CubeSat Formation Flying

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Workshop on CubeSat-based Low Frequency Radio Astronomy Missions

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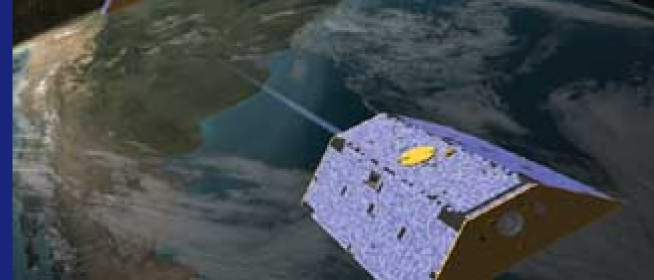
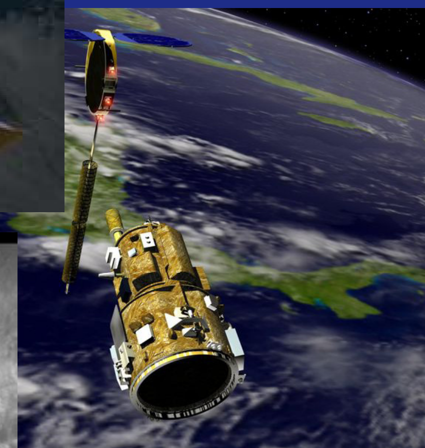
Image: *UT-Austin Satellite Design Lab*

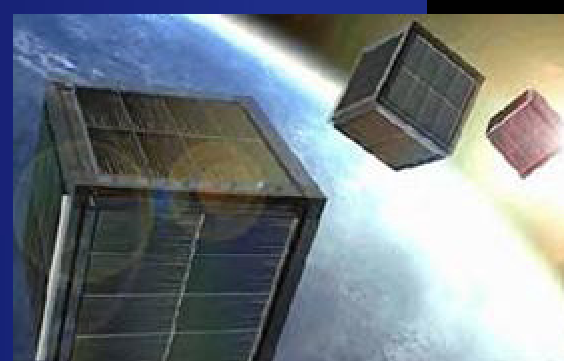
Formation Flying Missions: Past and Future

A partial list of relevant missions

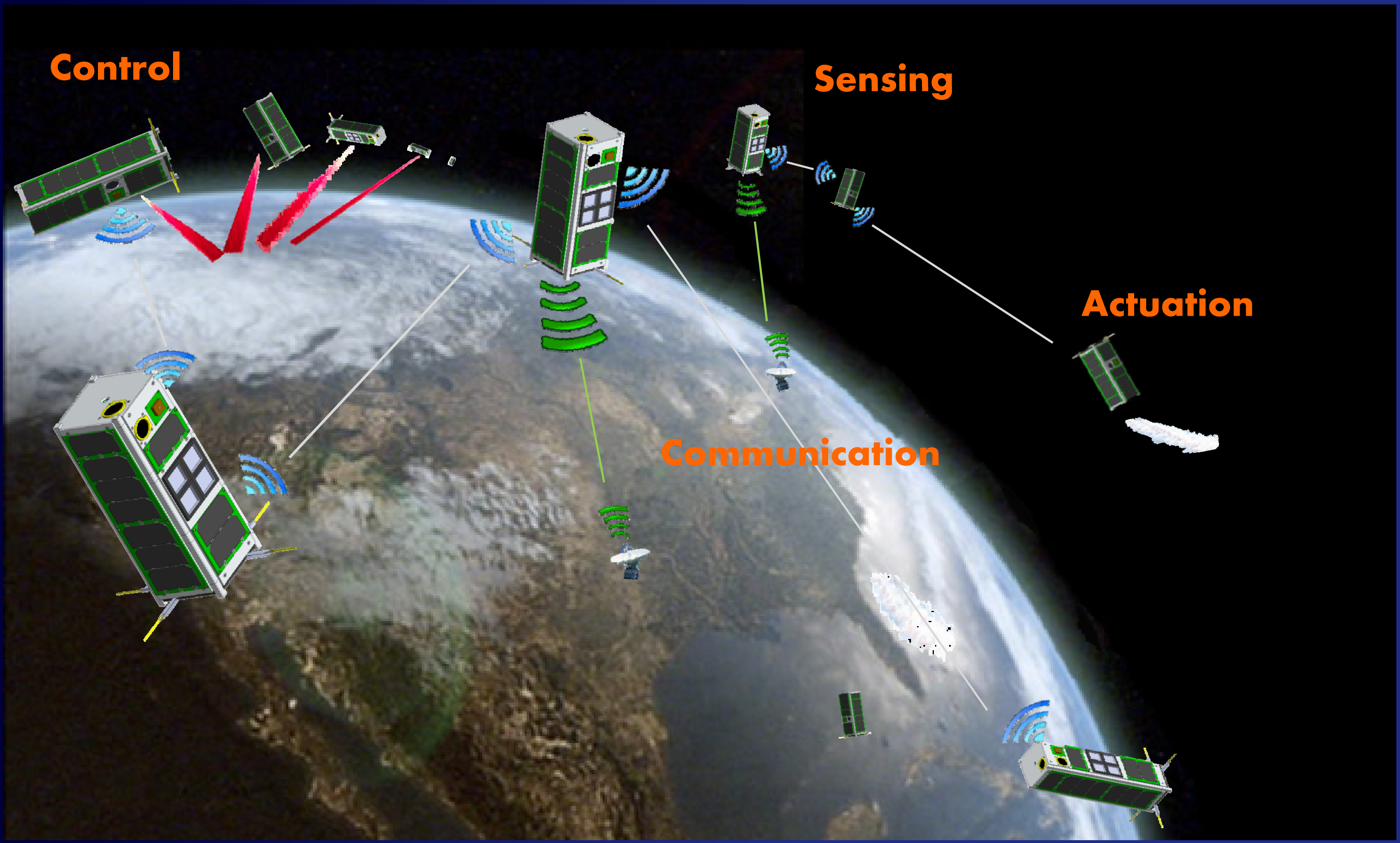
- EO-1 (NASA, 2000)
- SNAP-1 (Europe, 2000)
- GRACE (NASA, 2002)
- DART (NASA, 2005)
- XSS-11 (DOD, 2005)
- Orbital Express (DOD, 2007)
- ANDE (DOD, 2009)
- FASTRAC (DOD, 2010)
- Prisma (Europe, 2010)
- TanDEM-X (Europe, 2010)
- LoneStar-2 (NASA, 2013)
- EtherSat (NASA, ~2014)
- QB50 (Europe, ~2015)





Formation Flying
Technology Elements

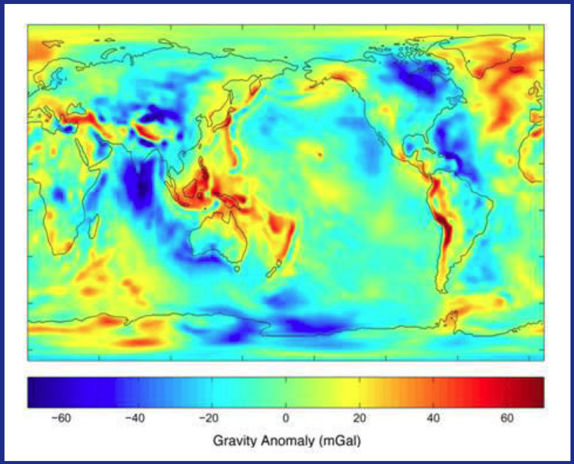


Sensing

Considerations

- Measurement Accuracy
- Active vs. Passive
- Absolute vs. Relative
- LEO vs. Beyond LEO
- Real-time vs. Post Processed
- Compatibility with Science Measurement
- Technical Maturity and Availability
- Size, Weight, Power and Cost (always!)

