The Distributed Spacecraft Autonomy project is developing a suite of software tools that enable an operator to command and receive data from a swarm as a single entity, enable a swarm to autonomously coordinate its actions via distributed decision making and reactive closed-loop control, and model swarm behavior in the presence of anomalies or failures. Our use case is the mapping of the electron density of the ionosphere using radio tomography by coordinating the selection of appropriate GPS channels, and by recording Total Electron Count (TEC) measurements. DSA will be demonstrated onboard the NASA Ames Starling mission – a swarm of four small, LEO spacecraft, scheduled to launch in 2021. We will also perform a ground demonstration with simulated and hardware-in-the-loop elements, to validate the tools for controlling swarms of up to 100 assets.

The capability to communicate autonomously between the swarm satellites is demonstrated via a sophisticated simulation architecture. Historical Plasmasphere TEC data obtained via dual-band Novatel GPS Receivers are utilized as a representative input dataset for the swarm. The representative TEC data and GPS satellite observability information is fed to the autonomous software package in place of a true real-time ground data collection process. The swarm satellites actively share status updates amongst one another and utilize multi-agent decision making to optimally identify regions of interest in the TEC distribution. The software, aware of the bandwidth limitations of the swarm satellites, prioritizes explorative measurements, which define the range of observability for the satellites, as well as exploitative measurements, which focus on maximizing the observance potential of regions with prolonged, elevated TEC density. The science of this study can ultimately be used to determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs. The findings can be applied to the imaging of critical, transient phenomena in the magnetosphere in later missions. Meanwhile, the swarm autonomy capabilities have far reaching potential in future satellite missions.

As an experimental demonstration of the autonomous capabilities of the network, a message is first printed within a core Flight Executive (cFE) application. Two cFE applications that communicate with one another within the same core Flight System (cFS) are shown. Communication between mission applications on the internal cFE bus is extended to utilize Data Distribution Service (DDS) for vehicle-to-vehicle networking. The DDS middleware provides reliable delivery, routing, and topic subscription features over User Datagram Protocol (UDP). Leveraging Linux containerization, a networked set of satellite instances are generated by script to simulate swarm behavior. Swarm commanding and synchronization through the network is demonstrated under various topologies and data-loss conditions. Finally, autonomous swarm scalability from 2 satellites to 100 satellites is shown.

National Aeronautics and Space Administration

Distributed Spacecraft Autonomy (DSA):

Development of Swarm Autonomy Capability and Scalability for Spacecraft

Jason Fugate

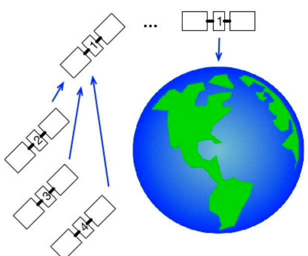
March 25, 2020

Outline

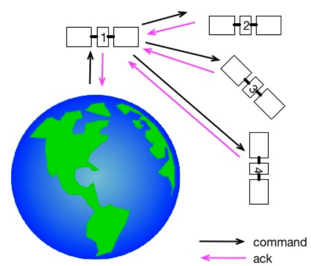
- Project Overview
- Scientific Use Case
- Experimental Architecture

Project Overview

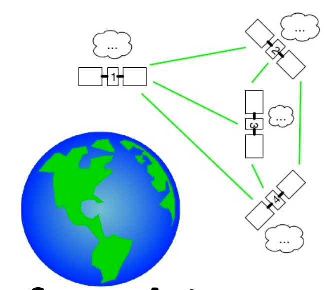
- Project Goals:
  - Develop software to enable an operator to command and receive data from a swarm of satellites as a single entity
  - Enable a swarm to autonomously coordinate its actions via distributed decision making and reactive closed-loop control
  - Model swarm behavior in the presence of anomalies or failures
  - Perform a ground demonstration with simulated and hardware-in-the-loop elements to validate the tools for controlling swarms of up to 100 assets



