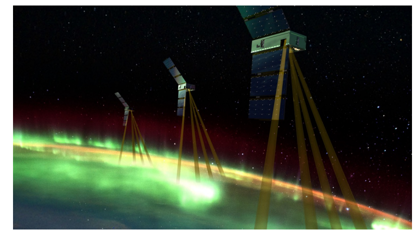
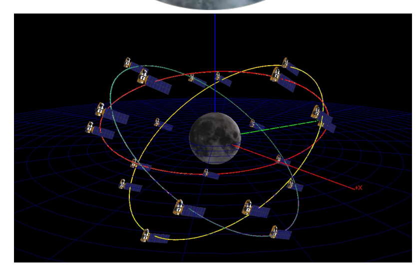
The Distributed Spacecraft Autonomy (DSA)

Caleb Adams, Project Manager | Jeremy Frank, Deputy Project Manager

Talk Roadmap

- Distributed Space Missions
- The Distributed Spacecraft Autonomy Project
- DSA-Starling
- DSA-LPNT
- Lessons Learned
- Bibliography





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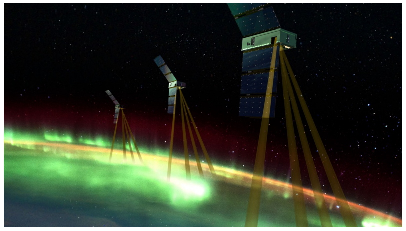
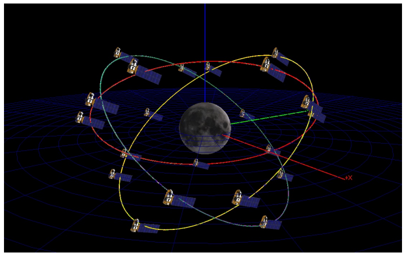
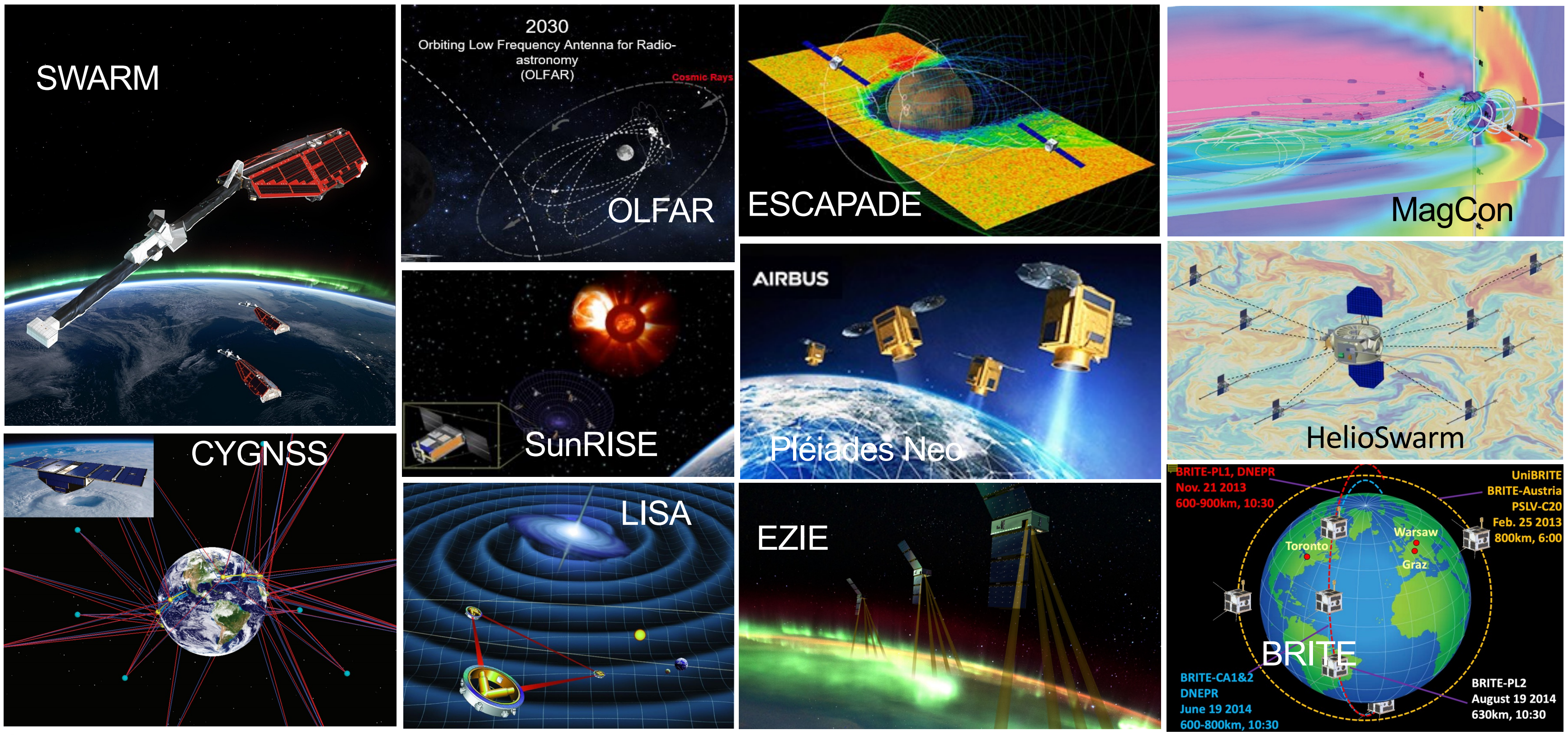




Distributed Space Missions

- **What are Distributed Space Missions?**
  - Distributed Space Missions (DSMs) are systems that utilize multiple spacecraft to accomplish mission objectives.
  - DSMs can involve heterogeneous spacecraft, consisting of different types, or homogeneous spacecraft, all the same type.
- **Why Distributed Space Missions?**
  - These missions have become more prevalent due to the decreased launch costs and development costs per vehicle.
  - Multiple spacecraft can increase spatiotemporal coverage of space missions. This is invaluable for many science needs, both on Earth and in deep space.
  - DSMs with space-to-space communications enable decreased data delivery latency (elapsed time from detecting event to delivery to ground). This is invaluable for disaster response, space weather, and other applications.

