Swarm Technology Development Strategy

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Internal Study

The NASA Need

"There is one type of mission class that is of high priority for multiple disciplines and ***which deserves focused investment and development—the creation of swarms and constellations of CubeSats****. Many high-priority science investigations of the future will require data from constellations or swarms of 10 to 100 spacecraft that, for the first time, would have the spatial and temporal coverage to map out and characterize the physical processes that shape the near-Earth space environment.*

Recommendation: *Constellations of 10 to 100 science spacecraft have the potential to enable critical measurements for space science and related space weather, weather and climate, as well as some for astrophysics and planetary science topics. Therefore,* ***NASA should develop the capability to implement large-scale constellation missions*** *taking advantage of CubeSats or CubeSat-derived technology and a philosophy of evolutionary development."*

Committee on Achieving Science Goals with CubeSats; Space Studies Board; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine, 2016, Committee Chair: Thomas Zurbuchen

The 2016 NAS/SSB report describes science application areas for multiple spacecraft in terms of Constellations or Swarms.

Constellations vs. Swarms

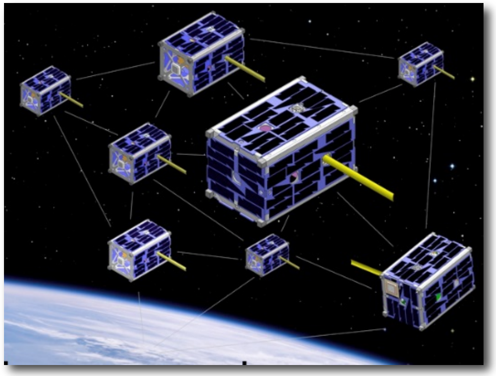
Constellation

- Multiple (small group) spacecraft in different orbits
- Each spacecraft is **individually controlled** by ground (expensive and limited performance)
- Spacecraft can exchange data, but do not necessarily have knowledge about each other's motions and movements
- Examples: GPS, Iridium, etc

Constellation

Swarm

- Multiple (large group) spacecraft that may operate in close proximity and require spatial configuration
- Swarms can **actively work as a "collective"** to accomplish a common task:
  - Distributed, multi-point measurements
  - Redundancy (spatial coverage, comm, etc.)
- Various configurations: same orbit (with in-train gap), constrained ellipse (no active control), fixed formation



Swarm

Sample Swarm Behaviors & Applications

Earth Orbit:

(1) In-train gap maintenance: The spacecraft are all in the same orbit, and need to maintain spacing within the orbit. (ex: Earth Observing sensing)

(2) Statistically sampled spacing: The spacecraft are flying in a constrained ellipse, but without active control of the spacing. Spacecraft have position knowledge and the 3D spacing in the ellipse is adequately sampled over time. (ex: Heliophysics field-measurement)

(3) Fixed spacing & position: The spacecraft are flying in a fixed “formation”, with control of both the inter-spacecraft distance and the orientation of the formation.. (ex: Astrophysics interferometry) Note: some interferometer applications can use type #3 (above) as well

Deep-Space:

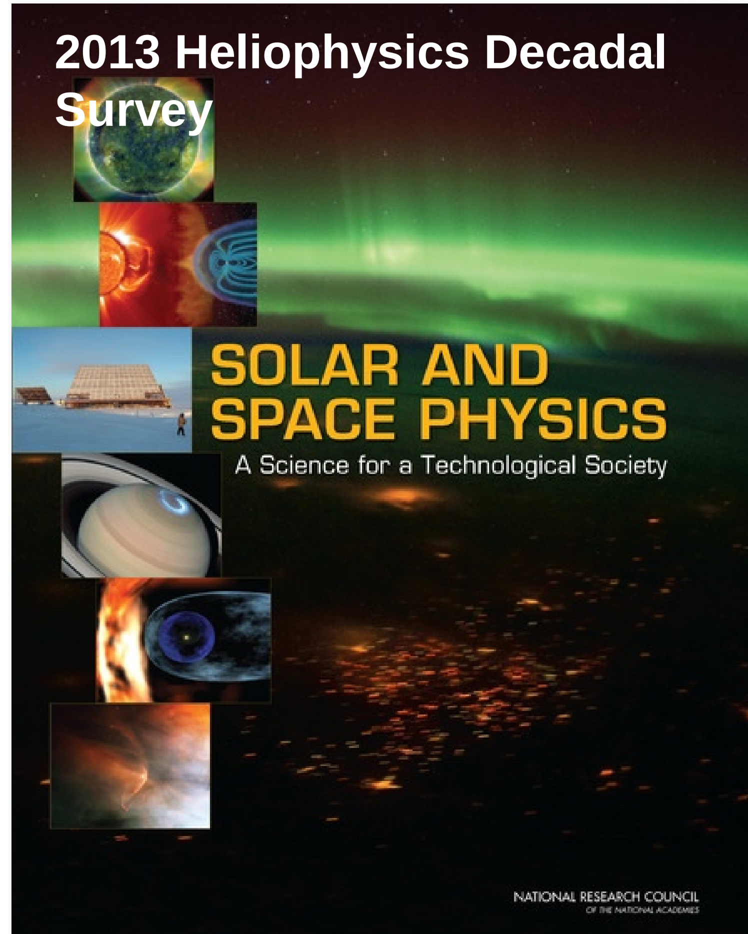
(1) Element positional knowledge: Knowledge requirements without control requirements. (ex: Astrophysics interferometer in Lunar orbit).