Swarm Telemetry
Relayed s/c telemetry to establish swarm health



Swarm Commanding
Relayed swarm commands to operate swarm as one



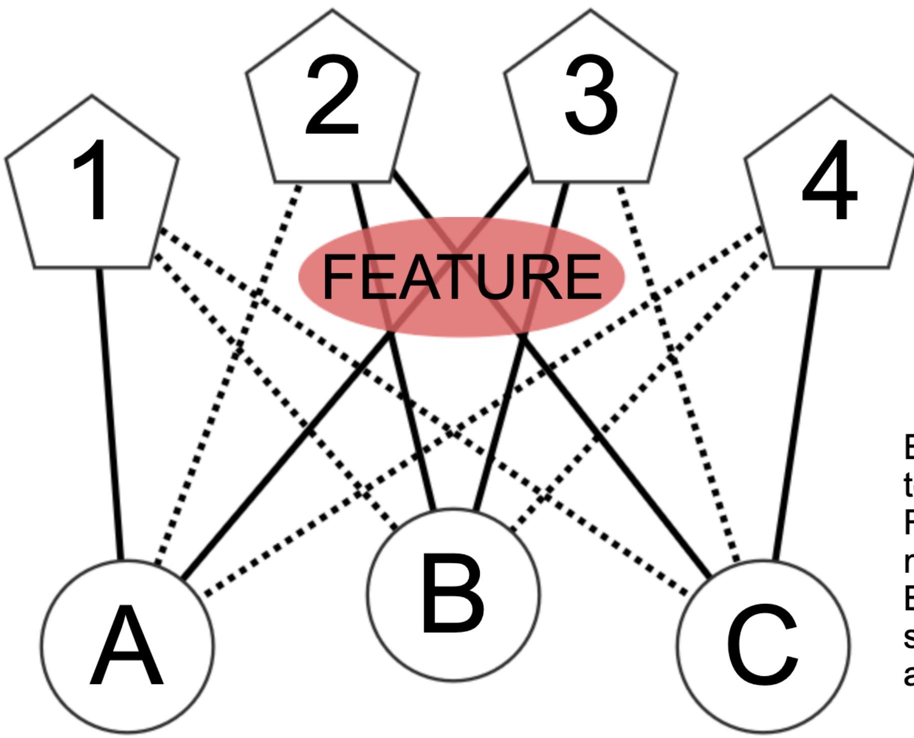
Swarm Autonomy
Coordinated autonomy of swarm of s/c

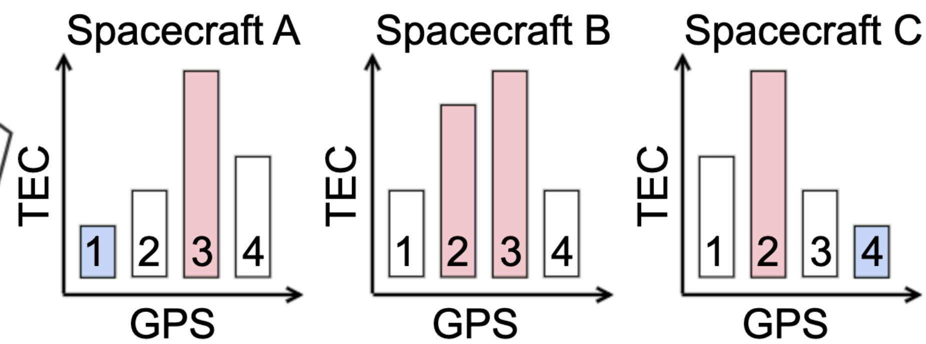
- DSA will be demonstrated onboard the NASA Ames Starling Mission – a swarm of four small, LEO spacecraft, scheduled for launch in 2021.

