Distributed Spacecraft Missions (DSM) Technology Development at NASA Goddard Space Flight Center

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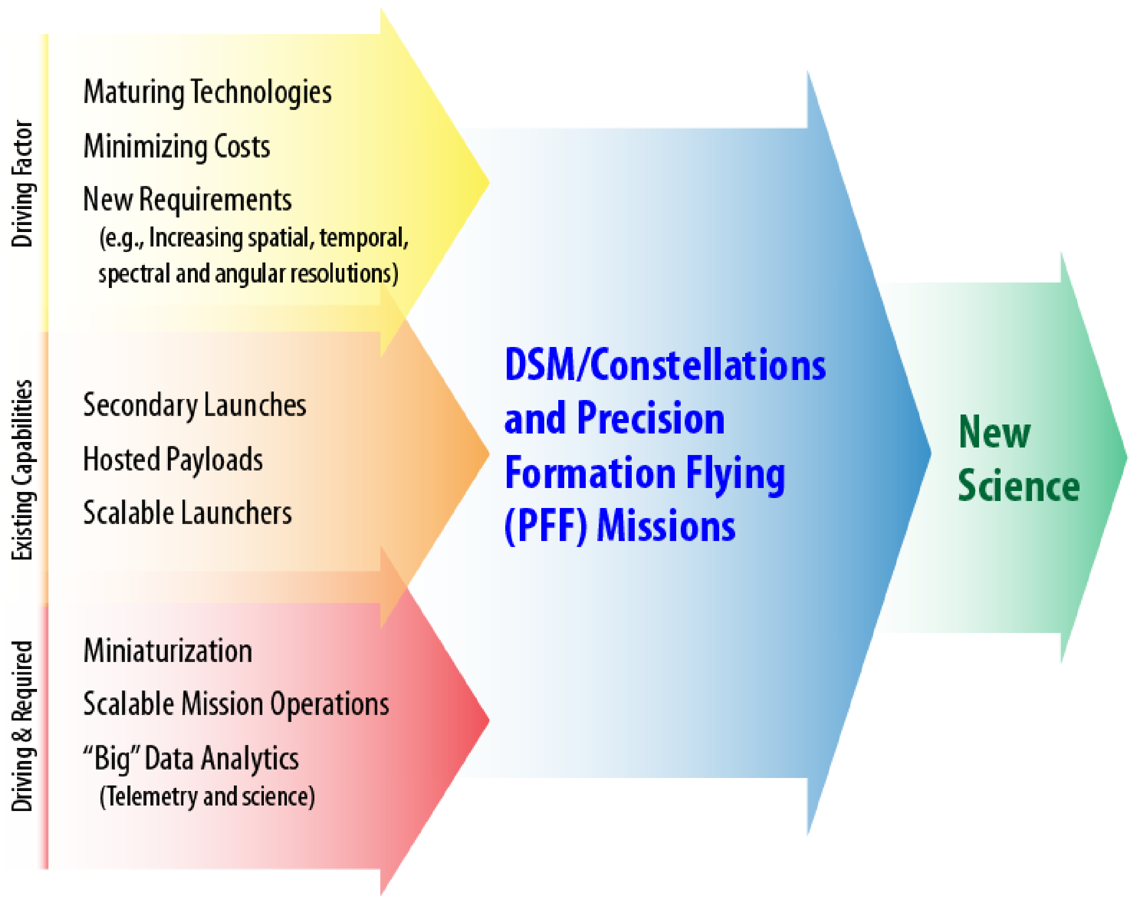
Distributed Spacecraft Missions

What is a Distributed Spacecraft Mission (DSM)?