Distributed Space Missions



Autonomous Distributed Space Missions

- **Little to no autonomy in any of the previously described DSMs.**
- **Advantages of Distributed Autonomous Space Missions**
  - Enhanced adaptability and flexibility: Enables spacecraft to make autonomous and localized decisions based on local perception and information.
  - Efficient task allocation and coordination: Spacecraft can autonomously allocate tasks among themselves based on their capabilities, proximity, and availability.
  - Increased robustness to communication delays and failures: Spacecraft can continue operating even in scenarios where communication between nodes is intermittent or disrupted.

Autonomous Distributed Space Missions

- **Technical Challenges of Autonomous Distributed Space Missions**
  - Knowledge – How does each spacecraft know its own positions and movements, and those of the spacecraft in the DSM?
  - Communications – How do spacecraft get information to and from ground and each other?
  - Control – How do the spacecraft maintain the configuration the DSM?
  - Operations – How do we inform the DSM of the desired configuration? How does the DSM achieve the desired configuration on its own?
  - Access – How do we get the DSM into space and deploy it?
- **Enter DSA!**

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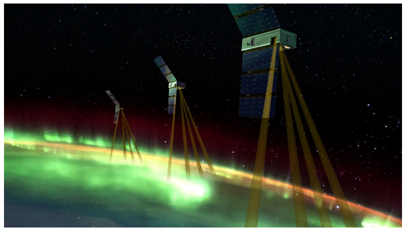
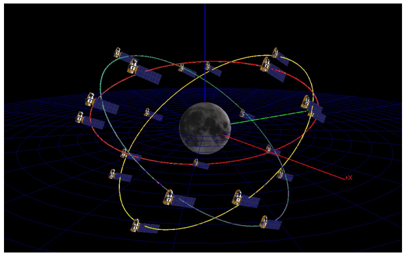
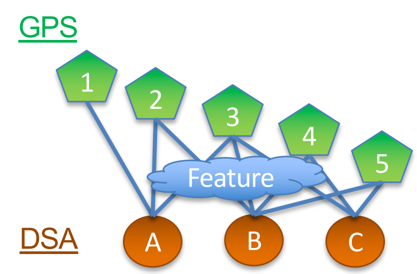


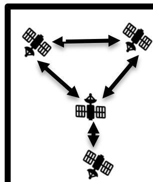


Distributed Spacecraft Autonomy

- **NASA's Distributed Spacecraft Autonomy (DSA) Project focuses on the following technical areas:**
  - Enhanced adaptability and flexibility: Distributed decision-making enables spacecraft to make autonomous and localized decisions based on local perception and information.
  - Efficient task allocation and coordination: By distributing decision-making, spacecraft can autonomously allocate tasks among themselves based on their capabilities, proximity, and availability.
  - Ad hoc Network Communications: communication infrastructure that is scalable, robust, and automatically self-configuring.
  - Human-Swarm Interaction: ground control software that enables the ability to command and interact with a DSM as a collective, rather than managing individual spacecraft.



$$\max \sum_{s,g} \alpha\, r^{e}_{s,g} o_{sg} + (1-\alpha)\, r^{x}_{s,g}\, o_{sg}$$
$$+ \sum_{s,g} \alpha\, g^{e}\, c_g + (1-\alpha)\, g^{x}\, c_g$$
$$s.t. \forall s \sum_{s} o_{sg} < s_c$$
$$\forall g \sum_{g} o_{sg} > n$$



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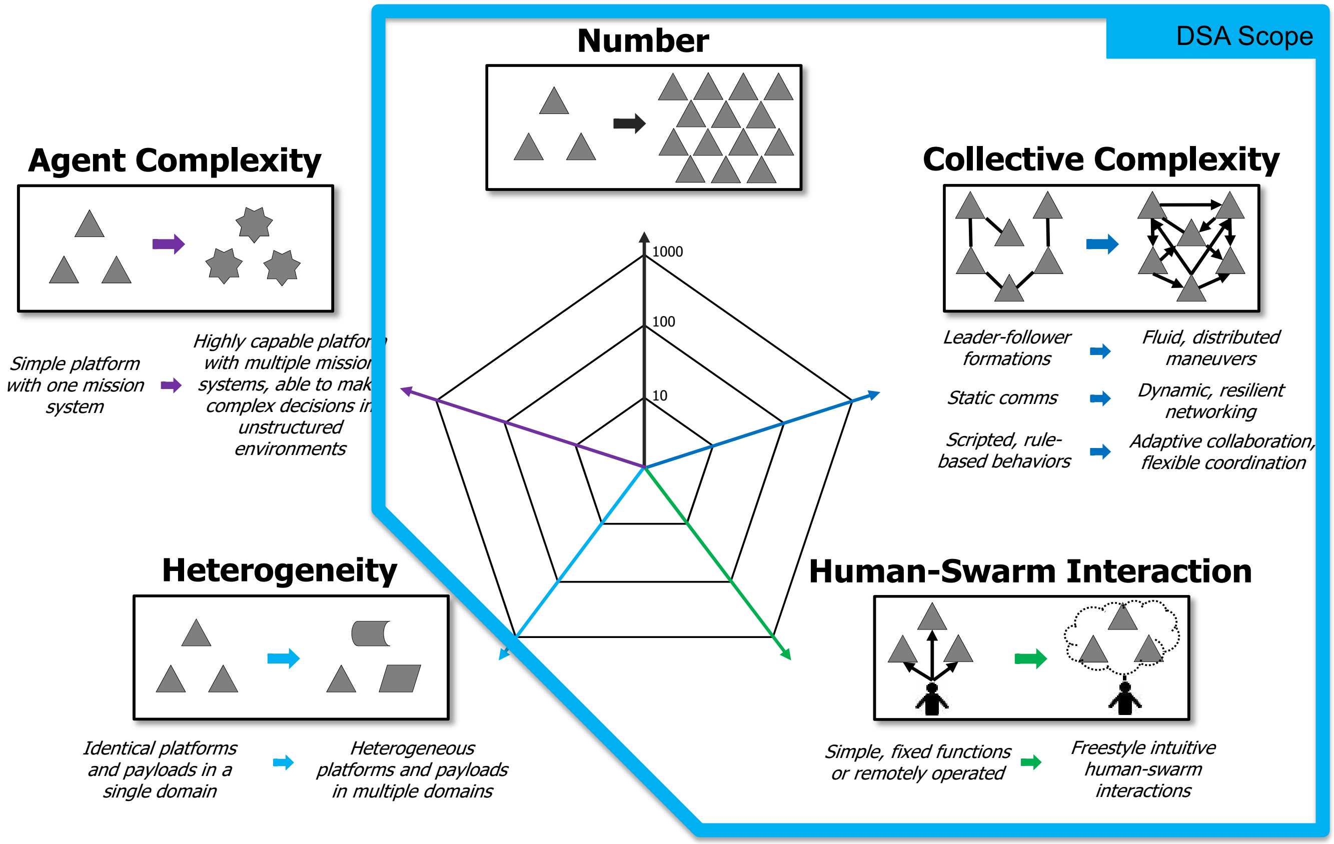
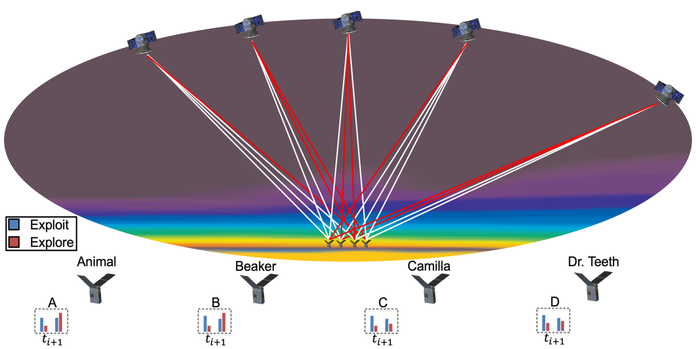
Example Swarm Topology