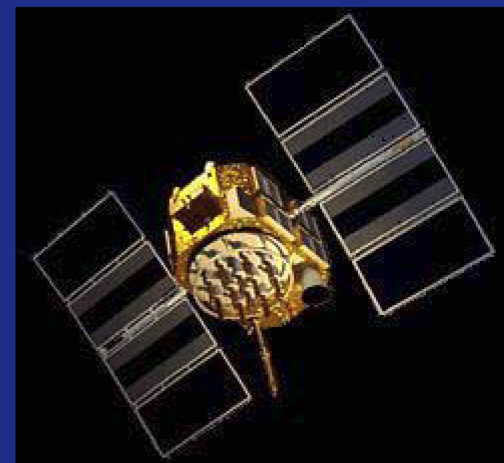
Example real-time navigation problem

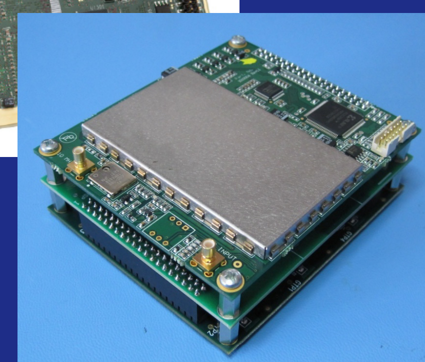


Scientific result based upon post-processed navigation (GRACE)

Absolute Position Sensing in LEO

- Global Navigation Satellite Systems (e.g. GPS)
- Need for low-cost navigation makes GPS receivers ubiquitous on LEO space missions
- Performance unlikely to be matched by any other comparable technology
- Absolute Nav in WGS-84 geodetic reference frame
- Passive, LEO navigation sensor (up to ~1000+ km, higher with special systems)
- Weak signal susceptible to self-induced EMI
- Real-time nav accuracy: meter-level
- Post-processed accuracy: decimeter/centimeter-level



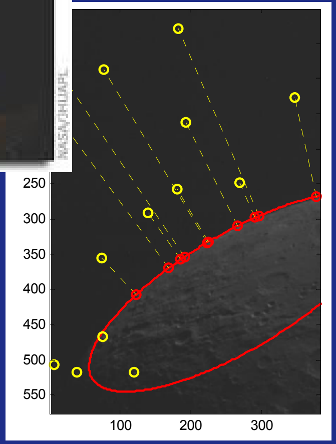


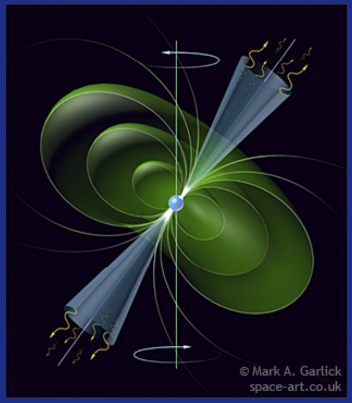
Example CubeSat capable GPS receivers (Novatel and FOTON)

Absolute Position Sensing Beyond LEO

- Deep Space Network: traditional comm beyond Earth orbit
  - Requires scheduling dedicated NASA resources
- Optical Navigation via planetary imaging
  - Requires satellite be near a moon or planet
  - Accuracies are low (km-level)
- Future nav: X-ray pulsars?
  - Timing of pulses acts like GPS wavefronts for navigation
  - Low Technology Readiness Level
  - Questionable implementation on CubeSats

NASA's Deep Space Network



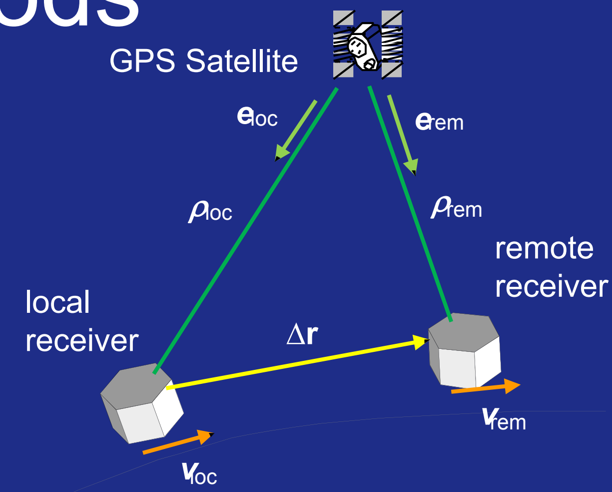


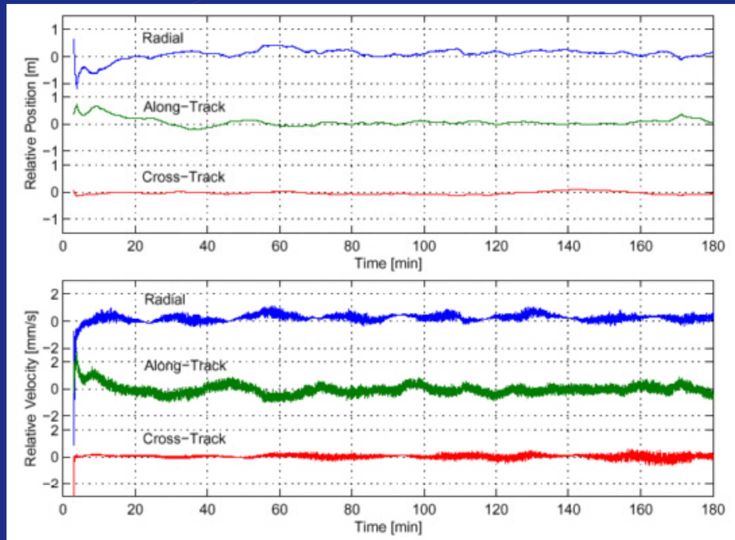
Optical nav using star-horizon measurements; an X-ray pulsar

Relative Position Sensing
Differencing Methods

- Differencing measurements allows correlated errors to cancel, enabling more accurate relative measurements
- Independent noise sources are root-sum-squared, increasing noise
- Overall accuracy depends on which effect dominates

- Common timing source is essential (GPS or independent clock)
- GPS position fixes or raw measurements (e.g. pseudorange and carrier phase) may be differenced
- Problematic approach beyond Earth orbit due to limited availability of a common signal source (e.g. GPS)

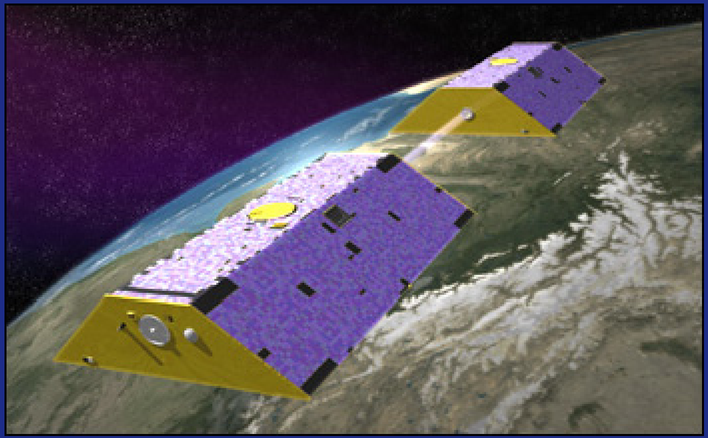


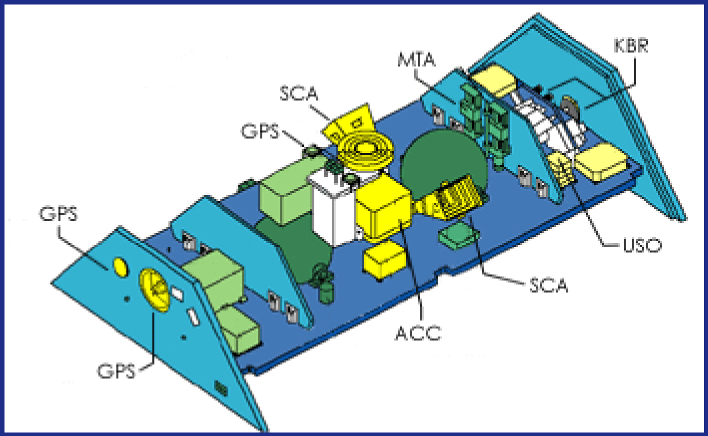


GPS relnav can achieve sub-meter accuracy

Relative Position Sensing
One Way Ranging Methods

- Potentially more accurate than differencing methods
  - E.g. GRACE Ku-band
- Can work in combination with absolute nav system like GPS
- Can be customized to system design
- Some technology development needed for CubeSat hardware
- Requires time synchronization (from GPS or external clock)
- Satellite networks may use overdetermined systems to improve accuracy/robustness