(2) Element positional control: Knowledge and control requirements together. (ex: MagCat, a particle and fields mission)

(3) Element fine tracking: Fine position and rate knowledge requirements. (ex: Gravimetric mapping of an asteroid)

Driving Case: Heliophysics Reference Mission

- **MagCat: twenty spacecraft mission**
  - Acquire two-dimensional images of the equatorial outer magnetosphere and multipoint in-situ observations
  - Fluxgate magnetometer, electrostatic analyzers, relaxation sounder, etc.
  - Each satellites transmits to all others, enabling tomographic images of plasma
  - Address critical Sun-Earth processes (plasma entry, bow-shock structure, etc).
- **Derived Requirements**
  - Minimize s/c costs: spacecraft manufacturing and mission operations
  - Intra-spacecraft command, control and science data communications capability
  - Spacecraft position knowledge, control capability, and time synchronized.



Source: section 9.5.3.2: Magnetospheric Constellation & Tomography (MagCat)

MagCat Requirements Trace

Magnetospheric Constellation and Tomography Mission (derived from: 2013 Heliophysics Decadal Survey)

Goals	Objectives	Reference Mission	Reference Requirements
Science: Address some of the most critical processes in Sun-Earth connec-tions: plasma entry into the magnetosphere, plasma-sheet forma-tion and dynamics, and investigation of bow-shock structure, plasmaspheric plumes, and other mesoscale structures that form in response to solar-wind variability.	**Science:** Provide a combination of two-dimensional images of the equatorial outer magnetosphere and multipoint in-situ observations made concurrently and in the same imaged region.	A 20 spacecraft swarm able to perform observations with a minimum spatial resolution of 0.5 Re at a minimum time cadence of 15 sec	• Intra-spacecraft command and control communications capability • S/C Position Knowledge: 0.003 Re • S/C Control Capability: 0.03 Re • S/C Time Synchronization: 15 msec
		The spacecraft should be in two coplanar orbits that pass through critical regions in the magnetotail, flank, and subsolar magnetosphere	Swarm must be able to achieve and then maintain the desired science orbits
		Each spacecraft shall carry: (1) 3-axis fluxgate magnetometer, (2) electrostatic analyzers for 3D ion and electron distributions, (3) relaxation sounder to determine the ambient density, (4) a radio tomography instrument	Each satellite would transmit radio waves to all others, obtaining 190 line-of-sight densities, enabling tomographic images of plasma density over large regions with an average spatial resolution of 0.32 Re at 12sec cadence.
Programmatic: The pre-CATE estimate for the MagCat mission was deemed beyond the scope of the budget in the coming decade, so the mission implementation should be implemented in a cost-effective manner.	**Programmatic:** Implement efficient mfg. to mass produce a large number of spacecraft and instruments, and implement lower cost approaches to operations, while achieving acceptable reliability levels.	Produce large numbers of identical spacecraft and instruments at acceptable quality levels.	Implement mass production techniques, automated quality control, and automated testing in order to achieve lower hardware costs.
		Implement high-level operations paradigms capable of controlling multiple spacecraft.	Implement high-level commanding of the swarm as a collective. Implement collective fault management in order to provide acceptable mission lifetime and reliability.

MagCat Enabling Capabilities

Reference Requirements
• Intra-spacecraft command and control communications capability • S/C Position Knowledge: 0.003 Re • S/C Control Capability: 0.03 Re • S/C Time Synchronization: 15 msec
Swarm must be able to achieve and then maintain the desired science orbits
Each satellite would transmit radio waves to all others, obtaining 190 line-of-sight densities, enabling tomographic images of plasma density over large regions with an average spatial resolution of 0.32 Re at 12sec cadence.
Implement mass production techniques, automated quality control, and automated testing in order to achieve lower hardware costs.
Implement high-level commanding of the swarm as a collective. Implement collective fault management in order to provide acceptable mission lifetime and reliability.

Implies: multi-hop communications network between spacecraft for command, control, timing & data

Implies: position knowledge and position control

Implies: science instrument cross coordination

Implies: on-board swarm autonomy control of some form, including goal-directed commanding and fault response

Enabling Swarms: The Problem

Current state-of-practice allows satellite groups to be implemented using ground control of individual spacecraft.

- Used in existing constellations
- Scaling operations to large sets of spacecraft is “operations” cost prohibitive.
- Maintaining a desired swarm configuration often needs rapid corrections, driving operations requirements.

Enabling very large swarms (e.g. 30-100 spacecraft) suggests the swarm be operated as a ‘single unit’.

- High-level only commanding from the ground
- The swarm must maintain its own configuration to achieve the ground-commanded goals.

Enabling Swarms: Technologies

The core technologies enabling swarms are a mixture of mature in-space, mature on-the-ground, and new to-be-developed:

Knowledge – How do we know the positions and movements of the spacecraft in the swarm?

Communications – How do we get information to and from the spacecraft in the swarm?

Control – How do we maintain the configuration of spacecraft in the swarm?