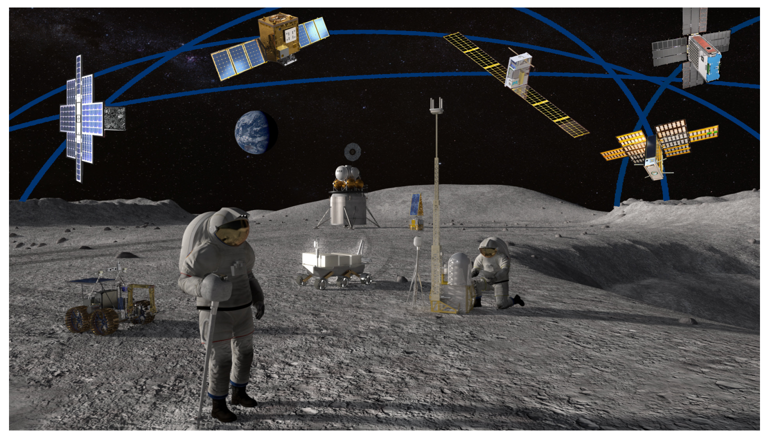
Distributed Spacecraft Autonomy



Distributed Spacecraft Autonomy

- **NASA's Distributed Spacecraft Autonomy (DSA) Project**
  - DSA is organized into two major sub-projects.
  - DSA-Starling is a software payload on the Starling space mission.
  - DSA-LPNT is a processor-in-the-loop scalability study building on DSA-Starling.





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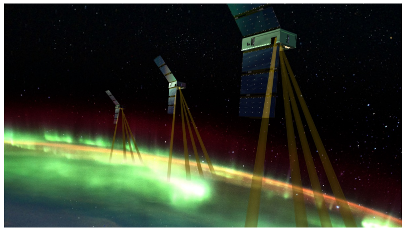

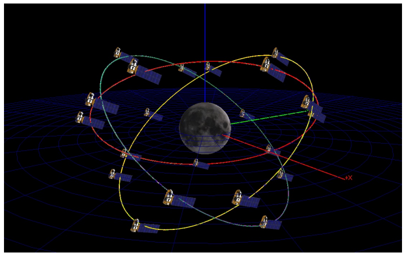

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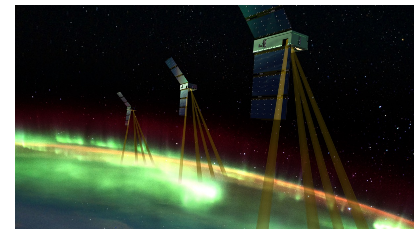
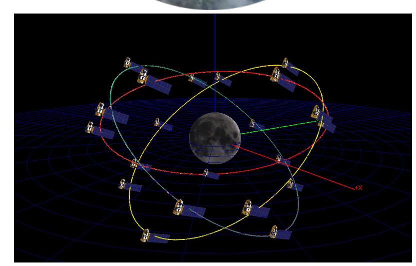
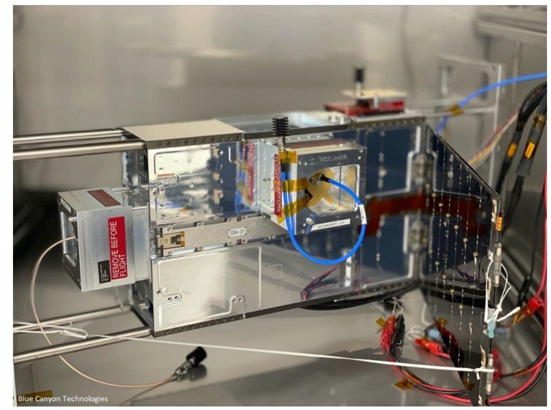


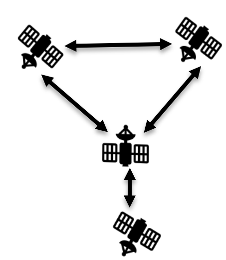


DSA-Starling

DSA-Starling

- **The Starling Mission**
  - Starling consists of 4 Cubesats in a Sun-synchronous orbit more than 480 km above Earth and 270 km apart.
    - Sun-synchronous orbits are nearly polar orbits that allow a spacecraft to consistently see the same amount of sunlight each orbit and generate the same amount of power with its solar panels.
  - Spacecraft communicate with each other via radios in a broadcast network.
    - Mobile Ad-hoc Network (MANET): Starling spacecraft communicate with each other via two-way S-band crosslink radios/antennas. If one spacecraft communications node fails, the communications route automatically reconfigures to maintain full communication capabilities for the remaining spacecraft.