Scientific Use Case

- DSA technology will be utilized for mapping electron density of the ionosphere using radio tomography by:
  - Coordinating the selection of appropriate GPS channels
  - Recording Total Electron Content (TEC) measurements
  - Identifying regions of interest in the TEC distribution
- Based on bandwidth limitations, software prioritizes:
  - ***Explorative Measurements***: which define the range of observability for the satellites
  - ***Exploitative Measurements:*** which focus on maximizing the observance potential of regions with prolonged, elevated TEC density
- Findings could be applied to the imaging of critical, transient phenomena in the magnetosphere in later missions

Scientific Use Case





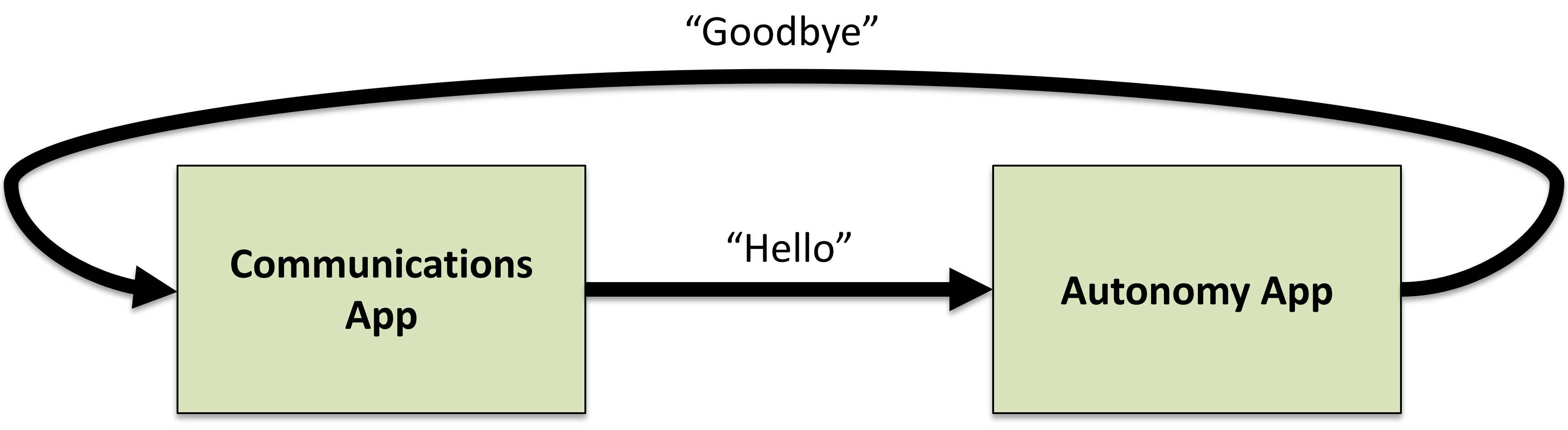
Each spacecraft can see four GPS satellites but can listen to only two.
Red TEC values correspond to *exploitative* selections- i.e. multiple spacecraft listen to a single GPS
Blue TEC values correspond to *explorative* selections- spacecraft listen to a GPS that none of the other spacecraft are listening to

Experimental Architecture

- Summary:
  - Historical Plasmasphere TEC data obtained via dual-band Novatel GPS Receivers during the ESA "Swarm" mission are utilized as a representative input dataset for the swarm
  - The representative TEC data and GPS satellite observability information is fed to the autonomous software package in place of a true, real-time ground data collection process
  - An experimental demonstration of the autonomous capabilities of the network is performed