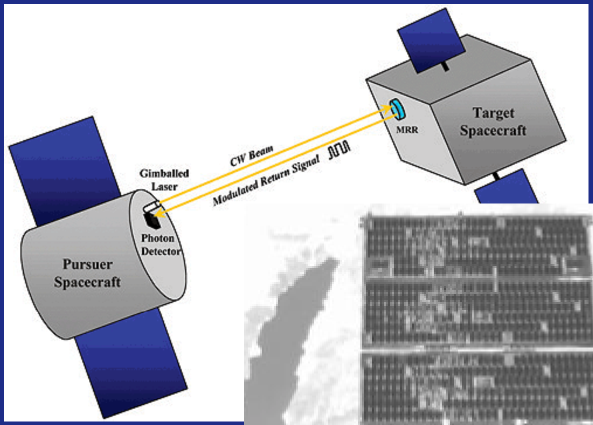


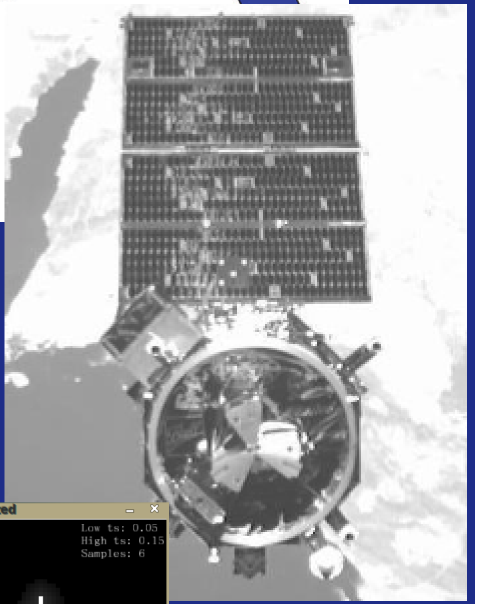


GRACE is an example of a combined GPS/Ku-band ranging system

Relative Positioning Sensing Optical/Infrared Methods

- Optical Comm can act as a one way ranging signal
  - Requires t tighter pointing capability
  - Hardware non-existent for CubeSats
- Visual nav may be either pose-based or centroid-based
  - Good accuracies (meter-level) are possible over short distances (~100 m)
  - Consider lighting conditions and optics
  - Can detect motion (object identification), extract 2D velocity information
- Infrared systems are centroid based with longer range than visual
  - As long as line of sight is maintained, can track objects up to ~3 km
  - Centroid/blob based motion detection and tracking
  - Sensor technology still low TRLs for CubeSats

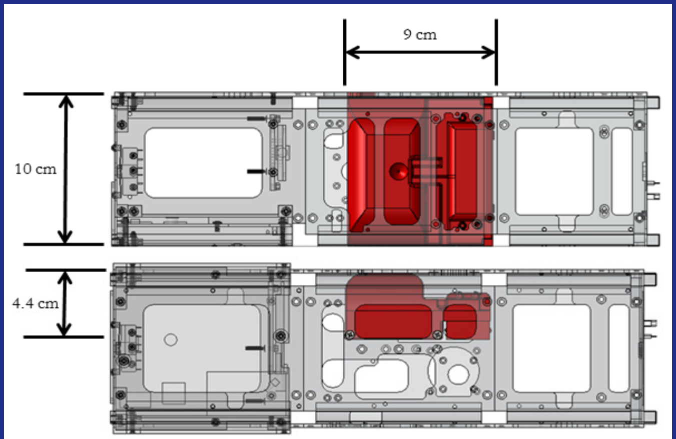




Optical, vision, and IR nav sensors

Actuation

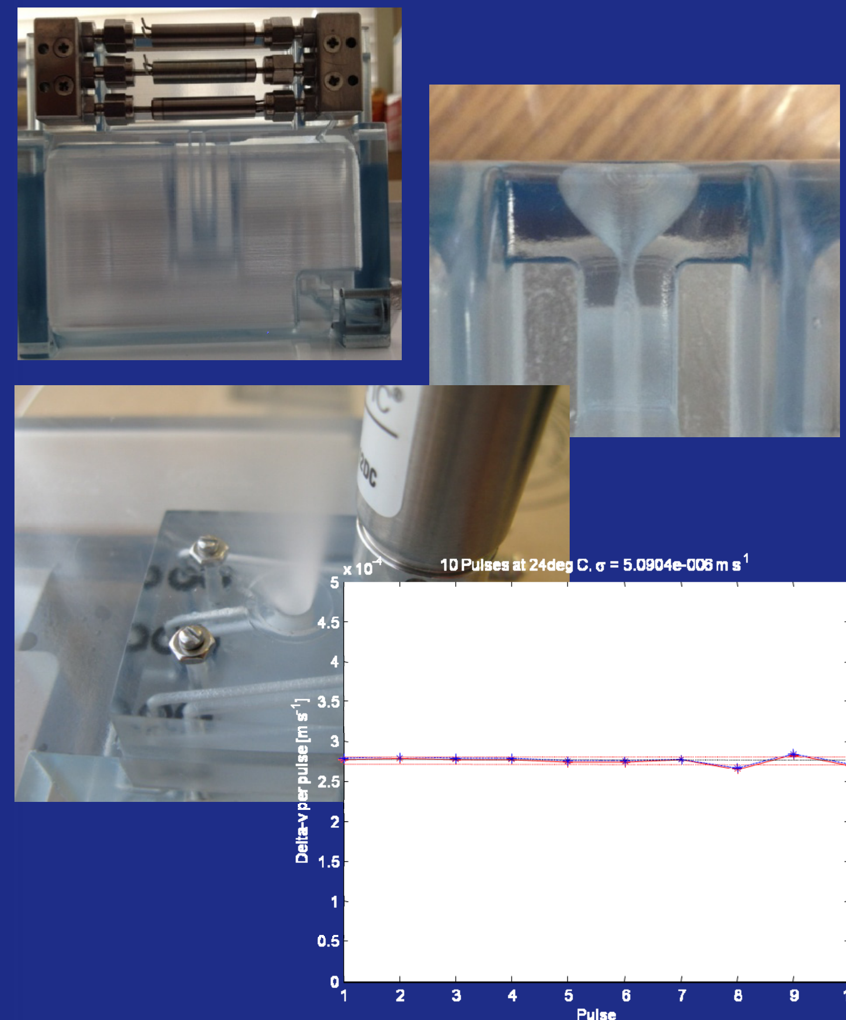
- Some “formations” do not require position-keeping; position determination is all that is necessary
- If position-keeping is required (relative or absolute), then actuation of some type is required
- Actuation may be classified as impulsive (instantaneous) or low-thrust (acts over time)
- Limited volume and power constrains choice of actuators for CubeSats
- Simplicity and cost are also design drivers



Example: CubeSat impulsive cold-gas Thruster design occupies 0.5U of a 3U volume

Impulsive Actuation: Propulsive Thrusters

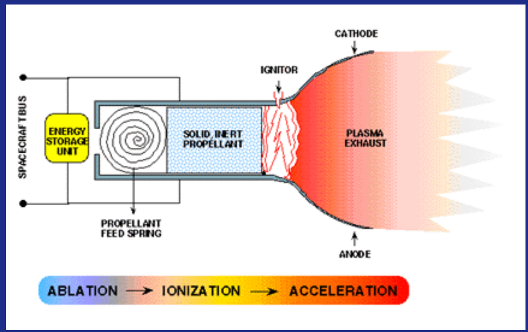
- Cold-gas thrusters are only technology available to provide impulsive actuation for CubeSats
- New rapid-prototype (SLA) design method (demonstrated on MEPSI, 2006) seems well-suited for CubeSat missions
- Using refrigerants as low pressure saturated liquid, propellants, 10-100 m/s delta-v's are possible on 3U and 6U CubeSats
- These are "green" propellants because they do not involve toxic materials or chemical reactions
- Hydrazine or other chemical propellants may be considered for higher delta-v capacity at the expense of simplicity and cost