Operations – How do we command the swarm configuration and return data from it?

Access – How do we get the swarm into space and deploy it?

We know how to do all of these with small swarms and traditional operations, but not how to do it cost effectively for large swarms.

LEO Swarm Demonstration Configurations

Less Difficult

Difficulty

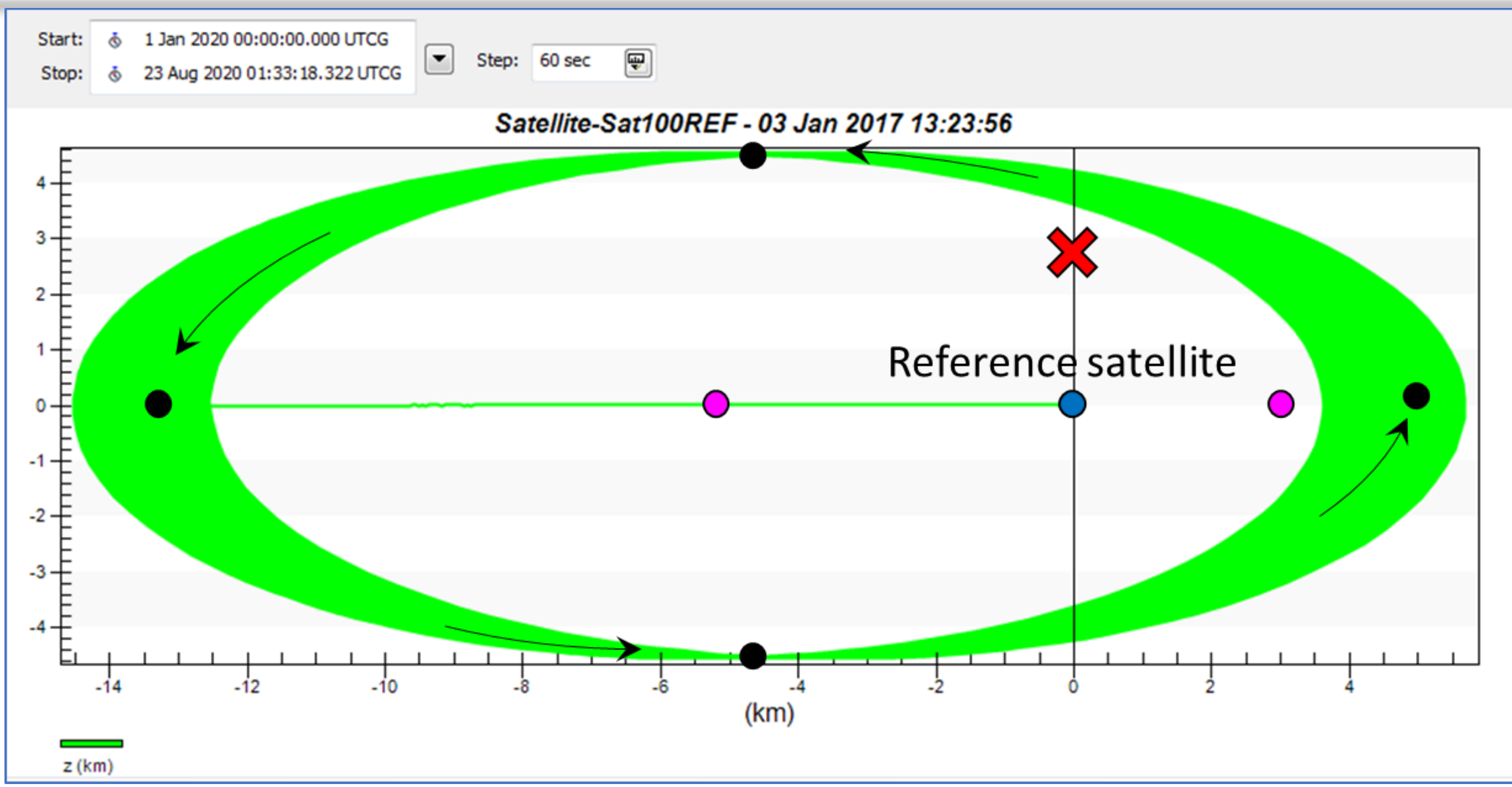
(1) In-train gap maintenance: this is most useful for Earth Observing applications. The spacecraft are all in the same orbit, and need to maintain spacing within the orbit. The DRM for technology demonstration could be 3 or more spacecraft in one orbit with active control of the inter-spacecraft distance.

(2) Statistical sampling spacing: this is most useful for Heliophysics field measurement applications. The spacecraft are flying in a constrained ellipse, but without active control of the spacing. The goal is that they are always within the ellipse, but can wander around within it as long as there is position knowledge and the 3D spacing is adequately sampled over time. The DRM for tech demo could be 4-6 spacecraft flying within a specified ellipse, but allowed to wander around within the ellipse in order to achieve a statistical distribution.

(3) Fixed in-plane spacing: this is most useful for Astrophysics interferometry applications. The spacecraft are flying in a “plane”, with control of both the inter-spacecraft distance and the orientation of the “plane”. The DRM for tech demo could be 3-4 spacecraft flying in a formation with active control of both the spacing and orientation of the plane of the formation.

