbulence using a swarm of nine satellites in a highly eccentric, 2:1 lunar resonant orbit

- The Observatory (1 “Hub” spacecraft plus 8 “Node” spacecraft) launches with all Nodes integrated on the Hub
- Hub transports Nodes to science orbit and provides communications, timing, and ranging for the Observatory
- Hub spacecraft is based on a propulsive ESPA
- Node spacecraft is based on a commercial small satellite bus with identical instrument suites including a faraday cup, fluxgate magnetometer, and scan coil magnetometer
- Hub carries an identical instrument suite to the Nodes with the addition of an ion electrostatic analyzer to provide context to the Node measurements

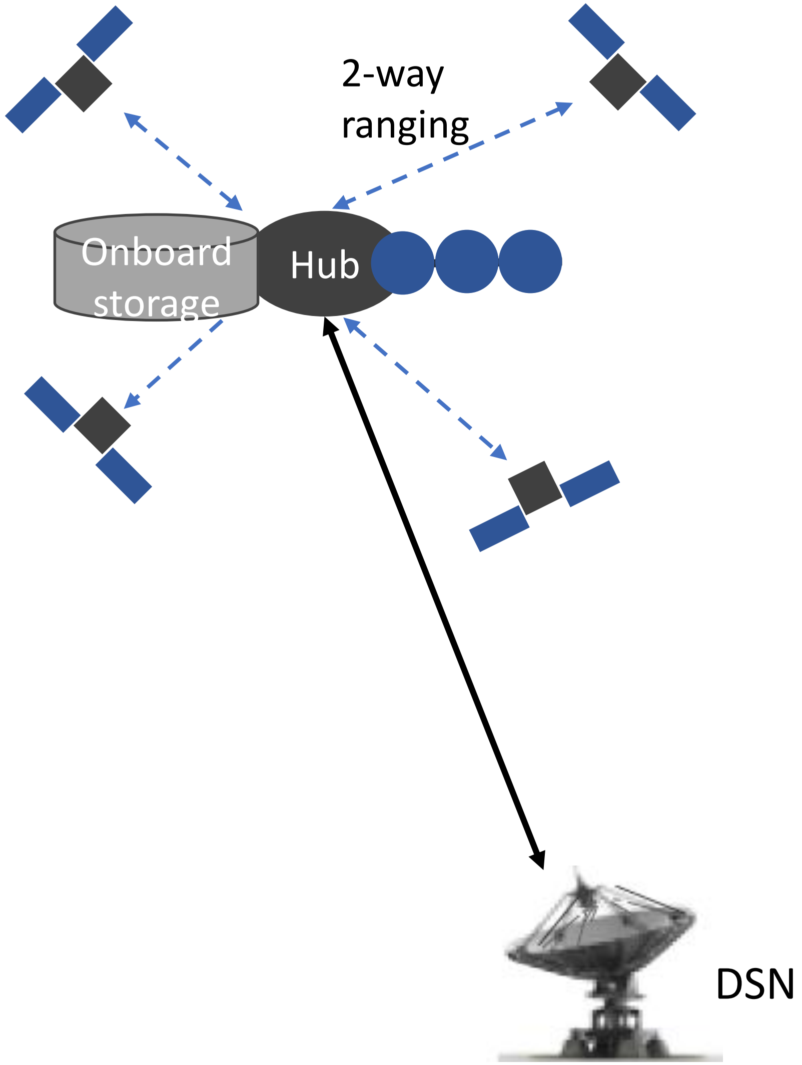
Concept of operations:

1. Hub launches to first of 3.5 phasing loops to a lunar gravity assist
2. Hub maneuvers to 2:1 lunar resonant HEO science orbit (orbital period ~13.7 days)
3. Once established in science orbit, Nodes separate from Hub and independently maneuver to nearly-repeating relative trajectories (“loops”) – Node Commissioning Phase
4. Nodes perform periodic maneuvers to maintain relative trajectories



Inter-Satellite Relative Ranging

- Only the Hub spacecraft will communicate with the ground
  - Analyses to date have assumed the use of NASA's Deep Space Network (DSN) for this purpose
- Each Node will only be capable of communicating with the Hub
  - There are no Node-to-Node or Node-to-ground communication links
- Once the Nodes separate from the Hub, the Hub will perform two-way inter-satellite ranging with each Node which is used to establish and maintain their state estimates
  - The Hub will be restricted to performing inter-satellite ranging with one Node at a time
- During the DSN tracking supports, all stored inter-satellite ranging measurements from all eight Nodes will be downlinked to the ground



Analysis Motivation

Is there an upper limit (“not to exceed” value) to the tracking data gap?

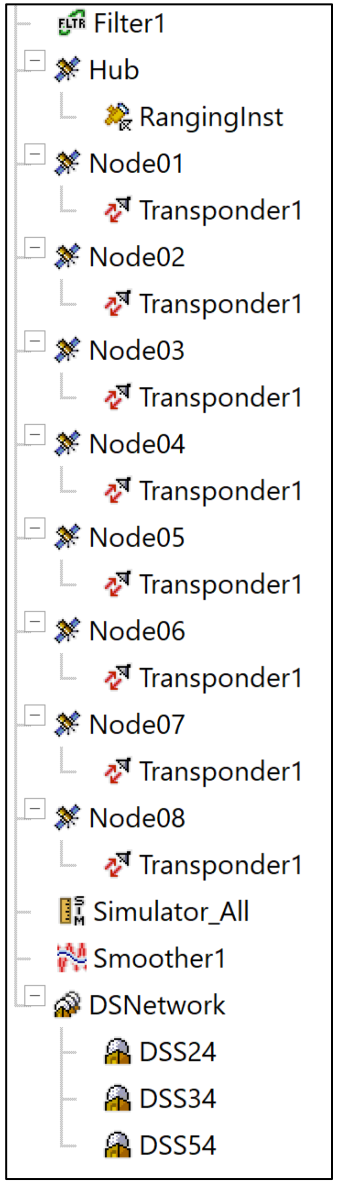
- Since each Node’s orbit uncertainty continues to grow in the absence of tracking data, there may exist an upper limit to this gap that, if exceeded, could preclude establishing adequate state knowledge to perform the planned sequence of Node maneuvers
- A lower bound of 30 minutes has already been defined to allow time for Node initialization