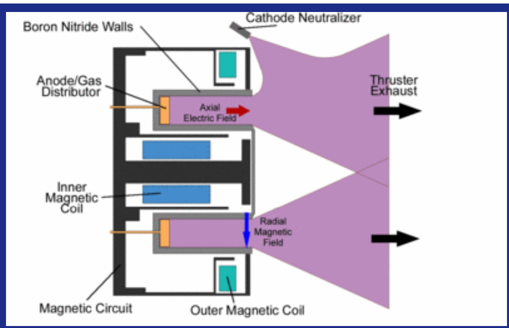


Stereolithographic (SLA) cold-gas thruster

Low Thrust Actuation: Propulsive Thrusters

- Pulsed-plasma thrusters (PPTs) and Hall-effect (ion) thrusters use solids (teflon) and inert gases (xenon) to create low-thrust actuators
- Such devices deliver small forces (e.g., ~1-100 microNewtons) over long periods of time to achieve an integrated effect
- For example, an orbit-raising maneuver could occur over several years to escape Earth's orbit
- Any mission using these devices must consider the time required and the implications for spacecraft reliability (e.g. radiation)
- Also consider high voltage effects, and spacecraft charging due to thruster operation
- The lack of impulsive capability makes these devices less useful for normal formation flying



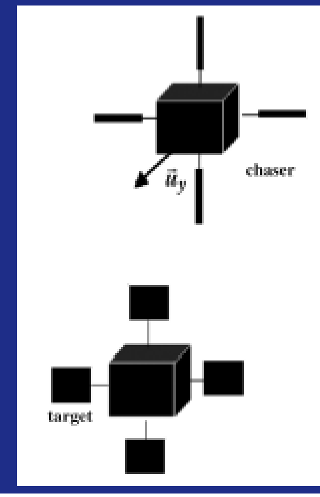


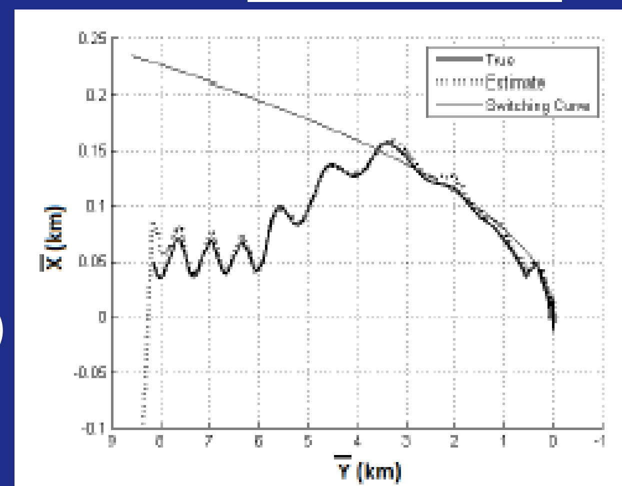
Block diagrams for PPT and Hall tthruster; xenon gas plasma glow

Low Thrust Methods in LEO: Drag/Differential Drag

- In LEO, can use the Earth's atmosphere as an actuator by changing vehicle's cross section along the velocity direction
- Can be done with drag control panels (picture) or by rotating the vehicle (attitude control)
- Differential drag force can be used to maneuver one vehicle's position relative to another
- Drag force only acts along velocity vector,

  so out-of-plane perturbations must be controlled using another method (e.g. thruster)
- Potentially useful method of "free" control to reduce mission delta-v requirements