More Difficult

LEO Orbital Motion of Swarms

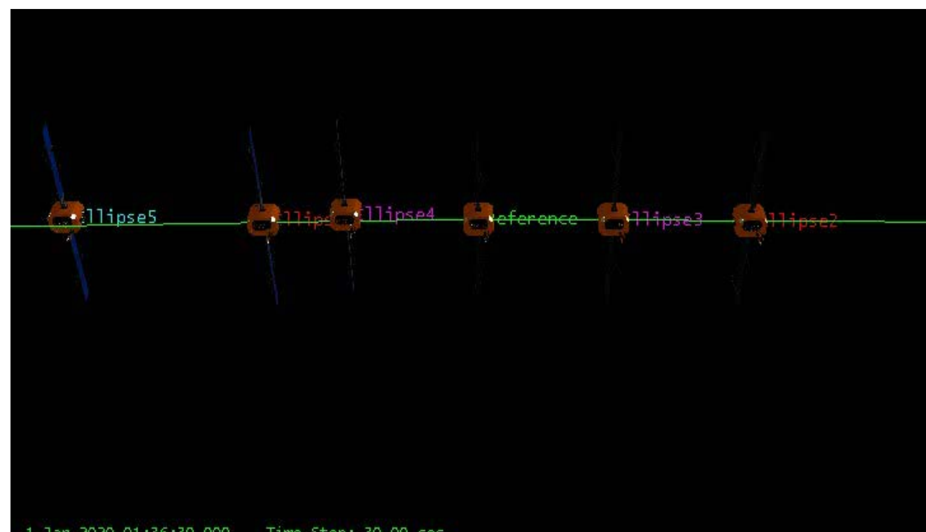


- Blue is the reference satellite, in its (continually decaying) LEO orbit
- Pinks are in the same orbit with the same rate of decay. They appear fixed ahead and behind Blue. They must be at the same altitude.
- Blacks are in the same orbit plane, with radial excursions above and below the reference altitude occupied by Blue and Pinks.
- Blacks are in the same orbit as one another. In their frame of reference, they are "in train."
- Blacks are in continuous motion relative to Blue and Pinks.
- It is not possible to maintain a position fixed above or below a satellite in orbit like Red without constantly thrusting. Differences in altitude cause satellites to move ahead and behind one another.

LEO Swarm Examples

Type 1: In-train gap maintenance: The spacecraft are all in the same orbit, and need to maintain spacing within the orbit.

*Click images to see animations



Type 2: Statistical sampling spacing: The spacecraft are flying in a constrained ellipse, but allowed to wander around within the ellipse in order to achieve a statistical distribution.

Enabling Technologies for Swarms

SWARM Technology Components

Key: **L** = Large Spacecraft, **S** = Small Spacecraft
Low = Low precision, **High** = High precision

General	Specific	Technologies	Availability (TRL)								
			1	2	3	4	5	6	7	8	9
Knowledge	Absolute Position & Velocity of swarm	Ground Ranging/Tracking of one element									X
		GPS (if LEO)									X
		JSPOC Elsets									X
	Absolute Orientation of Swarm	Derived from element positions					X				
	Relative Position of swarm elements	Element-to-element mapping (RF Radar)					X				
		Element-to-element mapping (Optical imaging)				S					L
		Differential GPS within swarm (if LEO)					X				
	Relative Motion of swarm elements	Element-to-element ranging (RF ranging)					S				L
		Element-to-element ranging (RF Radar)					S				L
		Element-to-element ranging (Optical ranging)				S				L	
		Differential GPS within swarm (if LEO)				S					
Communications	Swarm-Ground	Traditional RF (HF, S, X, Ka)							S		L
		Optical						S			L
	Intra-swarm (between elements)	Traditional RF (HF, S, X, Ka)							S		L
		Non-traditional RF (higher bands)					X				
		Optical					X				
Control	Swarm element orientation	Reaction Wheels									X
		Propulsive (e.g. cold gas)									X
		Mag Torquers (if LEO)									X
	Swarm element relative position	Propulsive (pressurized)								X	
		Propulsive (chemical)					X				
		Propulsive (electric)				X					
		Differential drag (if LEO)					X				
Operations	Swarm element commanding	Direct ground-to-element									X
	Intra-swarm command relay	Ground relay through one swarm element						X			
	Swarm autonomy	High-level commanding of the entire swarm			X						
		Swarm self-navigation			X						
Access	ISS	Deployment									X
	Secondary Payload	Deployment									X
	Commercial Hosted	Interface Standards								X	
	NASA Hosted (carried by a primary)	Accommodation Standards								X	
	Mothership (powered-ESPA or custom)	Accommodation Standards								X	
		Communications Relay					X				X
		Relative Navigation				X					
	Dispenser	Simultaneous Deployment						High			Low
		High Precision Deployment						High			Low

TRL levels are based on: whether we know how to do it on the ground (4/5), whether we have done an in-space demo (6), or whether it routinely flies (9). Below 4 means we don't yet know how to do it aside from early research.