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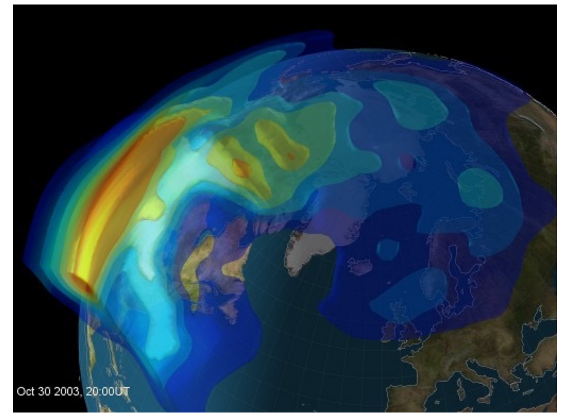
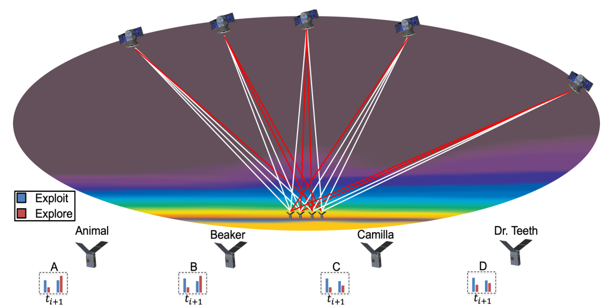
Example Swarm Topology

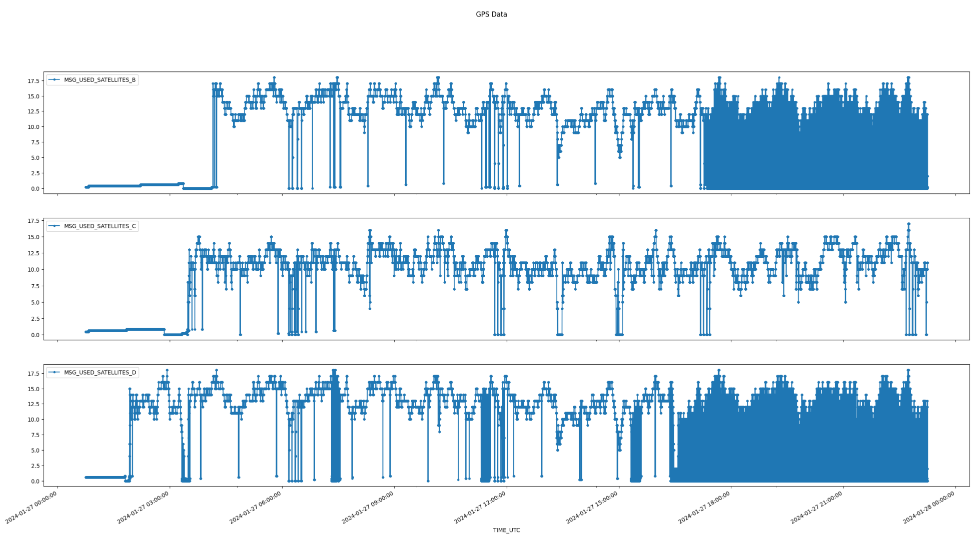
DSA-Starling

- **DSA-Starling Science Proxy**
  - GPS satellites are geostationary satellites orbiting at 20,000 km.
  - Two upper atmospheric anomalies, Equatorial Bubble and Polar Patch, occur between the GPS satellite orbital altitude and the DSA-Starling orbital altitude.
  - Each satellite's GPS receivers will therefore detect the anomaly when Starling spacecraft pass through a region where the anomaly occurs.
  - For our purposes, the 'channel' refers to the signal a Starling spacecraft receives from a single GPS satellite.





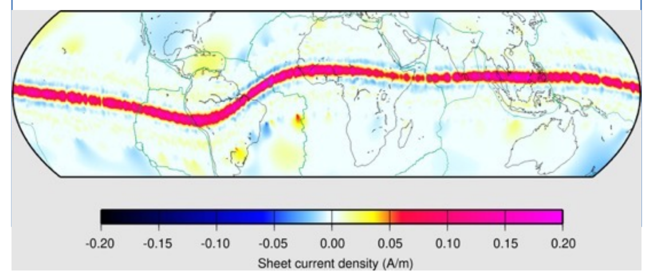
- **DSA-Starling Science Proxy**
  - Typically, 10-20 GPS satellites are in view of each Starling spacecraft.
  - The GPS receivers can typically receive data from all in-view GPS satellites.
  - For our experiments, we artificially limit the number of GPS channels any Starling spacecraft can receive (e.g. to 4). This limitation drives choices in which channels to receive in the presence of the equatorial anomaly or the polar patch phenomena.



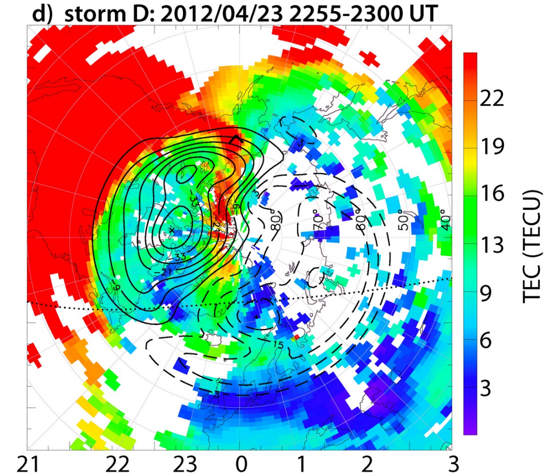
DSA-Starling

- **DSA-Starling Science Proxy**
  - The behavior of the high TEC signal requires distinct GPS channel allocation strategies.
  - During equatorial passes, we want to ensure that the maximum number of GPS channels are covered by DSA a whole. We ‘*Explore’ TEC over the Equator.*
  - Use Polar Patches to characterize the ability of DSA to react to transient, localized phenomena. Some GPS TEC rays will pass through the patch and some will not. A satellite that determines that it is passing through a patch will communicate which GPS satellites it is watching to the other satellites so that they may begin observing before they also enter the patch. *We ‘Exploit’ TEC over the Poles.*