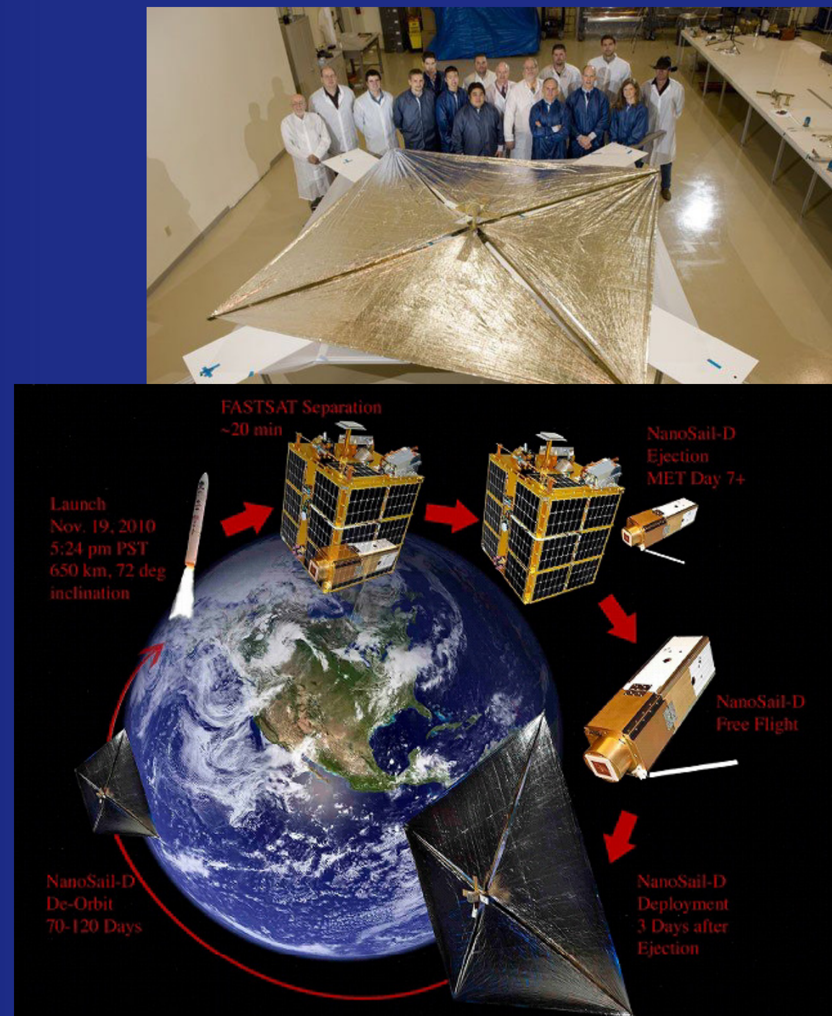




Drag panel conceptual design; simulated rendezvous using differental drag

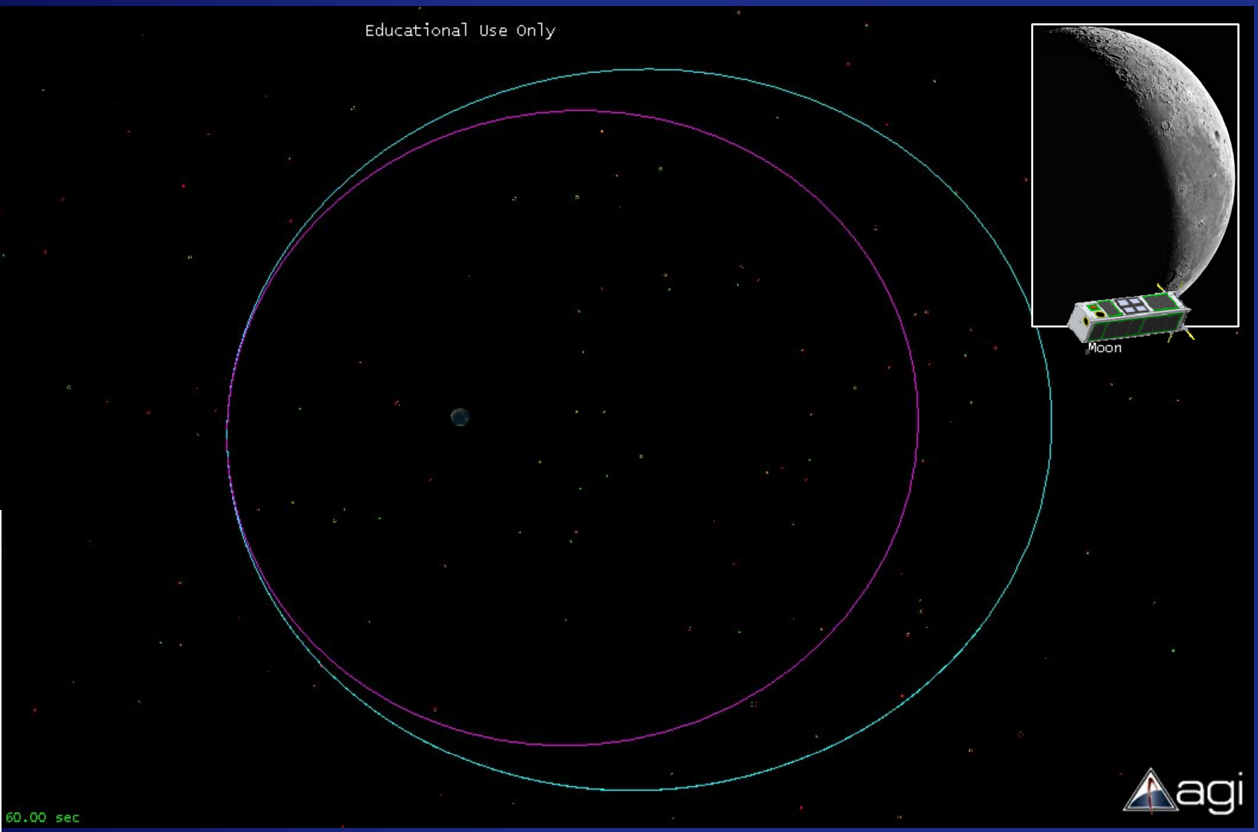
Low Thrust Actuation: Solar Sails

- Low-thrust force derived from photons bouncing off reflective material (e.g. mylar)
- To be efficient, material must cover a large area and be low mass
- Solar sail deployment from a CubeSat was demonstrated on Nanosail-D (2011) and is planned on Lightsail-1 (~2013)
- As a low thrust device, shares same system advantages and disadvantages as PPTs and Hall thrusters
- Control force is not possible in every direction instantaneously
- One of the coolest maneuver technologies being developed



CubeSat deployed solar sail and Nanosail-D

Kordylewski Cloud Mission Concept

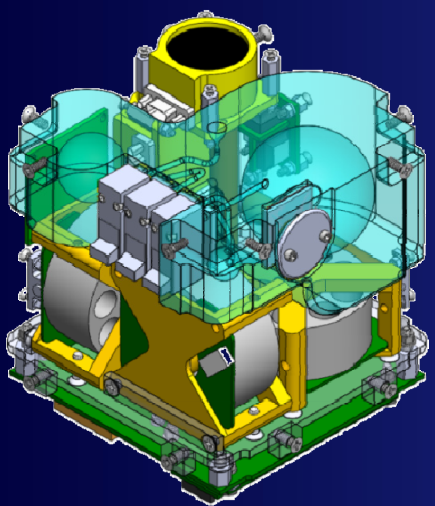


Images: *ESA, Univ. Stuttgart, Aerospace Corp., UT Austin Satellite Design Lab*

- CubeSat probe carried as a secondary payload during an Earth-Moon transfer
- Ejected from a SMART-1 type mission for L4/L5 fly-through
- Impulsive cold-gas thruster is able to provide needed delta-v for mission

Attitude Determination and Control

- Another possible type of formation flying
- CubeSat COTS integrated ADC solutions exist, but most are intended for LEO



Example: Integrated 1U 3-axis ADC with thruster

External Sensors	Estimated Accuracy (degrees)	Comment
Sun Sensor	0.1	available
Star Camera	0.01	in development
Horizon Detector	varies	used near planets/moons
Deep Space Network	1	requires NASA support
Earth Sensor	0.1	Earth orbit
Magnetometer	1	LEO
GPS	1	LEO

Actuators	Estimated Accuracy (degrees)	Comment
Reaction Wheels	0.01	available
Impulsive Thruster	0.01	in development
Solar sails	1	in development
Torque Rods	1	LEO

Formation Flying Control Challenges

- Complexity
  - Systems of systems (interconnection/coupling)
- Communication and Sensing
  - Limited bandwidth, connectivity, and range
  - What? When? To whom?
  - Data Dropouts, Robust degradation
- Arbitration
  - Team vs. Individual goals
- Resources
  - Always limited, especially on a CubeSat

Formation Architectures

- Leader/Follower Systems
  - Generally two satellites, stationkeeping, autonomous rendezvous, swarms
- Centralized Control
  - Centralized planning and coordination, global team knowledge, fully connected network
- Distributed Control
  - Local neighbor-to-neighbor interaction, action evolves in parallel manner

Biologically Inspired Examples of Distributed Formation Flying

Flocking

Schooling

Swarming

Herding

Local Interaction (limited information relay)
Collective Group behavior

Can modern controllers produce similar dynamic behaviors?

Decentralized Control of Networked Multi-agent Systems – Research Overview

Problem Types

- Periodic motion coordination
- Consensus/synchronization/agreement
- Collective tracking with a dynamic leader
- Containment control with multiple leaders
- Distributed average tracking
- Distributed optimization

Dynamic Models

- Linear dynamics: single-integrator, double-integrator, general
- Rigid body attitude dynamics
- Lagrangian dynamics
- More general nonlinear dynamics

Challenges

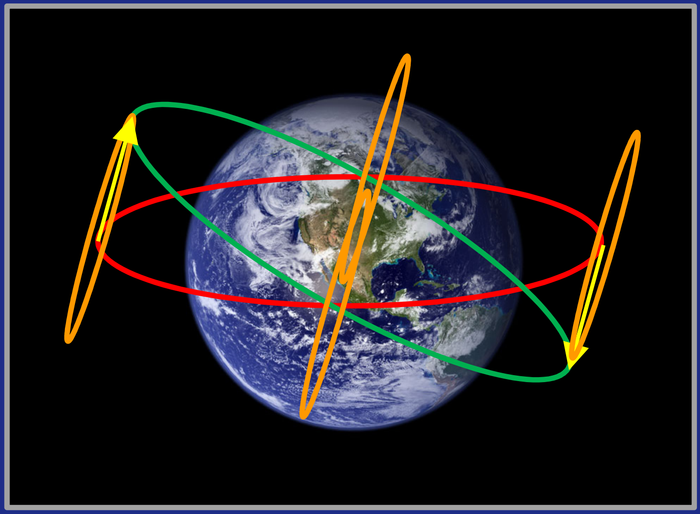
- Intermittent interaction, data dropouts
- Optimality, limited resources
- Time delay

Topologies

- Fixed network
- Switching network
- Extensible network

Passively Stable Formation Flying

- Linearized orbit dynamics admits passively stable solutions where one or more satellites co-orbits a circular reference orbit
- Satellites placed in these orbits can maintain a planar orientation relative to the reference orbit
- Accounting for perturbations still requires the existence of a control system

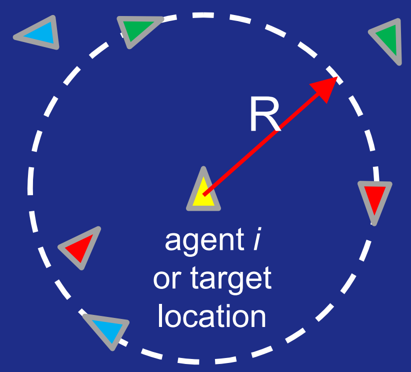


The satellite in the green orbit co-orbits the reference red orbit

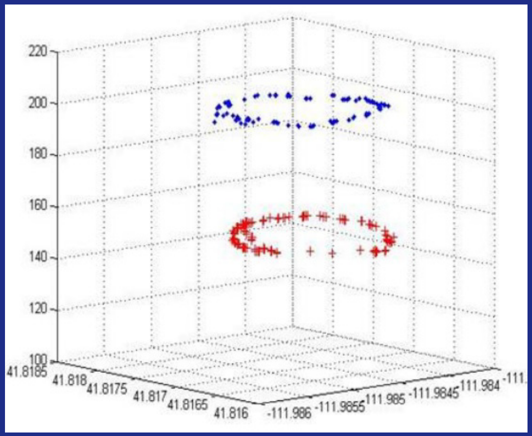
- Using a passively stable reference design can greatly reduce actuation requirements

Consensus Control

- Interact with local neighbors to reach an agreement
- Applications: cooperative timing, rendezvous, formation control, attitude synchronization, etc.
- UAV co-orbiting consensus result achieved in practice