Example Technology Demonstration Sequence

General	Specific	Technologies	Demonstration Targets
Knowledge	Absolute Position & Velocity of swarm	Ground Ranging/Tracking of one element	Mission 1
		GPS (if LEO)	Mission 1
		JSPOC Elsets	Mission 1
	Absolute Orientation of Swarm	Derived from element positions	Mission 1
	Relative Position of swarm elements	Element-to-element mapping (RF Radar)	Mission 3
		Element-to-element mapping (Optical imaging)	Mission 2
		Differential GPS within swarm (if LEO)	Mission 1
	Relative Motion of swarm elements	Element-to-element ranging (RF ranging)	Mission 2
		Element-to-element ranging (RF Radar)	Mission 3
		Element-to-element ranging (Optical ranging)	Mission 2
		Differential GPS within swarm (if LEO)	Mission 1
	Timing	Spacecraft Clock Synchronization	Mission 1
Communications	Swarm-Ground	Traditional RF (HF, S, X, Ka)	Mission 1
		Optical	Mission 3
	Intra-swarm (between elements)	Traditional RF (HF, S, X, Ka)	
		Non-traditional RF (higher bands)	Mission 1
		Optical	Mission 2
Control	Swarm element orientation	Reaction Wheels	Mission 1
		Propulsive (e.g. cold gas)	Mission 2
		Mag Torquers (if LEO)	Mission 1
	Swarm element relative position	Propulsive (pressurized)	Mission 2
		Propulsive (chemical)	Mission 3
		Propulsive (electric)	Mission 2
		Differential drag (if LEO)	Mission 1
Operations	Swarm element commanding	Direct ground-to-element	Mission 1
	Intra-swarm command relay	Ground relay through one swarm element	Mission 1
	Swarm autonomy	High-level commanding of the entire swarm	Mission 2
		Swarm self-navigation	Mission 3
Access	ISS	Deployment	
	Secondary Payload	Deployment	Mission 1
	Commercial Hosted	Interface Standards	
	NASA Hosted (carried by a primary)	Accommodation Standards	
	Mothership (powered-ESPA or custom)	Accommodation Standards	
		Communications Relay	Mission 3
		Relative Navigation	
	Dispenser	Simultaneous Deployment	Mission 1
		High Precision Deployment	Mission 2

Demonstration Sequence Incremental Goals

Mission	Top-Level Goals	Individual Goals	Technology Focus
Mission 1	Knowledge	Absolute Position, Velocity & Orientation of swarm; Relative Position & Motion of swarm elements; clock sync	Ground, GPS, JSPOC and dGPS
	Communications	Swarm-to-Ground; Intra-swarm (between elements)	RF
	Control	Swarm element orientation and position	RW & MT; Differential Drag
	Operations	Intra-swarm command relay	RF
	Access	Secondary Payload	Low-precision deployment
Mission 2	Knowledge	Absolute Position, Velocity & Orientation of swarm; Relative Position & Motion of swarm elements	RF & Optical Ranging, Optical Imaging
	Communications	Swarm-to-Ground; Intra-swarm (between elements)	RF & Optical
	Control	Swarm element orientation and position	Propulsion (cold-gas) and Differential Drag
	Operations	High-level commanding of the swarm	Command & Maintain swarm configuration
	Access	Secondary Payload	High-precision deployment (time)
Mission 3	Knowledge	Absolute Position, Velocity & Orientation of swarm; Relative Position & Motion of swarm elements	RF RADAR, Optical LIDAR
	Communications	Swarm-to-Ground; Intra-swarm (between elements)	RF & Optical
	Control	Swarm element orientation	Propulsion (chemical) and/or Electric
	Operations	High-level commanding & Swarm self-navigation	On-board Nav with Ground-in-Loop
	Access	Secondary Payload	High-precision deployment (time & separation)

Swarm Technology Development Strategy

"Many high-priority science investigations of the future will require data from constellations or swarms of 10 to 100 spacecraft that, for the first time, would have the spatial and temporal coverage to map out and characterize the physical processes that shape the near-Earth space environment." – Achieving Science with CubeSats: Thinking Inside the Box (2016 NAS/SSB Report)

Swarm Technology Components

Knowledge	How do we know the positions and movements of the spacecraft in the swarm?
Communications	How do we get information to and from the spacecraft in the swarm?
Control	How do we maintain the configuration of spacecraft in the swarm?
Operations	How do we command the swarm configuration and return data from it?
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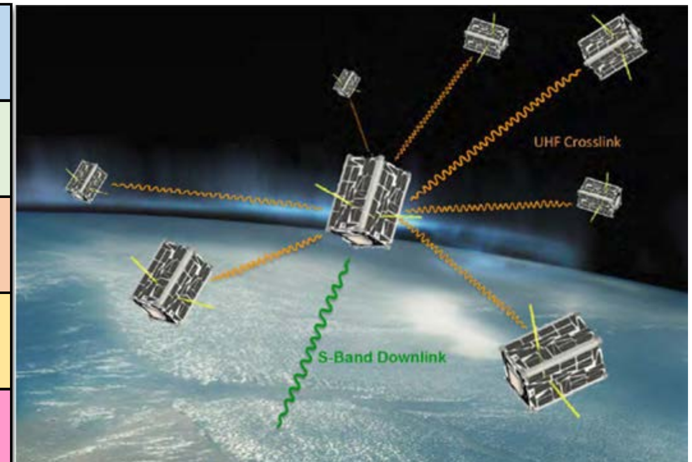