Equatorial Ionization Anomaly

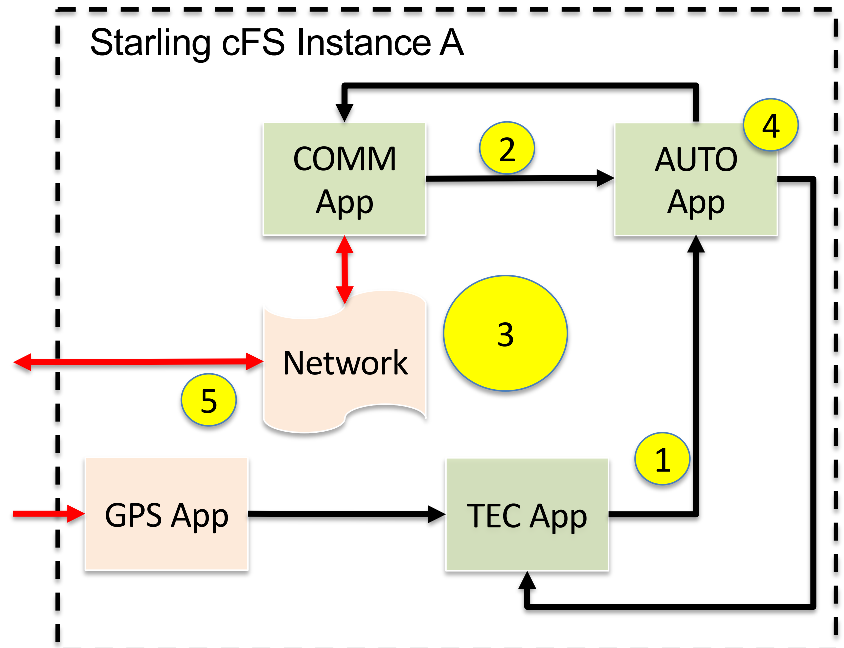


d) storm D: 2012/04/23 2255-2300 UT



DSA-Starling

- **DSA Distributed Consensus**
  - Each execution cycle, a spacecraft's AUTO app gets new TEC from its prior observation.
  - COMM broadcasts TEC which is received at 1 Hz as well.
  - DSA now has achieved 'Distributed Consensus'; all instances have the same information.
  - AUTO solves the new problem.
  - COMM broadcasts results of execution of plan.
- **AUTO-TEC-COMM App Cadence: One Hz!**



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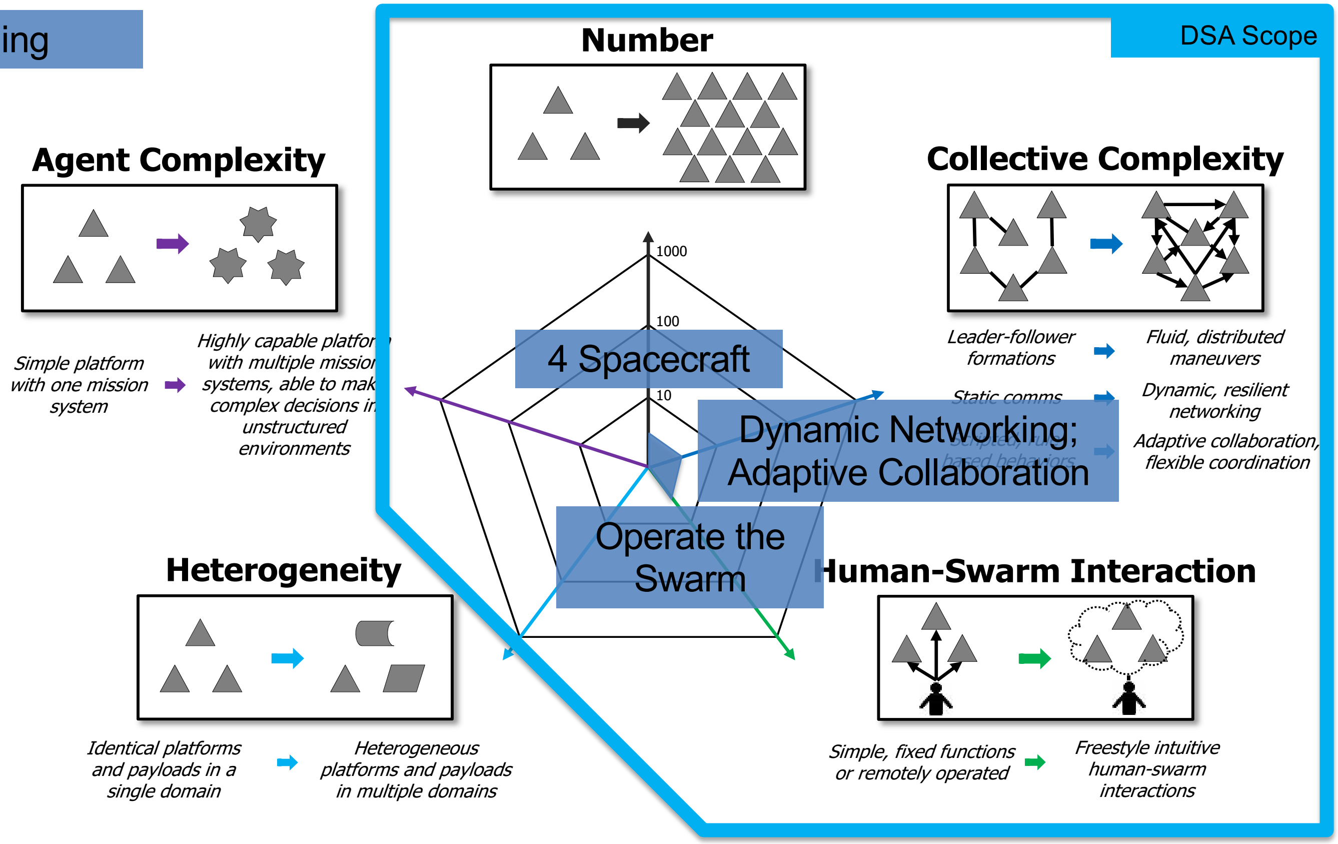

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  - Lunar Position Navigation and Timing Services
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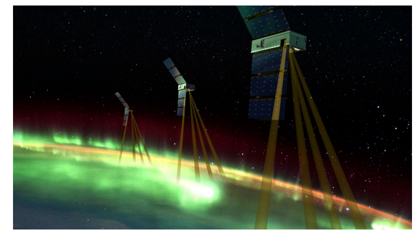
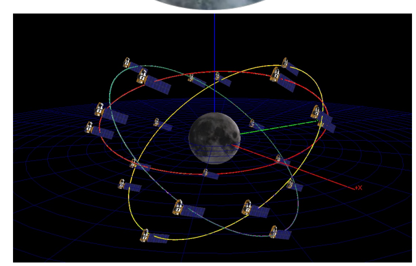