Neighboring agents initial and final co-orbiting positions



Reconstructed UAV formation flying trajectories

Consensus Example: Attitude Synchronization

Rigid Body Dynamics

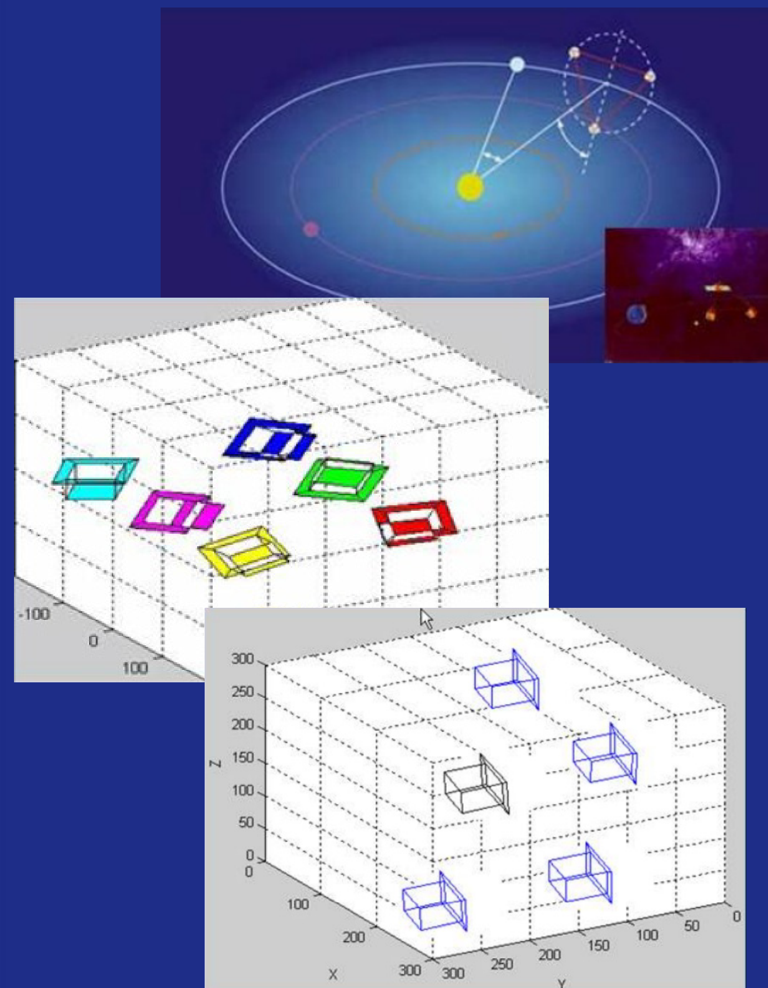
$$\dot{\hat{q}}_i = -\frac{1}{2}\omega_i \times \hat{q}_i + \frac{1}{2}\bar{q}_i\omega_i, \quad \dot{\bar{q}}_i = -\frac{1}{2}\omega_i \cdot \hat{q}_i$$

$$J_i\dot{\omega}_i = -\omega_i \times \left(J_i\omega_i\right) + \tau_i$$

Control Torque

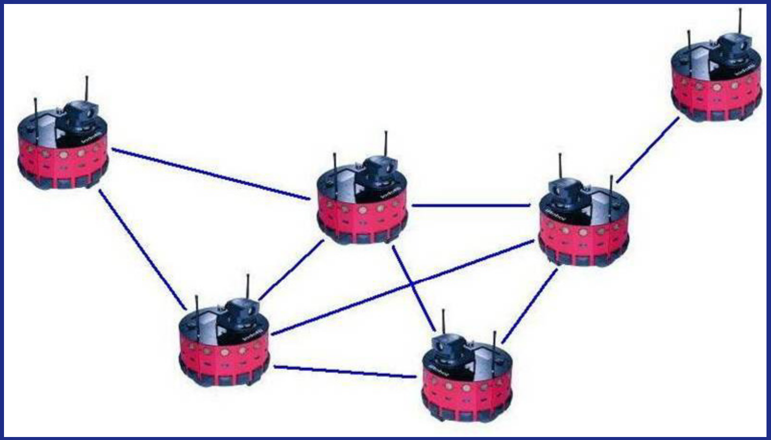
$$\tau_i = -k_G\hat{q}^d\hat{q}_i - d_G\omega_i - \sum_{j \in \mathrm{N}_i}\left[a_{ij}\hat{q}^*\hat{q}_i + b_{ij}\left(\omega_i - \omega_j\right)\right]$$

where k_G, d_G, a_{ij}, $b_{ij} > 0$;
q^d is desired constant attitude and
q^* is attitude error



Collective Tracking with a Dynamic Leader

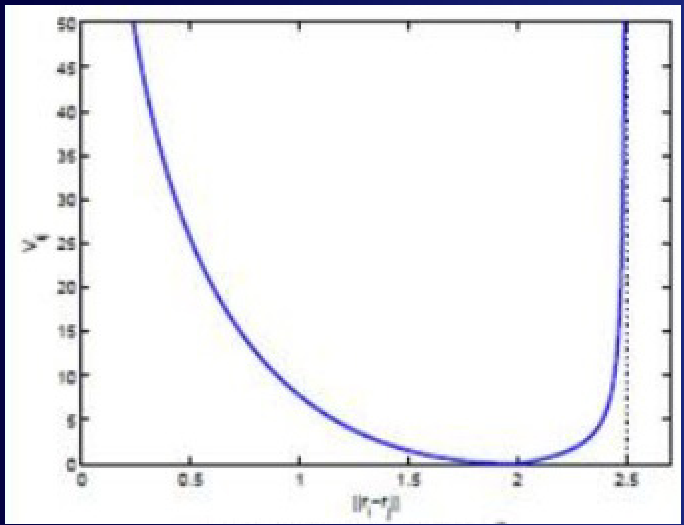
- Coordinated Tracking
  - A group of agents tracks or follows a dynamic leader in a prescribed manner
- Swarm Tracking
  - A group of agents moves cohesively with a dynamic leader while avoiding inter-agent collision
- Dynamic Leader
  - A physical agent, a location of interest, or a desired trajectory



Example robotic coordinated tracking with a dynamic leader

Swarm Tracking

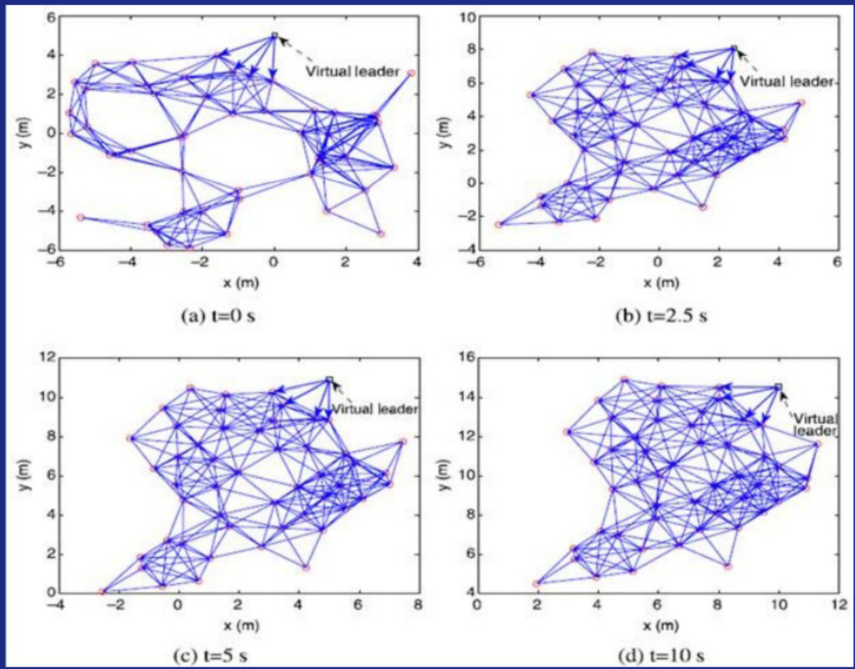
- Potential function V_{ij} function of each agent's pairwise distance with other agents