The “**tracking data gap**” is the time between a Node’s separation from the Hub and the first inter-satellite relative ranging activity.

Analysis Tools

This analysis used Ansys software:

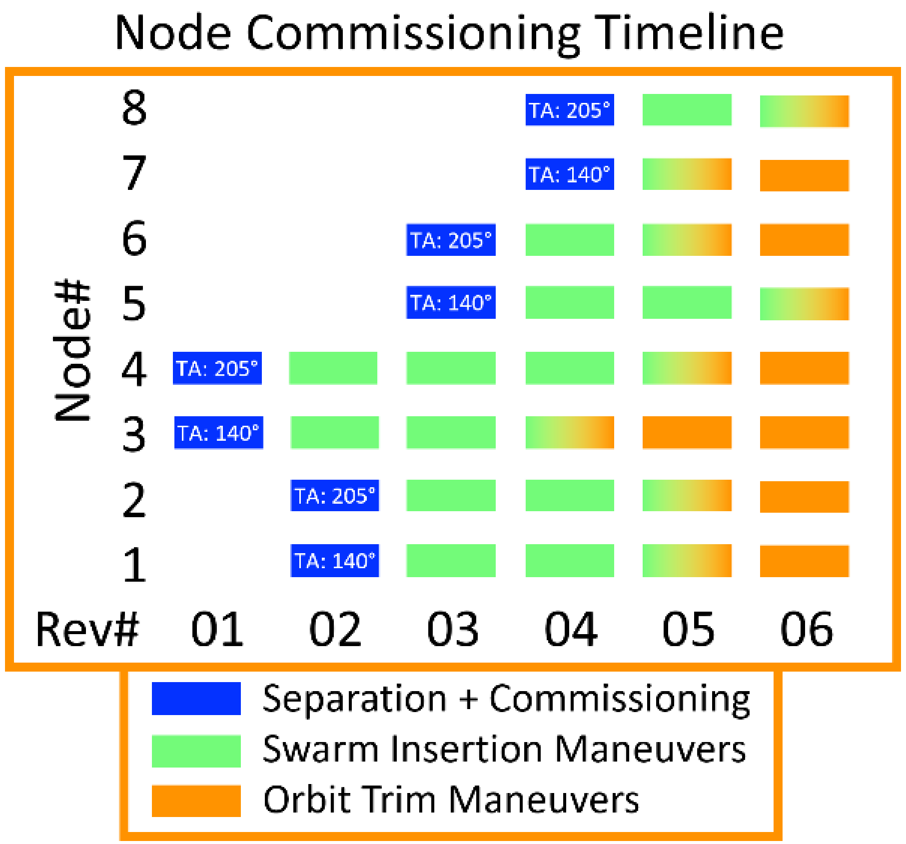
- **Orbit Determination Tool Kit** (ODTK) was used to perform the OD analysis based on prior successful application for navigation simulation, analyses, and operations with missions in a similar orbit regime as HelioSwarm, such as NASA's IBEX (3:1 lunar resonant orbit), LADEE (cislunar phasing loops), and TESS (2:1 lunar resonant orbit).
- **Systems Tool Kit** (STK) was used by the flight dynamics team at NASA Ames Research Center to develop the Swarm Reference Design (SRD) on which the OD analysis was based