DSA-LPNT

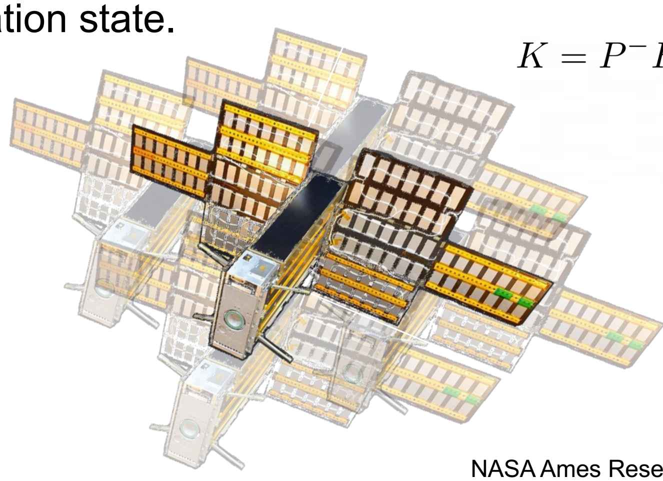
- **A New Use Case: Position Navigation and Timing**
  - Deep Space Network (DSN) based localization is available when missions are in view of the Earth; low-cost surface missions may not be able to support the large power, mass, and weight requirements that these navigation solutions would entail. Additionally, DSN is heavily oversubscribed.
  - High Altitude / Weak GPS has positioning errors of 100 m, which will not meet Lunar mission localization requirements.
  - We explore the potential of ad-hoc PNT services using proposed Lunar small-sat science missions in low Lunar orbit, at 100km. As an alternative, one could use dedicated spacecraft in ‘frozen’ lunar orbits (requiring low/no propellant for orbit maintenance) at 4000km.

Mission	**Altitudes (km)**	**Incl. (deg)**
Luna-Hmap (completed)	5 x 3000	90
LRO (completed)	20 x 165	90
Lunar Flashlight (failed)	20 x 1000	90
LADEE (completed)	25 x 60	157
KPLO/Danuri (ongoing)	100 x 100	90
Lunar Ice Cube (failed)	100 x 100	90
SELENE (completed)	100 x 100	90
Lunar Trailblazer (planned)	100km	90
Chandrayaan-1 (completed)	200 x 200	90

DSA-LPNT is an autonomy demonstration with **a new use case**

A Brief Diversion: Kalman Filters

- Kalman Filters are used for guidance, navigation and control of spacecraft (among other things.). For our purposes, the Kalman Filter is used to refine the position and velocity estimates of spacecraft in their orbit around the Moon.
- DSA really uses a Distributed Extended Kalman Filter (DEKF), which splits the state amongst spacecraft, and drives the need to communicate information to update the navigation state.



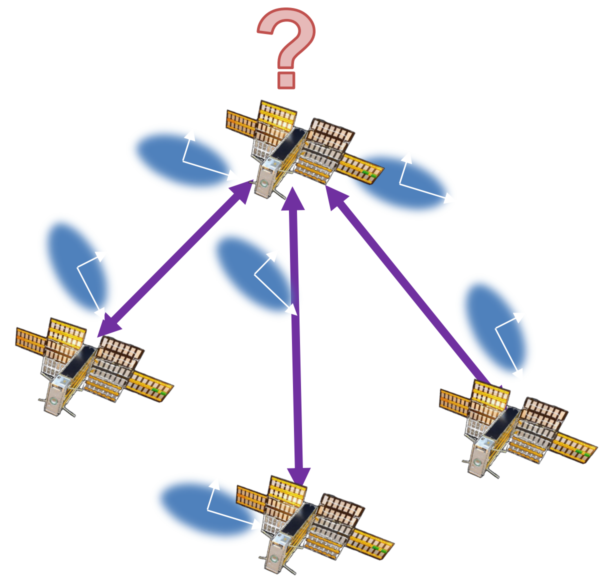
$$K = P^- H (H P^- H^T + R + \bar{H} \bar{P}^- \bar{H}^T)^{-1}$$

$$P^+ = (I - KH) P^-$$

$$x^+ = x_- + K(z - Hx^-)$$

DSA-LPNT

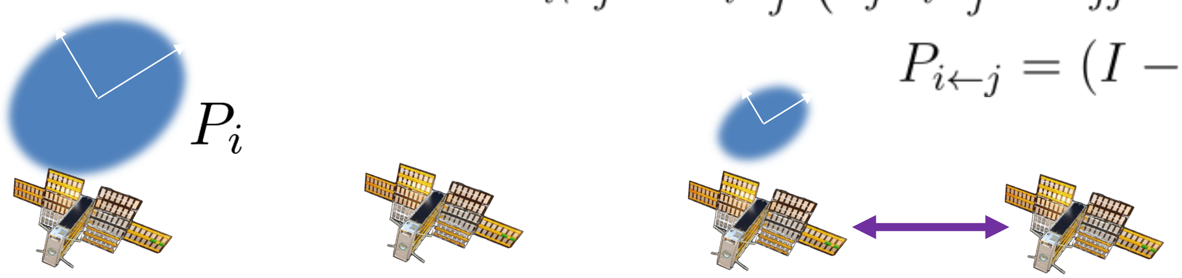
- **The Measurement Selection Problem**
  - Spacecraft may have limited communications capability (limited numbers of antennas, ranges, frequency and other hardware limitations).
  - Updating the DEKF requires taking measurements.
  - Measurement requires two spacecraft to simultaneously point antenna at each-other and activate radios. Both obtain measurements useful for localization. This means they need to maneuver or orient their antennas and simultaneously operate their radios.
  - This is why we can't have nice things, like all the measurements from all spacecraft all the time to drive the DEKF updates.