Experimental Architecture

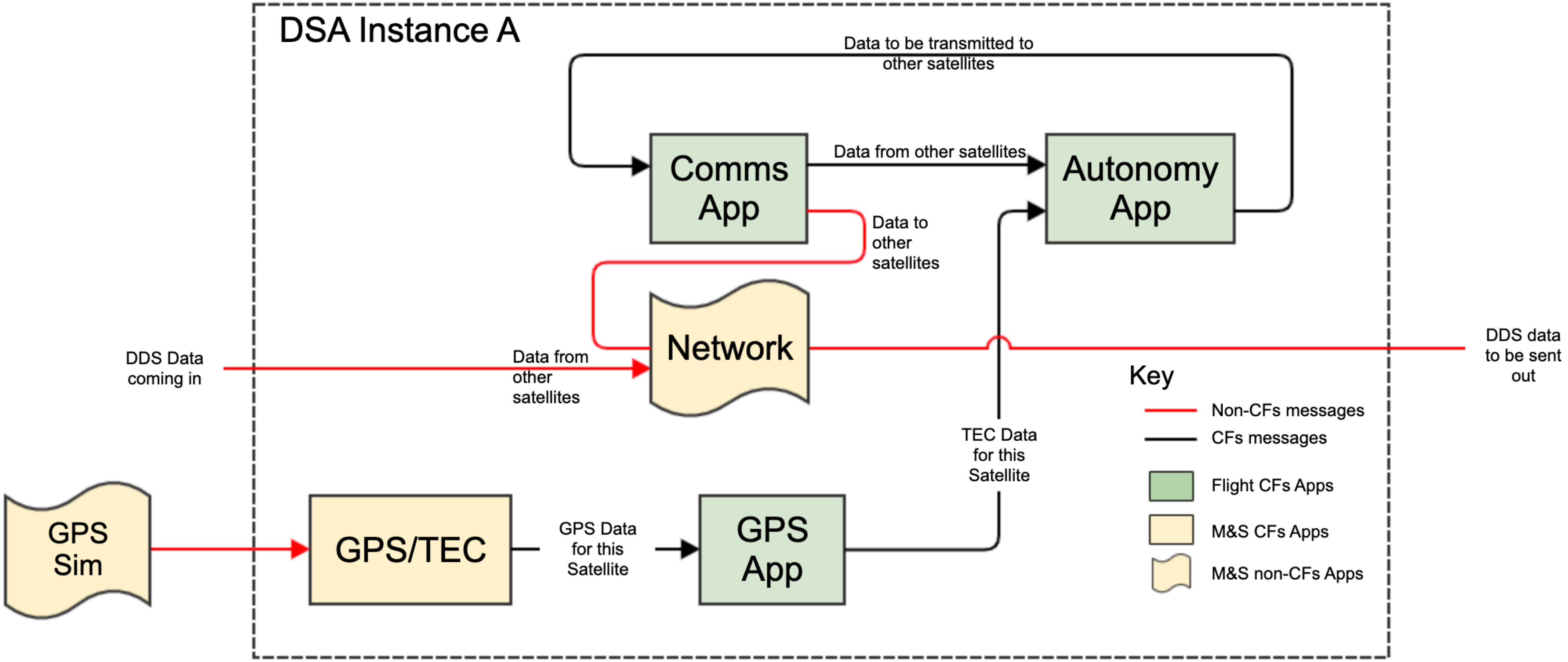
- A message is first printed within a core Flight Executive (cFE) application.



- Two cFE applications that communicate with one another within the same core Flight System (cFS) are shown.