ODTK Scenario Setup

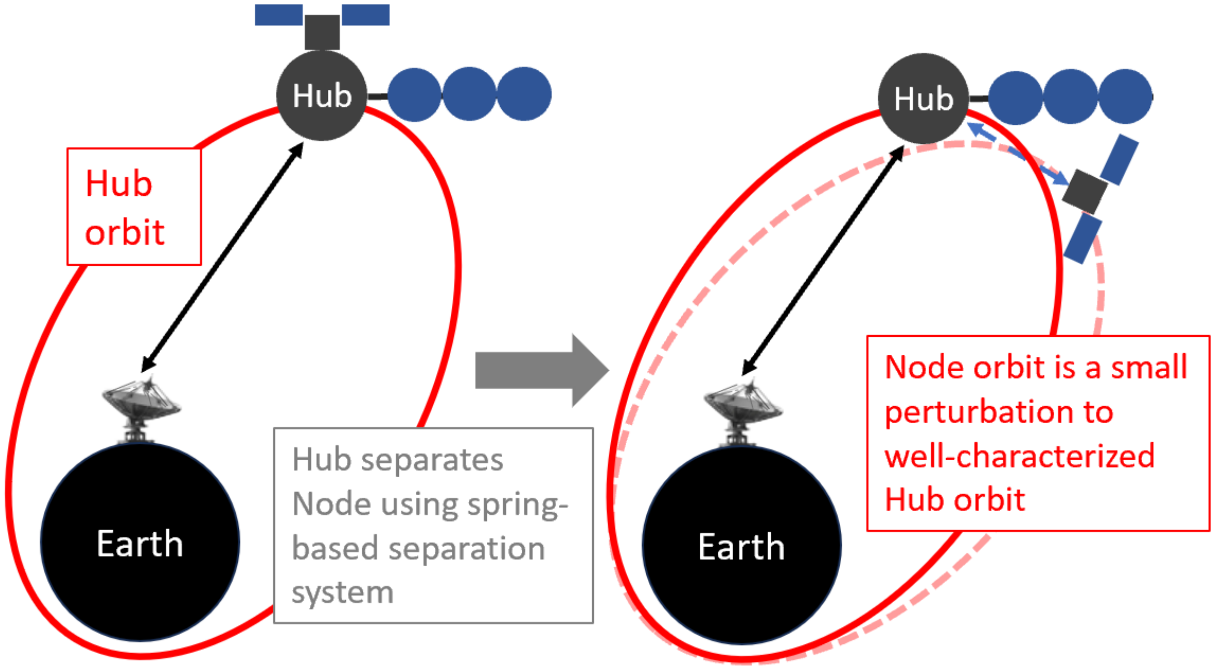
Node Commissioning Timeline

- ➢The time frame of this analysis covers a period of ~2 months over which all eight Nodes are separated from the Hub
- ➢Assumed ConOps is that the Nodes will be separated from the Hub individually, with two separations occurring each orbit revolution
    - ➢The time between Node separations will be, at minimum, around half an orbit (~7 days)



Node Separation Modeling in ODTK

- The ODTK Attachments functionality was heavily leveraged for this purpose
  - Using the attachments feature, the Hub satellite object is designated as a "parent" and the eight Node spacecraft are designated as the Hub's "children"
- The benefit of utilizing the ODTK Attachments feature is that it prevents the Node separation events from being treated like an initial orbit determination problem that might typically be seen post-launch when there tends to be significant uncertainty in the orbit estimate



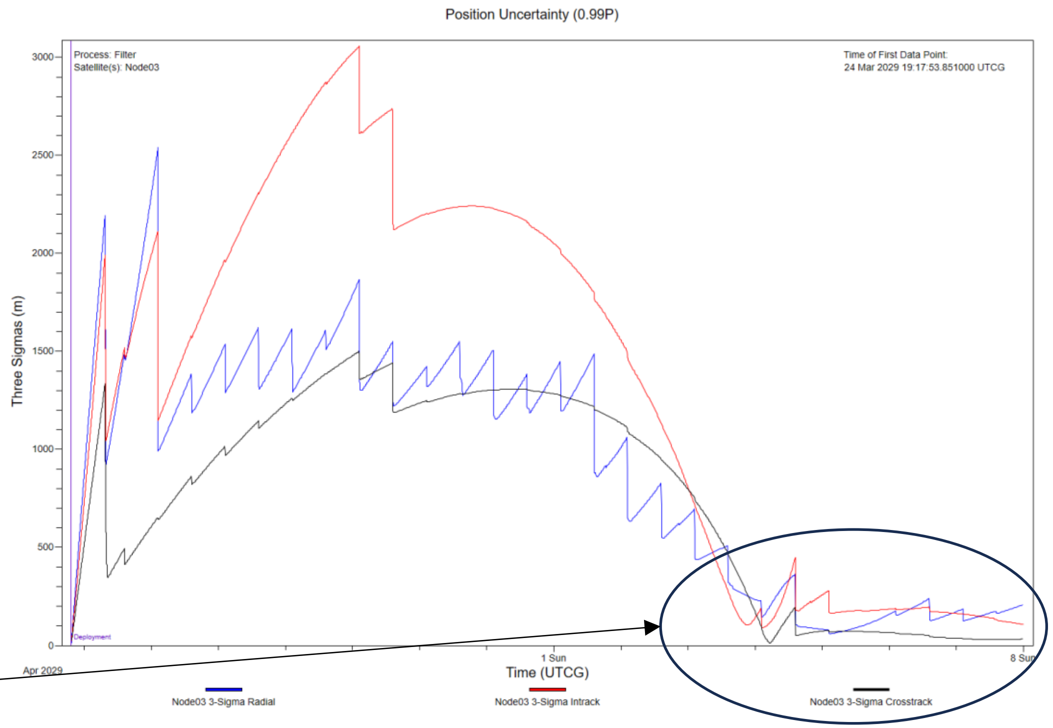
As long as the Node separations are appropriately modeled, each Node's post-separation orbit should remain relatively well-known, both in an absolute sense as well as relative to the Hub