Previous Missions: NODES, OCSD, CPODS

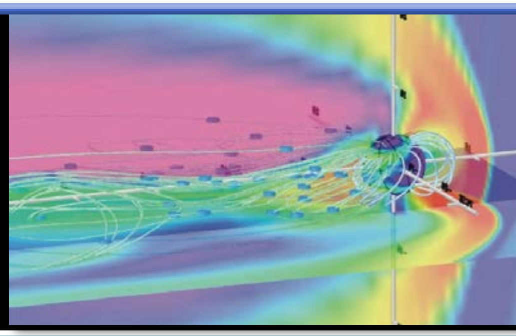
Technology Demonstration Missions (LEO)

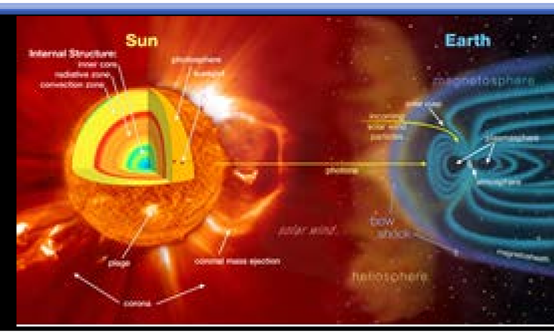
End Goal: Enable Swarm Technologies for future science missions

Mission 1	**Mission 2**	**Mission 3**
Ground, GPS, JSPOC and dGPS	RF & Optical Ranging, Optical Imaging	RF RADAR, Optical LIDAR
RF	RF & Optical	RF & Optical
RW & MT	Propulsion (cold-gas) and Differential Drag	Propulsion (chemical) and/or Electric
RF	Command & Maintain swarm configuration	On-board Nav with Ground-in-Loop
Low-precision deployment	High-precision deployment (time)	High-precision deployment (time & separation)

Swarm Technology Development Strategy

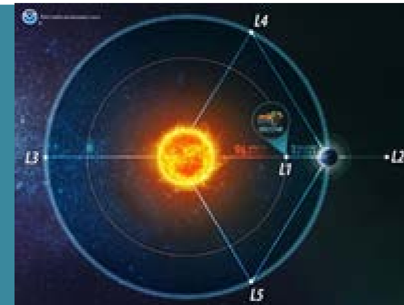
Decadal Missions





Deep Space

MIDEX-class Heliophysics Science Mission using swarms as the proving ground for larger Decadal Missions



Potential "MagKitty" concept

GEO/GTO

Mothership Relay Demo: A larger spacecraft carries the CubeSats to their destination orbit, deploys them, and then supplies communications relay functions to Earth

Potential Starling-4 demonstration

LEO

Previous Missions: NODES, OCSD, CPODS

Technology Demonstration Missions (LEO)

Starling 1,2 and 3

Mission 1		Mission 2		Mission 3	
	Ground, GPS, JSPOC and dGPS		RF & Optical Ranging, Optical Imaging		RF RADAR, Optical LIDAR
	RF		RF & Optical		RF & Optical
	RW & MT		Propulsion (cold-gas) and Differential Drag		Propulsion (chemical) and/or Electric
	RF		Command & Maintain swarm configuration		On-board Nav with Ground-in-Loop
	Low-precision deployment		High-precision deployment (time)		High-precision deployment (time & separation)

Enabling a Swarm Collective

The Problem: Swarm missions need on-board autonomy

- **Large numbers of spacecraft are extremely costly to operate**
  - Current practice requires a marching army at mission control ($$$$)
  - Ground control is a ops bottleneck (due to time delay, limited bandwidth, unavailable communications, # of spacecraft, etc.)
  - To be cost-effective, swarms must be **operable as a “collective”** (single unit)
- **We do not know how to work with a spacecraft collective**
  - We only know how to do complex planning, scheduling, etc for individual spacecraft
  - Many open issues with commanding, health management, reliability, etc.
  - To be effective, system architecture must be capable of **collective execution** and **collective management**
- **Acquiring adaptive and distributed measurements is hard**
  - Must orchestrate complex activities with sporadic, uncertain, or noisy data
  - Difficult to coordinate across and between multiple spacecraft
  - To be responsive, swarms must be capable of **adaptive reconfiguration** and **distributed decision making**