Distance-based potential function

- Swarm control law for followers

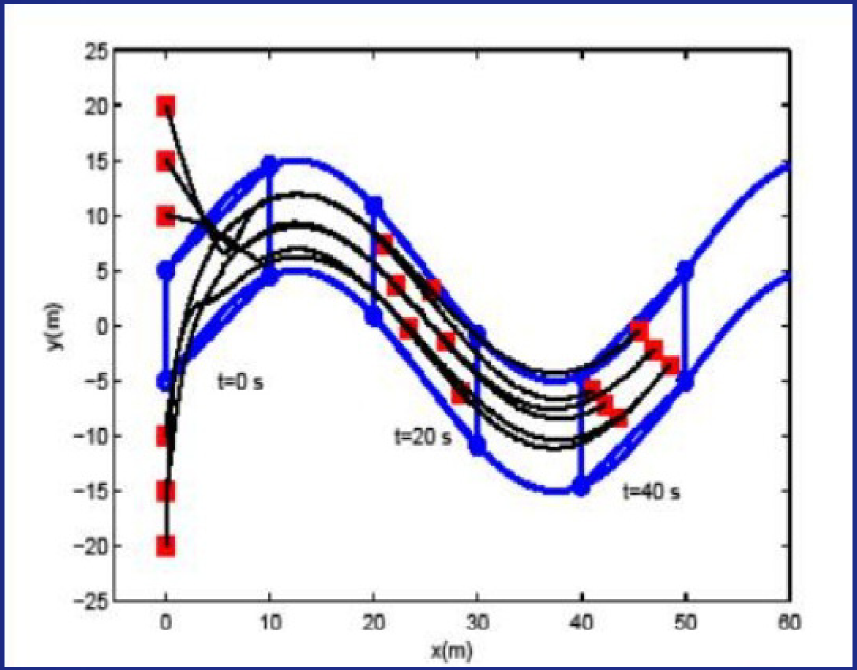
$$u_i = -\beta \operatorname{sgn}\left[\sum_{j \in N_i} \frac{\partial V_{ij}}{\partial \xi_i}\right], \quad i = 1, \ldots, n; \quad \beta > 0$$



Simulated swarming motion based on algorithm

Containment Control with Multiple Leaders

- A group of followers is driven by a group of leaders to be in the region formed by the leaders with only local interaction
- Applications: cooperative herding, grouping, autonomous convoys



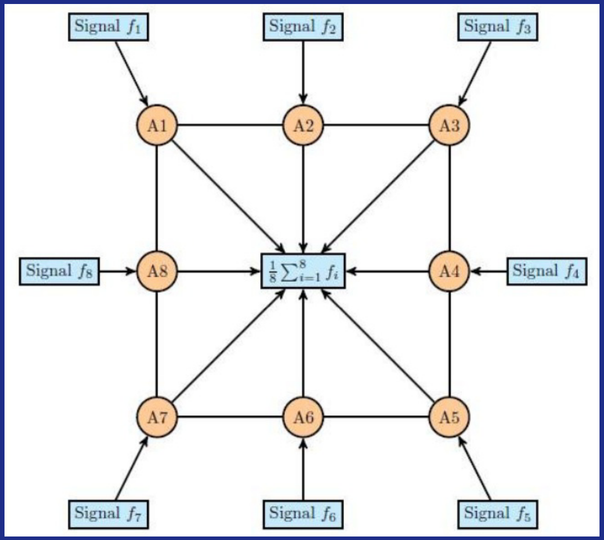
Containment control of formation while leader region is changing shape and moving

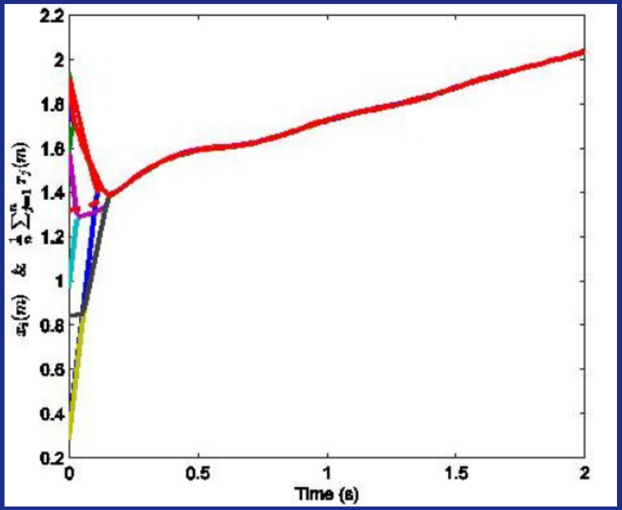
Distributed Average Tracking with Local Interaction

- Starting with separate initial conditions, all agents approach a common value in finite time with only local interaction

- Each agent maintains its own estimate of the average state and shares that with neighbors

- Example: All agents approach a common trajectory despite starting with different initial conditions





Communications Architectures

Intersatellite Communication Methods

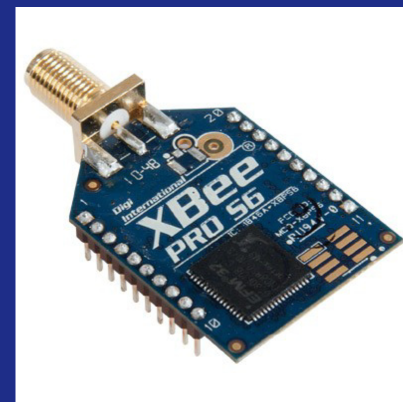
- Short range wireless
- Line of sight wireless
- Ground station relay
- Space based relay
- Space based communications network

Tradeoff Considerations

- Link distance
- Link bandwidth
- Frequency
- Number of contacts
- Data downlink
- Size, weight, power
- Technical Maturity/Risk
- Cost

Crosslink Communications

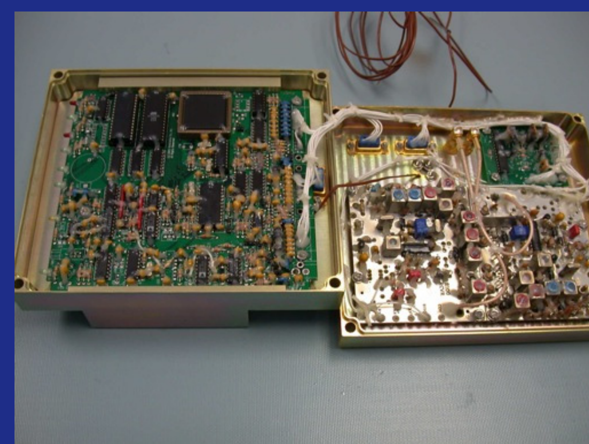
- Short Range Wifi
  - Employs existing standards and COTS components
  - Low size, weight, power, cost
  - Questionable survivability
  - Limited Range (few km)
  - Additional space-ground system required



Xbee Wifi transceiver

- Long Range (LOS) Crosslink
  - Traditional space-ground radios
  - Considerations: directionality of antennas, transmit power requirement, cost
  - Can also serve as space-ground link

- Multi-node frequency communication methods must be planned for formations (e.g. time indexing, CDMA, FDMA)

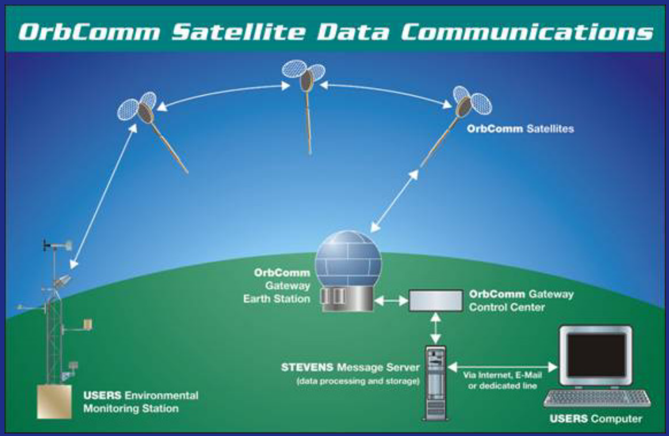


Kantronics KPC 9612
(used on FASTRAC)

Relay Architectures

- Ground Station Relays
  - Utilizes existing or new infrastructure
  - Store and forward concept enables over the horizon relays
  - Requires simultaneous visibility to satellites from multiple locations
  - Can be improved after launch
  - Cost could be a factor

- Space based Relays
  - Formation satellites relay messages to each other
  - Daisy chaining messages allows over the horizon to comms to any satellite in the network, provided each satellite can be seen by one other
  - Comm structure (frequency, format) would have to be developed custom for each mission