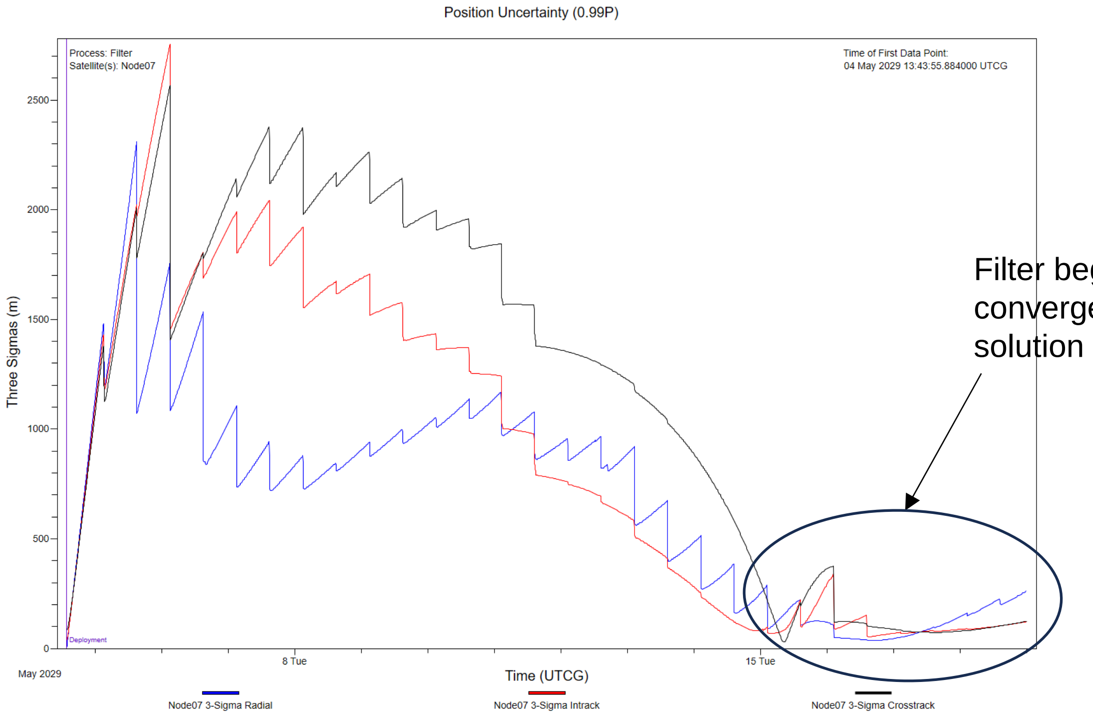
Node Tracking Data Gap Study Setup

- Tracking schedules were developed for the Hub and each of the eight Node spacecraft
  - Tracking schedule varied slightly by Node (~2-4 hours of relative ranging per Node per day)
- The ODTK simulator and filter were run to create and process simulated tracking measurements for all nine spacecraft simultaneously
  - Used ODTK's "Space-Based (SB) Range" measurement type
  - The state space for the simulator and filter are expanded each time there is a Node separation
- Multiple different Node tracking data gaps were assessed in this analysis:
  - 30-minute gap
  - 6-hour gap
  - 12-hour gap
- Only the 12-hour gap results are presented since that ultimately became the upper limit out of this study

Node Tracking Data Gap Study Results

- The RIC position uncertainty plots look as expected and demonstrate that the filter begins to converge on a solution after ~1 orbit
- The characteristic “rooster tail” pattern commonly seen in these highly eccentric lunar resonant orbits over the first half orbit or so prior to filter convergence is also seen





Filter begins to converge on a solution

Plots show 3-sigma Radial, In-track, Cross-track (RIC) absolute position uncertainty graphs for a subset of Nodes

Node Tracking Data Gap Study Takeaways

- The 12-hour gap was selected as the “not to exceed” value based on this study for several reasons:
  1. The preliminary results based on the 12-hour gap were acceptable
  2. The Mission Operations Systems (MOS) team expects the first relative ranging activity to occur within 12 hours post Node separation, assuming nominal operations
  3. Defining a more precise tracking gap limit offers limited utility with significantly more computational effort
- The 6-hour relative range tracking gap results were equally as acceptable as the 12-hour gap case
- The half-hour tracking gap results were generally worse
  - It is suspected that this poorer behavior is related to the very small Hub/Node range soon after separation since the Node has barely drifted away after 30 minutes
  - There may be a degeneracy in orbit solutions that can be fit to those range values

Summary and Conclusions

The analysis in the paper offers a preliminary answer to our initial question.

Is there an upper limit to the tracking data gap after a Node is separated from the Hub?

- The preferred timing from an OD perspective for beginning relative ranging between the Hub and each Node is between 6 and 12 hours after separation from the Hub, with the gap not to exceed 12 hours
- This was determined by analyzing various tracking gap durations and assessing the effect of each gap on several OD-related outputs over each Node's first orbit after separation from the Hub

This work is considered preliminary since it is assumed that the swarm design will evolve over the coming years.

Selected References

(Full reference list is included in the paper)

- Carrico, J., Loucks, M., Policastri, L., “Prelaunch Orbit Determination Design and Analysis for the IBEX Mission,” Paper No. AAS 09-133, AAS/AIAA Spaceflight Mechanics Meeting, Savannah, Georgia, February 2009.

- Woodburn, J., Policastri, L., Owens, B., “Generation of Simulated Tracking Data for LADEE Operational Readiness Testing,” Paper No. AAS 15-381, AAS/AIAA Space Flight Mechanics Meeting, Williamsburg, VA, Jan. 11 – 15, 2015.

- Policastri L, Carrico J, Craychee T, Johnson T, Woodburn J, Orbit Determination Operations for the Interstellar Boundary Explorer, Proceedings of the 19th AAS/AIAA Spaceflight Mechanics Meeting, Savannah, GA, 8-12 Feb 2009.

- Policastri L, Carrico JP Jr, Nickel C, Kam A, Lebois R, et al., Orbit Determination and Acquisition for LADEE and LLCD Mission Operations, Proceedings of the 25th AAS/AIAA Spaceflight Mechanics Meeting, Williamsburg, VA, 11-15 Jan 2015.