- **The Measurement Selection Problem**
  - As (part of) the DEKF Measurement Update Step, we can compute $P_{i\leftarrow j}$, which evaluates how spacecraft i's state uncertainty changes if we only use measurements from spacecraft j.
  - We only need the rows corresponding to measurement j from the Measurement Sensitivity Matrix *H*, *not the actual measurement*, to compute this quantity!
  - We can then use $P_{i\leftarrow j}$ to *choose the best measurement* to make.

$$K_{i\leftarrow j} = P_i h_j^T \left(h_j P_i h_j^T + r_{jj} + \bar{h}_j \bar{P}_i \bar{h}_j^T\right)^{-1}$$

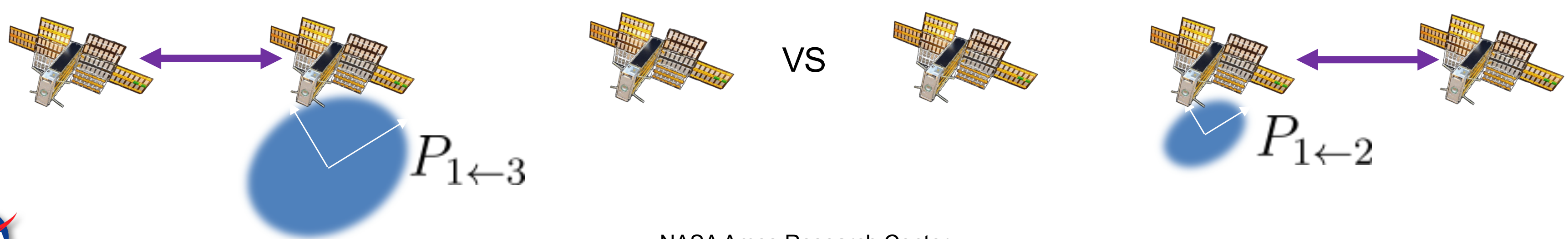
$$P_{i\leftarrow j} = (I - K_{i\leftarrow j} h_j) P_i$$



- **The parts of the DEKF we really need:**
  - The square of the Frobenius Norm of the matrix $P_{i \leftarrow j}$ is:

$$||P_{i \leftarrow j}||_F^2 = \sum_{ij} p_{ij}^2$$

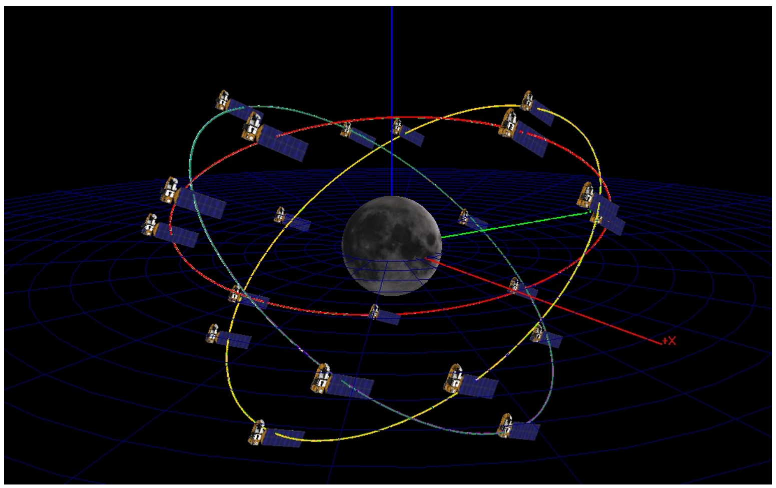
  - This is the scalar estimate of the resulting uncertainty of spacecraft i updating its position by communicating with spacecraft j. A large measure indicates high covariance, and a low measure indicates low covariance.
  - We can select the measurement that results in the lowest covariance.

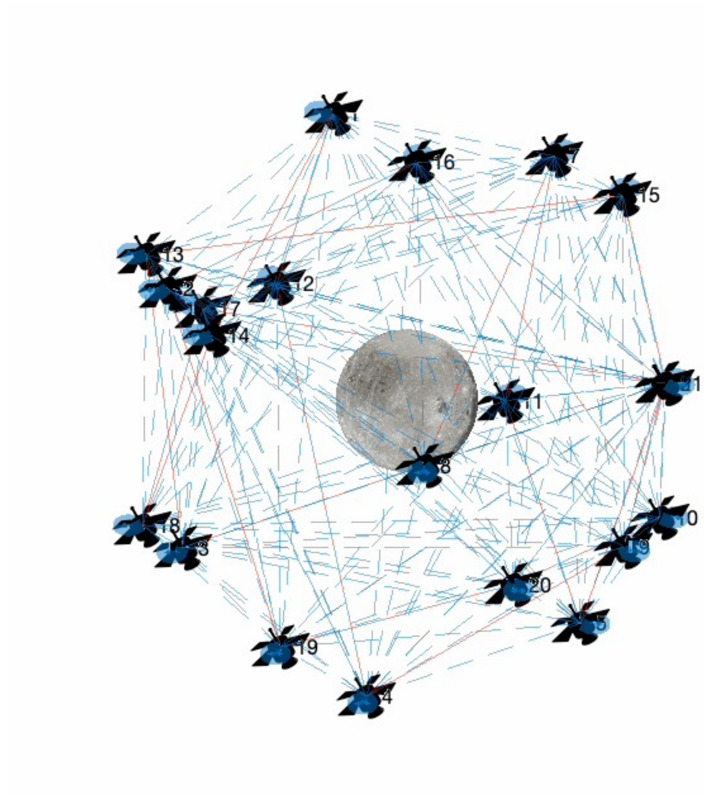


DSA-LPNT

- **The Distributed Measurement Selection Problem is a Matching Problem**
  - Suppose each spacecraft only has a *single* antenna.
  - Define $f_{ij} \equiv \|P_{i \leftarrow j}\|_{\mathrm{F}}^{2}$.
  - The 'global' quality for both spacecraft i and j if they communicate is thus $f_{ij} + f_{ji}$(each edge includes contributions from both spacecraft that communicate.)
  - If we have all of these qualities, we can solve the problem of finding the *best set of simultaneous communication activities to perform,* subject to the constraint that each spacecraft can perform only one communication act.
  - The resulting problem is a *minimum matching problem* (because we want to minimize the sum of covariances across the LPNT network.)
- **DSA-LPNT uses a similar (but not identical) Distributed Consensus approach to DSA-Starling.**