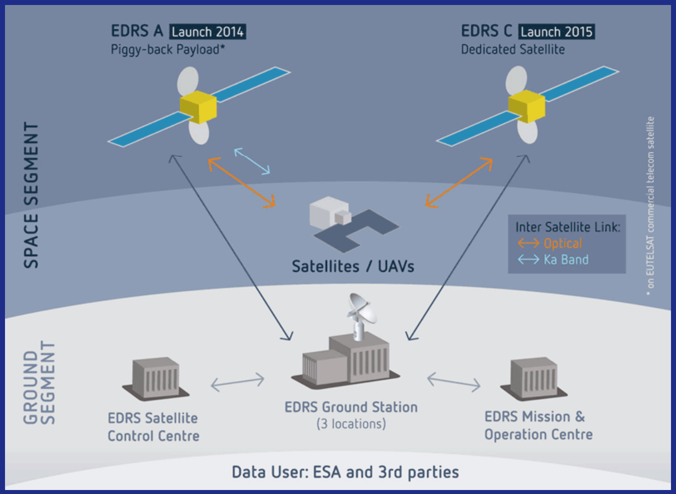


Example ground station relay (OrbComm)

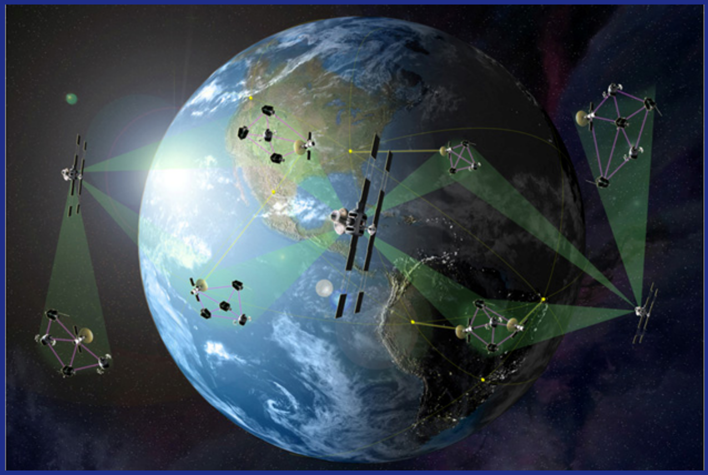
Example space based relay (Artemis)

Space Based Comm Network

- Concept: Utilize existing space-based commercial systems (e.g. Iridium, h<700 km) or future services (e.g. EDRS)
- Formation satellites use bent-pipe services to provide messages to other satellites
- Over the horizon capable
- Size, power, and range of the equipment must be considered (too large or too small)
- Amount of data transferred is a factor
- Only works in orbits where comm networks exist (e.g. LEO)
- Availability of future services is speculative

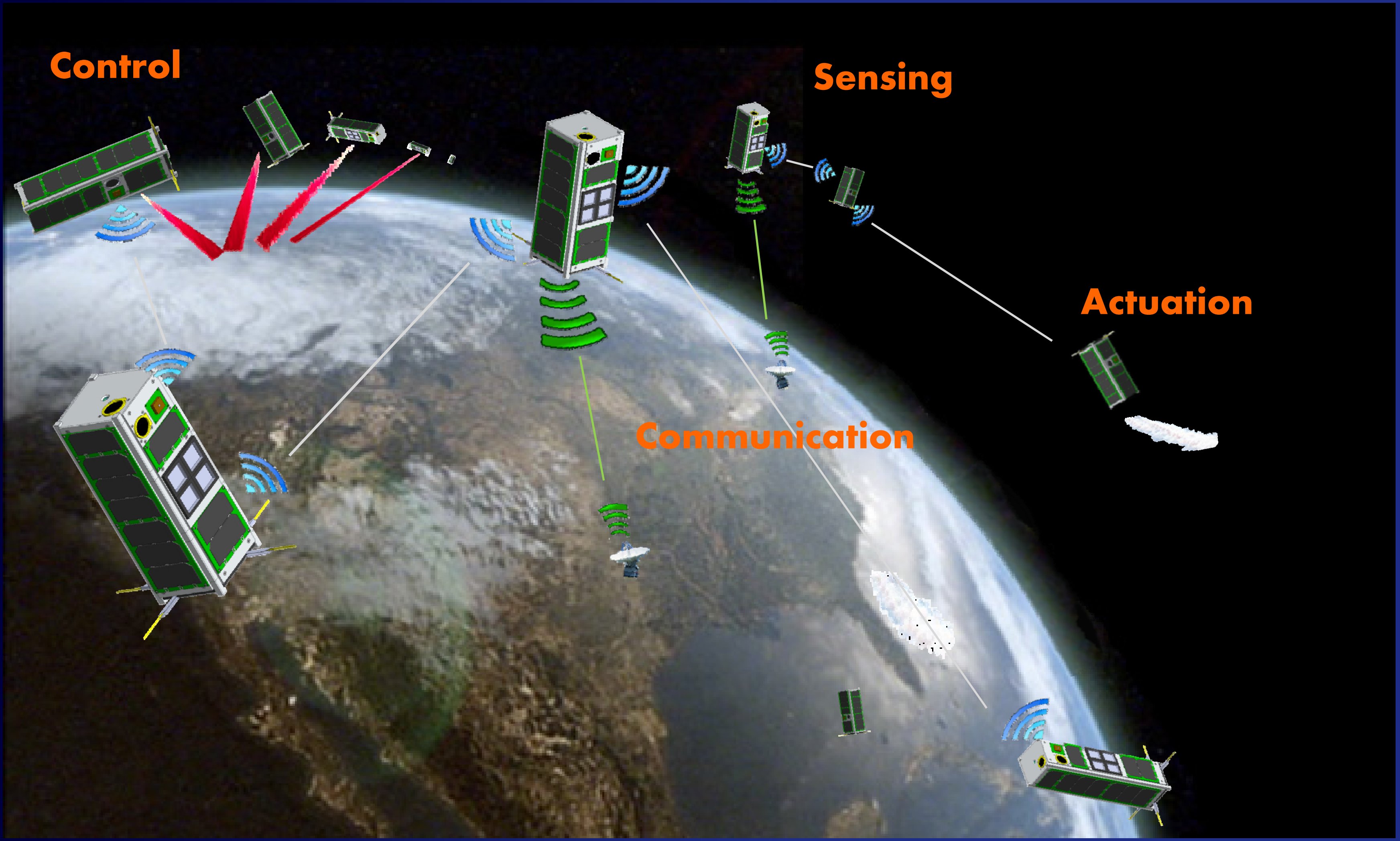


Astrium-proposed EDRS (ETA 2015)

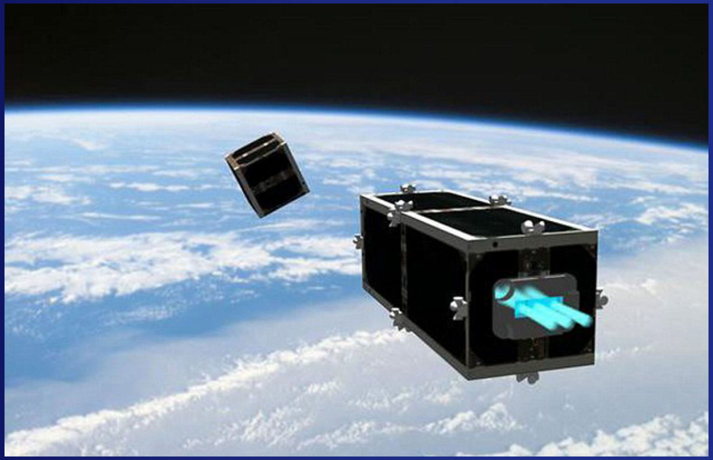


DARPA's F6 Vision of Comm Networks

Formation Flying Technology Elements



Conclusion



- While challenges exist, it is possible to credibly propose missions employing some type of CubeSat formation flying
- The fact that we can have a realistic conversation about CubeSat formation flying shows how far things have come in 10 years
- Enabling technologies should continue to develop and become flight proven over the next decade, reducing mission cost and risk
- CubeSat formation flying has a role to play by facilitating new missions which can answer important science questions

Thank You for Your Attention!