Backup Slides

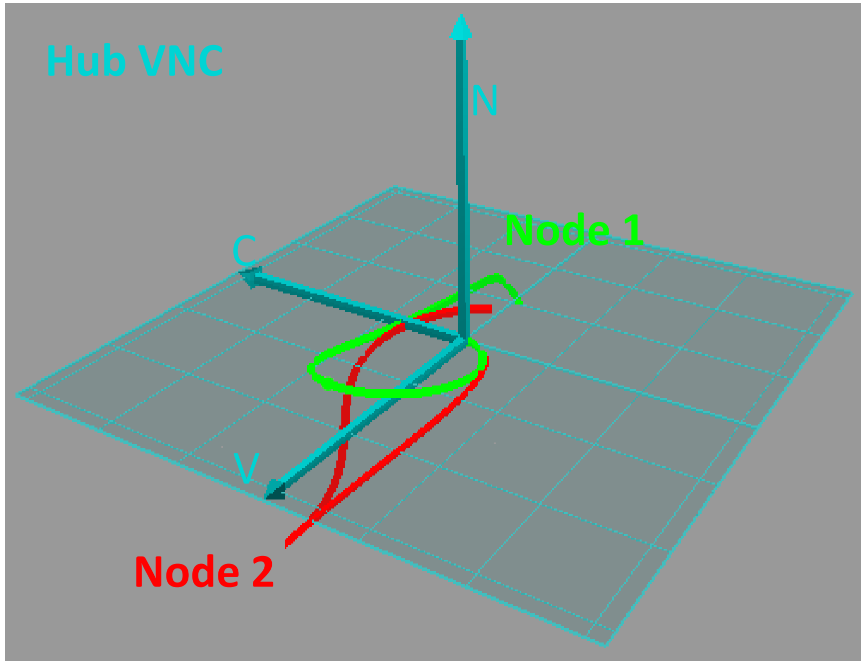
Node Separation Epochs

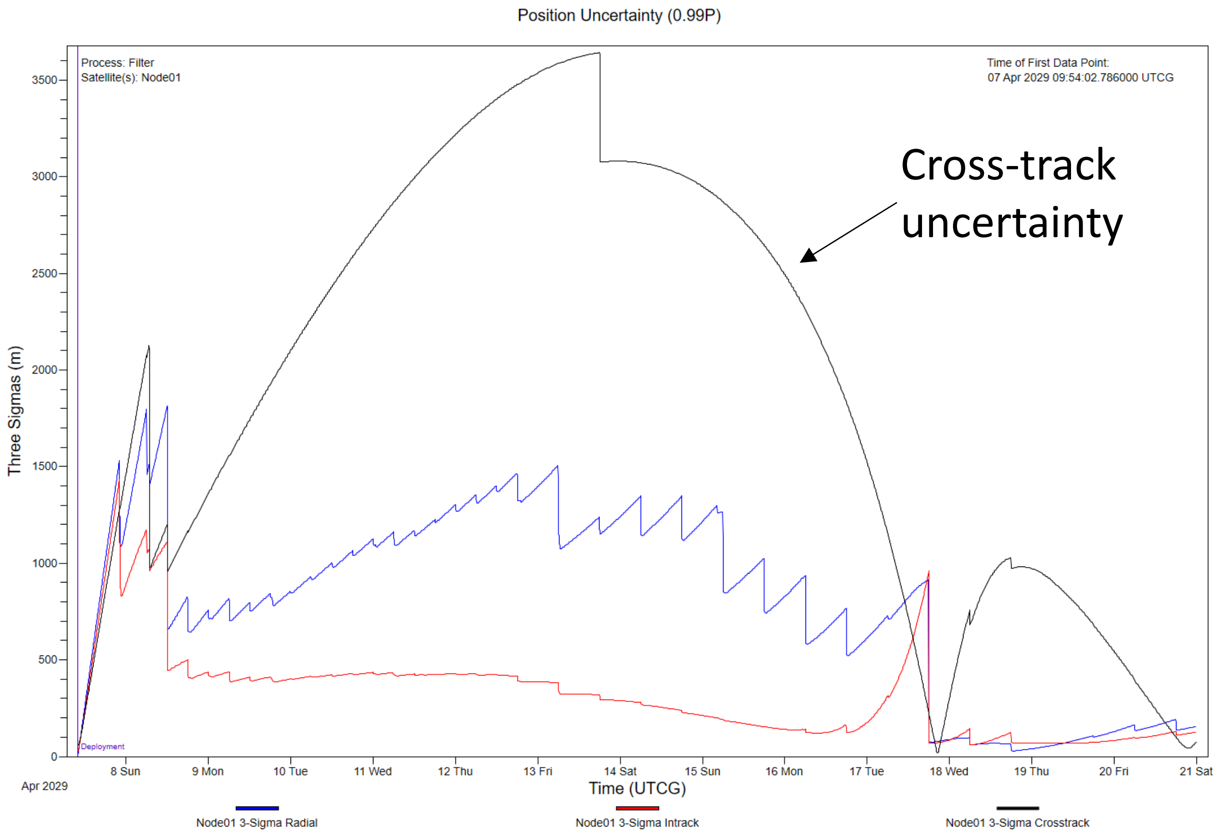
Node	Separation Epoch (UTCG)
Node 3	24 Mar 2029 19:17:53.851
Node 4	31 Mar 2029 08:12:55.572
Node 1	7 Apr 2029 09:54:02.786
Node 2	14 Apr 2029 05:21:46.254
Node 5	20 Apr 2029 20:59:41.713
Node 6	27 Apr 2029 21:07:38.960
Node 7	4 May 2029 13:43:55.884
Node 8	11 May 2029 21:01:17.009

Node separation epochs
taken from the STK SRD

Node Tracking Data Gap Study Results

Node 1 and Node 2 show interesting cross-track behavior, likely attributed to their large conormal component when separating from the Hub.