Swarm Autonomy is the Tall Pole

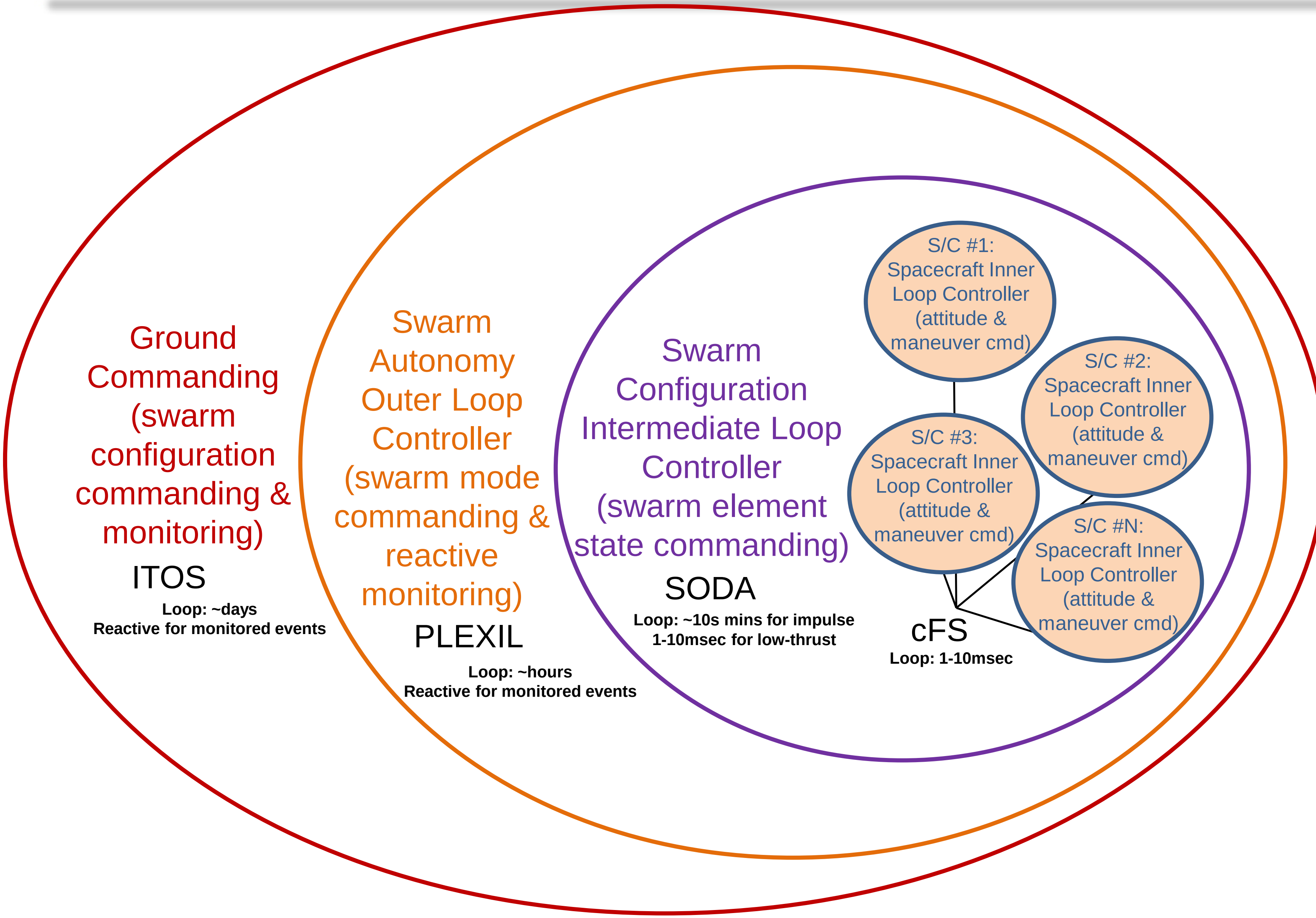
SWARM Technology Components

Key: **L** = Large Spacecraft, **S** = Small Spacecraft
Low = Low precision, **High** = High precision

General	Specific	Technologies	Availability (TRL)								
			1	2	3	4	5	6	7	8	9
Knowledge	Absolute Position & Velocity of swarm	Ground Ranging/Tracking of one element									X
		GPS (if LEO)									X
		JSPOC Elsets									X
	Absolute Orientation of Swarm	Derived from element positions					X				
	Relative Position of swarm elements	Element-to-element mapping (RF Radar)					X				
		Element-to-element mapping (Optical imaging)				S					L
		Differential GPS within swarm (if LEO)					X				
	Relative Motion of swarm elements	Element-to-element ranging (RF ranging)					S				L
		Element-to-element ranging (RF Radar)					S				L
		Element-to-element ranging (Optical ranging)				S				L	
		Differential GPS within swarm (if LEO)				S				L	
	Timing	Spacecraft Clock Synchronization					S				L
Communications	Swarm-Ground	Traditional RF (HF, S, X, Ka)							S		L
		Optical						S			L
	Intra-swarm (between elements)	Traditional RF (HF, S, X, Ka)							S		L
		Non-traditional RF (higher bands)					X				
		Optical					X				
Control	Swarm element orientation	Reaction Wheels									X
		Propulsive (e.g. cold gas)									X
		Mag Torquers (if LEO)									X
	Swarm element relative position	Propulsive (pressurized)								X	
		Propulsive (chemical)					X				
		Propulsive (electric)				X					
		Differential drag (if LEO)					X				
Operations	Swarm element commanding	Direct ground-to-element									X
	Intra-swarm command relay	Ground relay through one swarm element						X			
	Swarm autonomy	High-level commanding of the entire swarm			X						
		Swarm self-navigation			X						
Access	ISS	Deployment									X
	Secondary Payload	Deployment									X
	Commercial Hosted	Interface Standards								X	
	NASA Hosted (carried by a primary)	Accommodation Standards								X	
	Mothership (powered-ESPA or custom)	Accommodation Standards								X	
		Communications Relay					X				X
		Relative Navigation				X					
	Dispenser	Simultaneous Deployment						High			Low
		High Precision Deployment						High			Low

TRL levels are based on: whether we know how to do it on the ground (4/5), whether we have done an in-space demo (6), or whether it routinely flies (9). Below 4 means we don't yet know how to do it aside from early research.