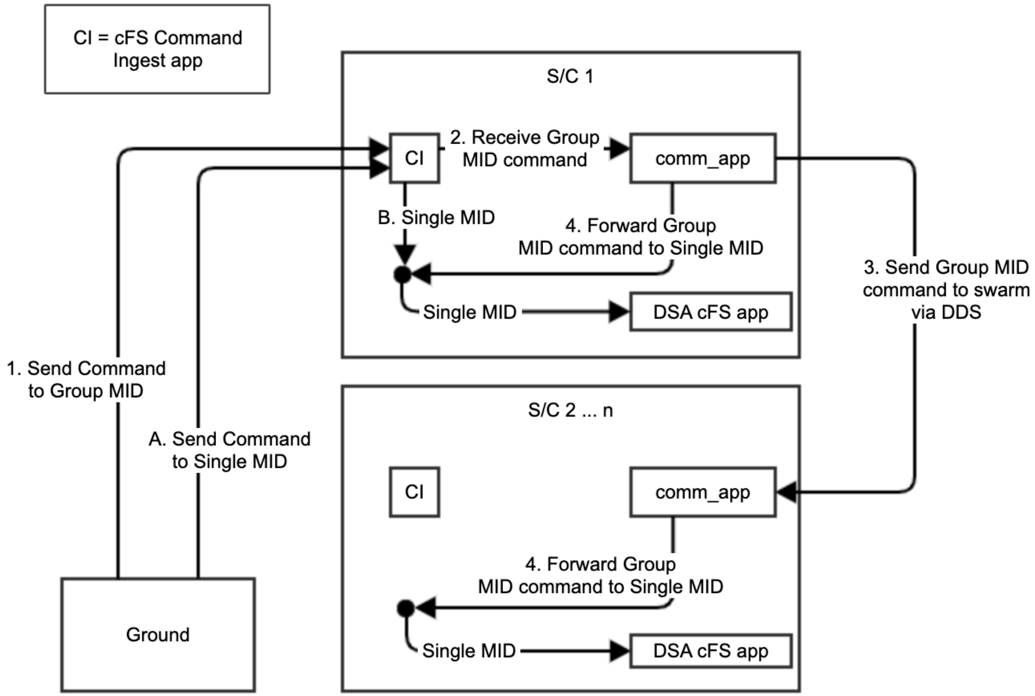
Experimental Architecture

- Communication between mission applications on the internal cFE bus is extended to utilize Data Distribution Service (DDS) for vehicle-to-vehicle networking.
  - The DDS middleware provides reliable delivery, routing, and topic subscription features over User Datagram Protocol (UDP).



Experimental Architecture

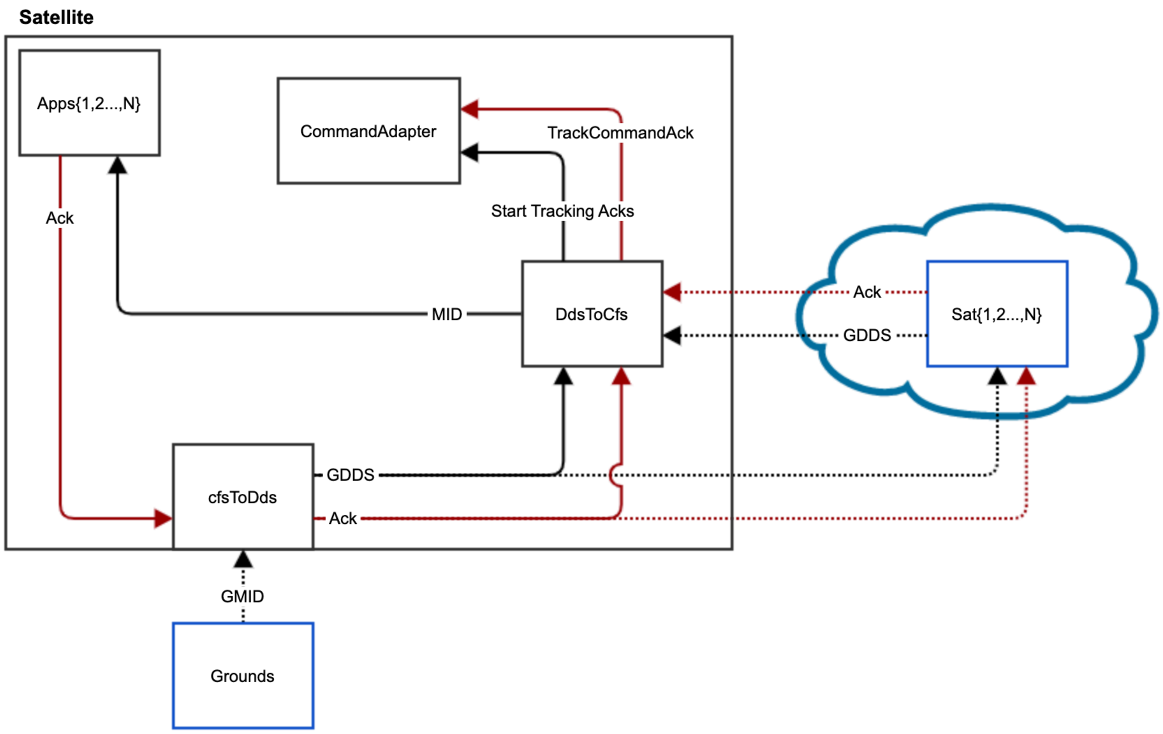
- Leveraging Linux containerization, a networked set of satellite instances are generated by script to simulate swarm behavior.



- Swarm commanding and synchronization through the network is demonstrated under various topologies and data-loss conditions.

Experimental Architecture

- Finally, autonomous swarm scalability from 2 satellites to 100 satellites is shown.



Questions?