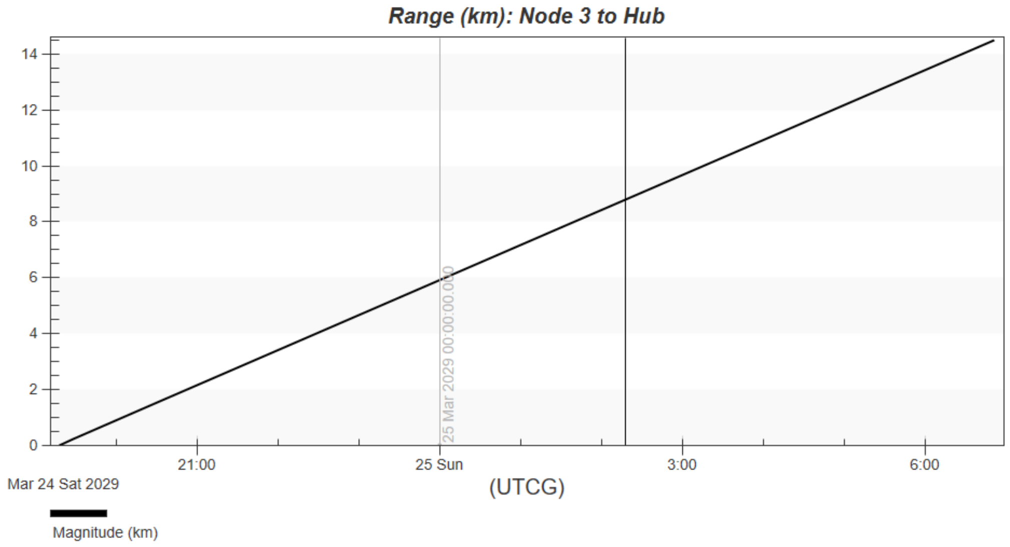




Their separation orientation results in primarily in-plane motion and, therefore, very little cross-track (orbit normal direction) observability.

Node Tracking Data Gap Study Results

- A 6-hour relative range tracking gap run was also performed, and the results were equally as acceptable as the 12-hour gap case
- Additionally, a half-hour gap run was also performed because 30 minutes is considered the quickest potential turnaround (i.e. shortest gap) for relative ranging to begin post-separation
  - The results for the half-hour gap case are generally worse for most Nodes (compared to the 6- or 12-hour gaps)



- 30 minutes after separation, the range between the Hub and a given Node is approximately half a kilometer
- The range increases to approximately 7.5 km after 6 hours and 15 km after 12 hours