Swarm Architecture as Nested Controllers



Swarm Controller Interfaces

Ground Commanding (swarm configuration commanding & monitoring)
ITOS
Loop: ~days
Reactive for monitored events

Swarm Autonomy Outer Loop Controller (swarm mode commanding & reactive monitoring)
PLEXIL
Loop: ~hours
Reactive for monitored events

Swarm Configuration Intermediate Loop Controller (swarm element state commanding)
SODA
Loop: ~10s mins for impulse
1-10msec for low-thrust

S/C #1: Spacecraft Inner Loop Controller (attitude & maneuver cmd)
cFS
Loop: 1-10msec

<u>Command</u>
Ellipse (traj/vol/limits desired)
Maintain (sci obs mode)

<u>Response</u>
Ellipse (traj/vol actuals)
Swarm out of limits alert
Sci Obs data

<u>Command</u>
Go To Ellipse (traj/vol/limits)
Maintain (traj/vol/limits)

<u>Response</u>
Actual Ellipse OD (traj/vol)
Traj out of limits alert

<u>Command</u>
S/C #1: T, dV

<u>Response</u>
S/C #1: OD
dV Exec Errors

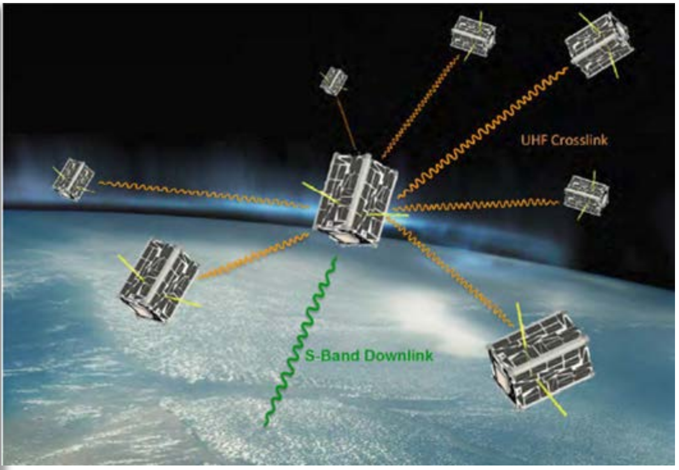
<u>Command</u>
S/C Mode (sci obs)

<u>Response</u>
S/C condition out of limits
Sci Obs data

Swarm Autonomy Development Strategy

Swarm Technology Components

Knowledge	How do we know the positions and movements of the spacecraft in the swarm?
Communications	How do we get information to and from the spacecraft in the swarm?
Control	How do we maintain the configuration of spacecraft in the swarm?
Operations	How do we command the swarm configuration and return data from it?
Access	How do we get the swarm into space and deploy it?



Lowest TRL Component

End Goal: Enable Swarm Capabilities for future science missions

Previous Missions: NODES, OCSD, CPODS

SSTP Technology Demonstration Missions

Starling Mission 1		Mission 2		Mission 3	
	Ground, GPS, JSPOC and dGPS		RF & Optical Ranging, Optical Imaging		RF RADAR, Optical LIDAR
	RF		RF & Optical		RF & Optical
	RW & MT		Propulsion (cold-gas) and Differential Drag		Propulsion (chemical) and/or Electric
	RF		Command & Maintain swarm configuration		On-board Nav with Ground-in-Loop
	Low-precision deployment		High-precision deployment (time)		High-precision deployment (time & separation)

Swarm Autonomy Development enables Missions 2 and 3 of an SSTP series

Technology Insertion Use-Case DRM

Context: 4-6 spacecraft, precision deployment (low dispersions & tip-offs)
Target swarm configuration: 350Km LEO, 20km x 10km x 5km ellipsoid, statistically even spatial coverage over 1 year.

Event	State Entered	Actions	Initiated By
Launch	Passive	None	N/A
Deployment	Spacecraft Activation	Individual swarm spacecraft power-up, enter power positive stable attitude, establish communications (cross or ground)	Separation
Swarm Activation	Swarm Activation	Swarm spacecraft establish cross-link capability and initiate swarm autonomy outer-loop control	ITOS
Initial Orbit Configuration	Swarm dV mode	Outer loop initiates intermediate loop, provides desired configuration, then intermediate loop commands S/C dV	PLEXIL
Baseline Operations	Swarm Nominal	Intermediate loop is monitoring swarm trajectories, and issuing correction maneuvers to individual spacecraft	SODA
Baseline Operations	Swarm Off-nominal	Outer loop is monitoring for off-nominal conditions and issuing new swarm configuration commands to intermediate loop per science plan	PLEXIL
Off-nominal condition	Swarm Safe Mode	Inner loops commanded to S/C safe mode. Intermediate loop transitions to passive mode. Outer loop diagnoses and attempts auto-recovery or responds to ground commands.	PLEXIL or ITOS