DSA-LPNT





DSA-LPNT

DSA-Starling

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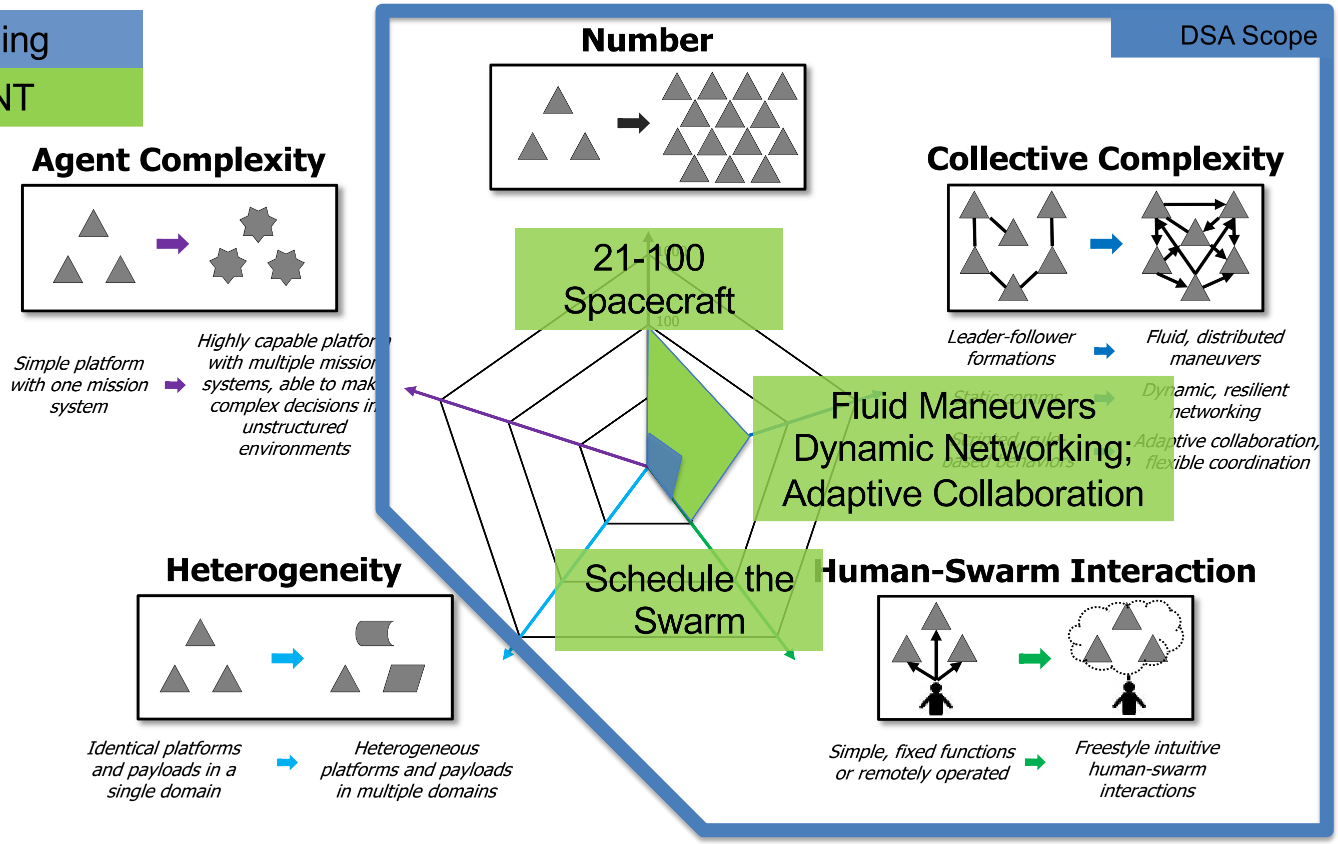

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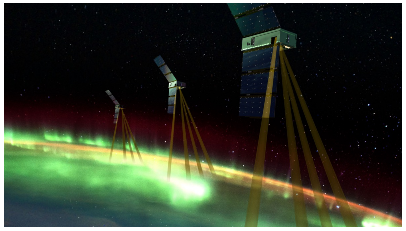
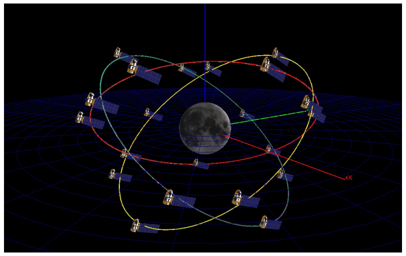
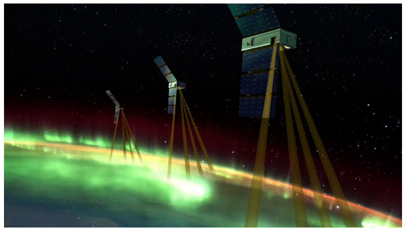
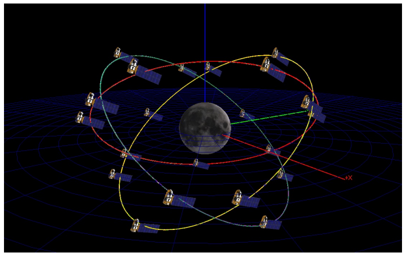




Lessons Learned

- Solving the Right Problem is Hard
- Real Problems are...Complicated
- The Drive for General Purpose Technology
- The Existential Pleasures (and Dreads) of Engineering
- The Existential Pleasures (and Dreads) of Operations
- Multi-Disciplinary Needs of the Team





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- **Related DSA papers**

  - S. Niemoeller and R. Burton and J. Frank and R. Levinson and N. Cramer. Scheduling Position, Navigation and Time Service Requests from Non-dedicated Lunar Constellations. Proceedings of the 43rd IEEE Aerospace Conference, 2022.
  - J. Frank, R. Levinson, E. Hillsberg, N. Cramer and R. Burton. Distributed Scheduling of Position Estimation Updates in Ad-Hoc Lunar Constellations. Proceedings of the AAAI Spring Symposium Series 'Can We Talk', 2022
  - Walter Vaughan, Alan George, Brian Kempa, Daniel Cellucci, Nicholas Cramer. Evaluating Network Performance of Containerized Test Framework for Distributed Space Systems. Proceedings of 36th Annual Small Satellite Symposium, 2022.

- **Everything I Know About Kalman Filters I Learned From This Cartoon**
  - https://www.bzarg.com/p/how-a-kalman-filter-works-in-pictures/

Thank you!