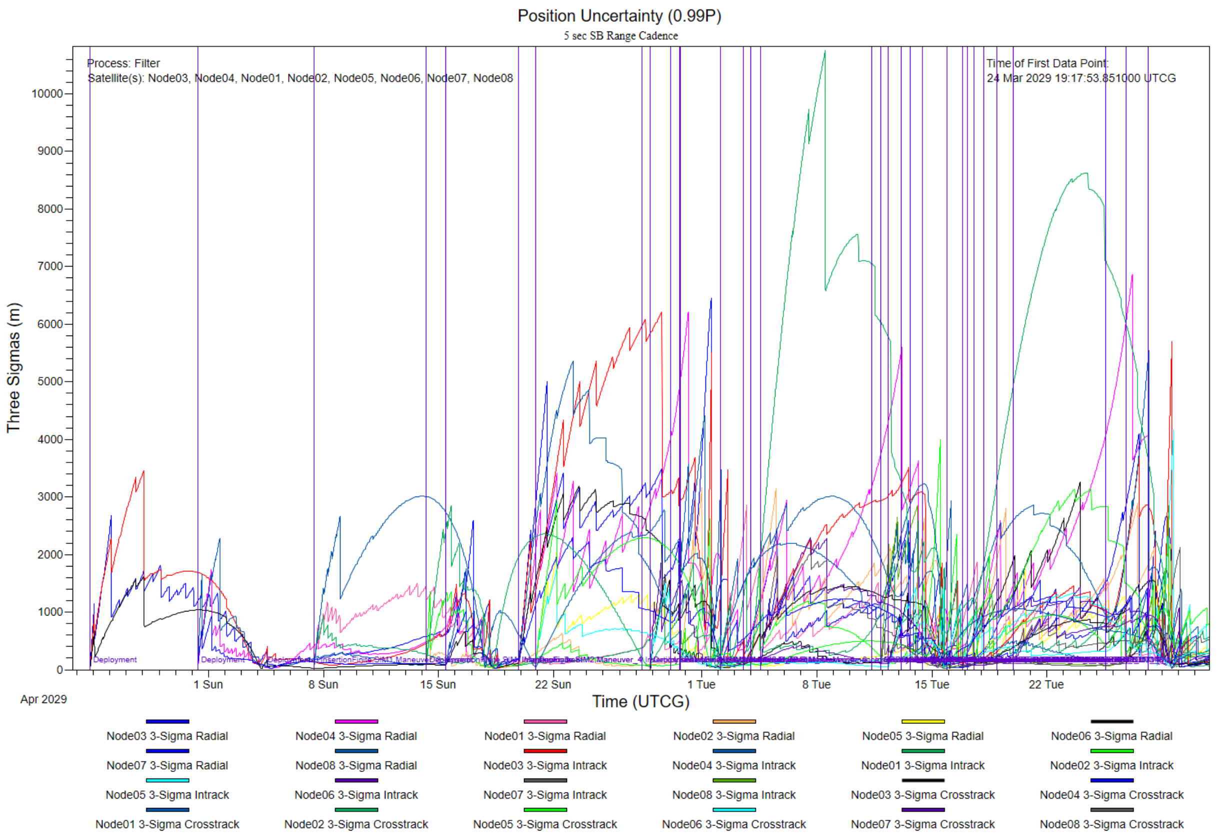
Relative Range Density Study

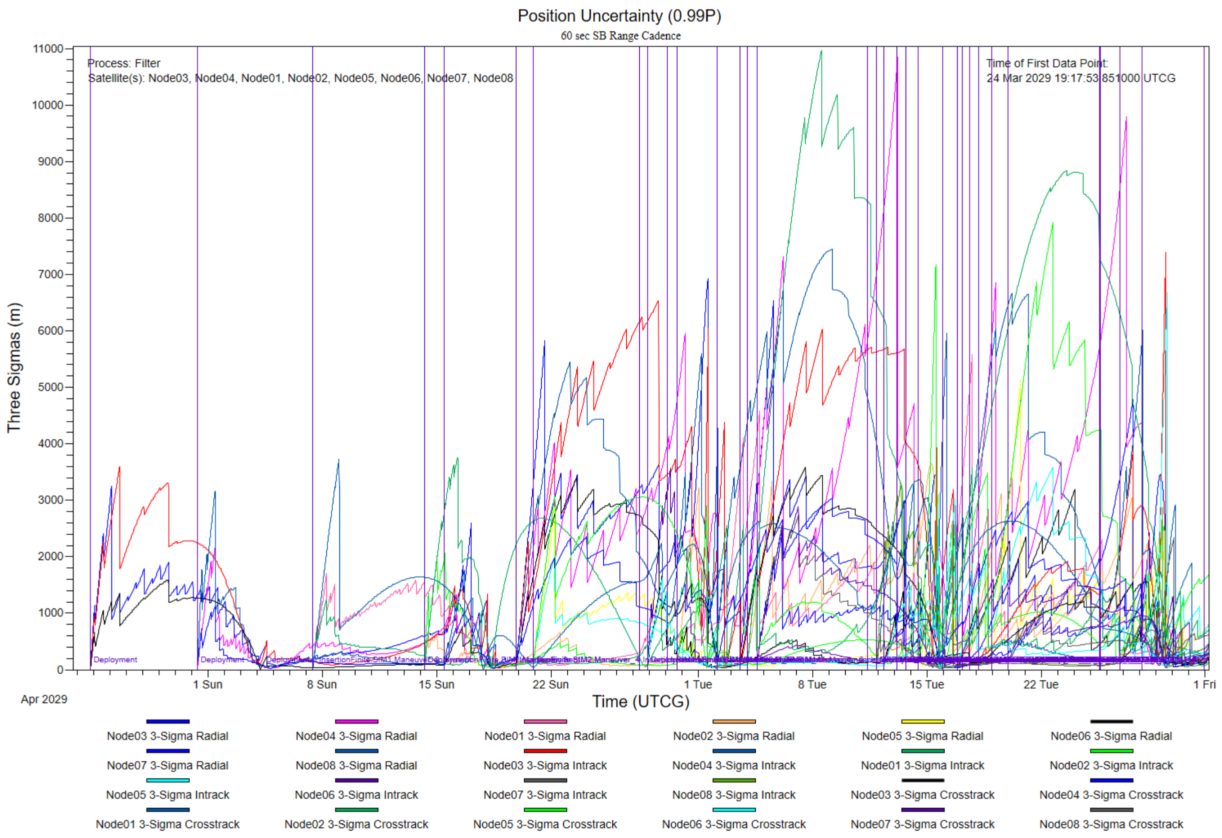
- An additional analysis was performed to assess the effect of decreasing the measurement density of Hub-to-Node relative range measurements, compared to the baseline measurement cadence of one measurement every 5 seconds as used in the analysis described above
- Two new OD runs were performed, in which the SB Range measurement cadence was decreased twice: first, to one measurement every 30 seconds and then to one measurement every 60 seconds
- Rather than re-simulating measurements, the ODTK filter's Custom Data Editing feature was used to manipulate the existing Node tracking data from the previous analysis by thinning the measurements
  - Filter runs were performed for the two cases by varying the Enabled flags as shown in the figure below

Filter.CustomDataEditing.Schedule

Enabled	Action	PrimaryObjects	SelectedObject	Trackers	SelectedTrackingStrand	MeasType	MeasTypes	ThinningTime	Intervals	Description
false	Thin	All Satellites		All Trackers	click to edit	Specific	click to edit	0.5 min	click to display	30s SBR density
true	Thin	All Satellites		All Trackers	click to edit	Specific	click to edit	1 min	click to display	60s SBR density

Relative Range Density Study

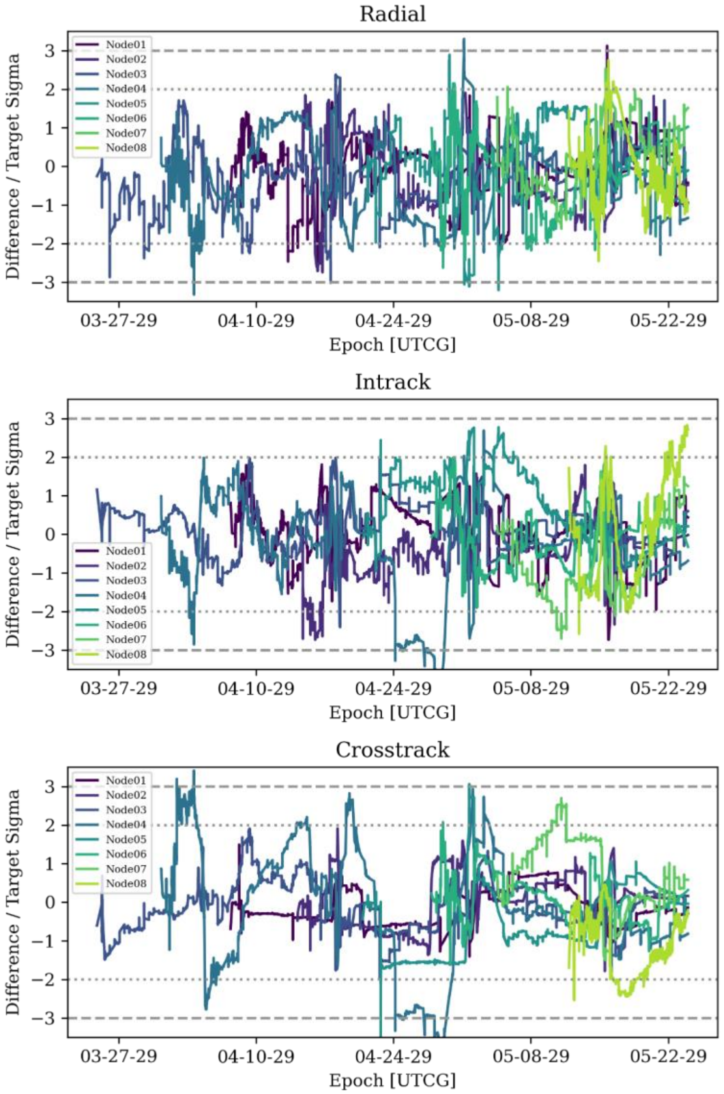




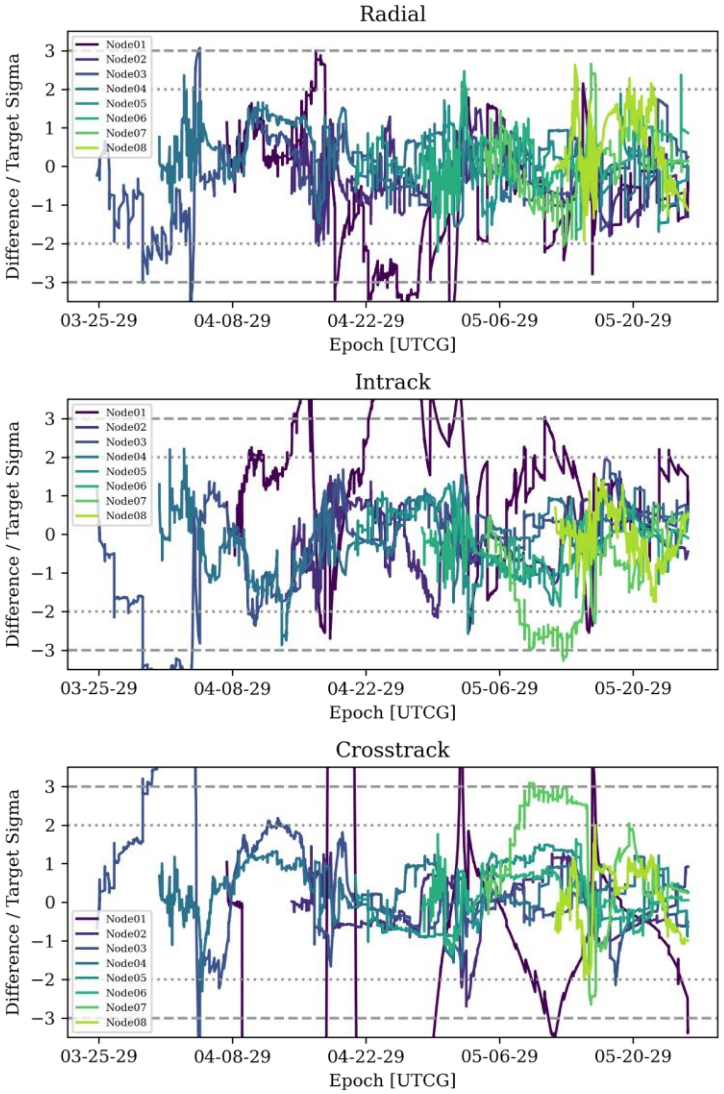
Nodes’ 3-sigma RIC position uncertainty for 60 s (r) SB range measurement cadence is acceptably larger than the 5 s (l) baseline cadence

Relative Range Density Study

5 sec Measurement Cadence



60 sec Measurement Cadence



- Position difference (truth vs. estimated) plots for 5 s measurement cadence (l) and 60 s cadence (r)
- The position difference plots are broken down into RIC components, and all Nodes are represented on each plot
- These plots help assess how well the filter is estimating/solving for the truth orbit; times during which a colored line falls outside of the 2-sigma or 3-sigma may indicate that the filter has converged on an incorrect orbit solution
- Based on the 30 s (not shown) and 60 s cadence results, there may be a benefit to keeping the baseline 5-second SB range measurement cadence during the Node Commissioning Phase