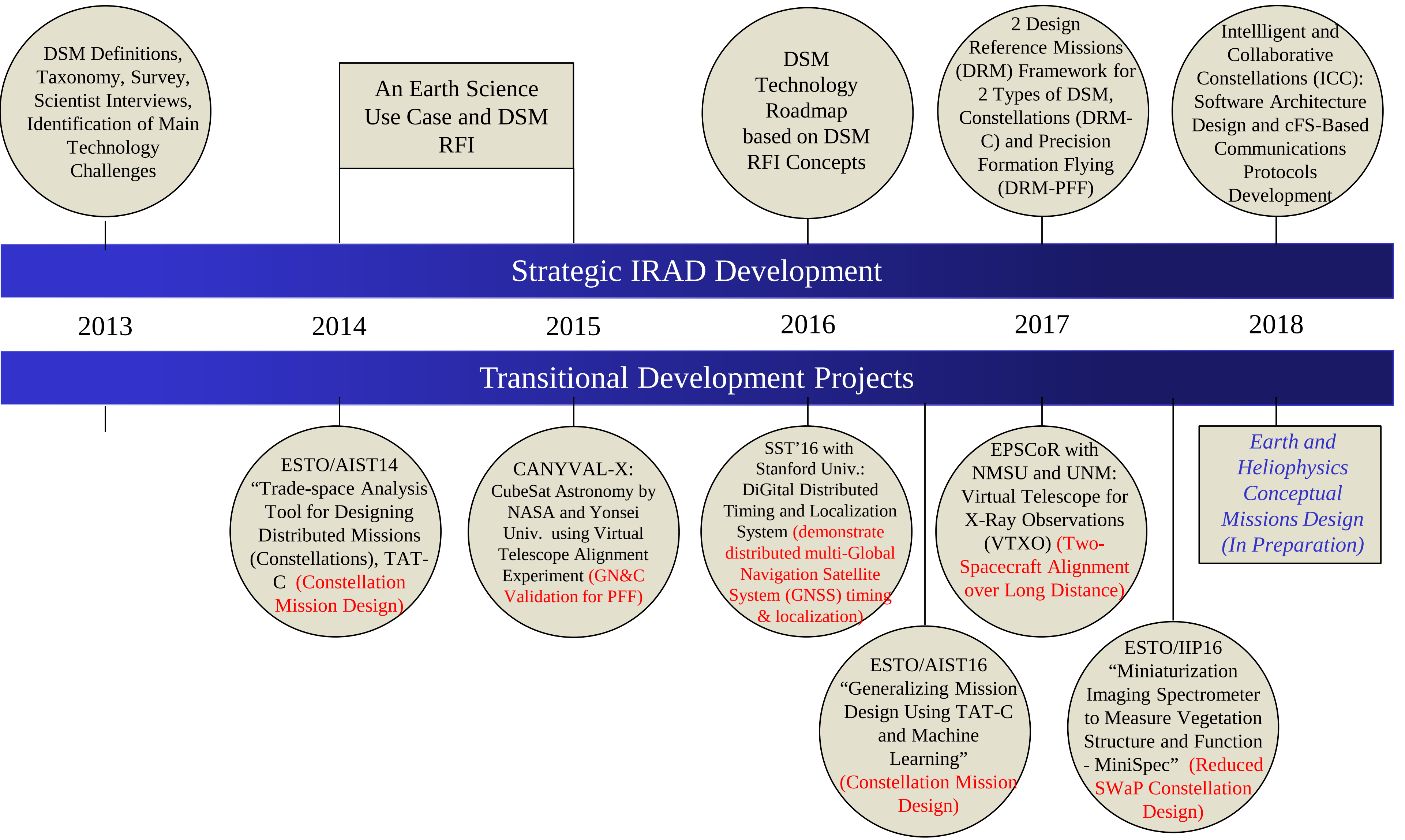
A DSM is a mission that involves multiple spacecraft to achieve one or more common goals.

Drivers

- Enable new science measurements
- Improve existing science measurements
- Reduce the cost, risk and implementation schedule of all future NASA missions
- Investigate the minimum requirements and capabilities to cost effectively manage future multiple platform missions and to cost effectively develop and deploy such missions



NASA Goddard DSM Activities



DSM Taxonomy

- 1. Organization
  - 1.1 Appearance
    - 1.1.1 Constellations
      - 1.1.1.1 Reconfigurable
      - 1.1.1.2 Homogeneous
      - 1.1.1.2 Heterogeneous
    - 1.1.2 Formations
      - 1.1.2.1 Reconfigurable
      - 1.1.2.2 Homogeneous
      - 1.1.2.2 Heterogeneous
    - 1.1.3 Fractionated
  - 1.2 Inter Spacecraft Relationship
    - 1.2.1 None
    - 1.2.2 Hierarchy (e.g., with mothership)
    - 1.2.3 Peer-to-Peer
    - 1.2.4 Rendezvous
      - 1.2.4.1 Cooperative
      - 1.2.4.2 Un-cooperative
- 2. Physical Configuration
  - 2.1 Spatial Relationship
    - 2.1.1 Coverage Defined
      - 2.1.1.1 Orbit Plane Definition
      - 2.1.1.2 Walker Constellation
      - 2.1.1.3 Spacing within Orbit (i.e., String of Pearls)
    - 2.1.2 Clusters (e.g., “Loose” clusters)
    - 2.1.3 Swarms
  - 2.2 Spatial Control
    - 2.2.1 Passive
    - 2.2.2 Ground Controlled
    - 2.2.3 On-Orbit Controlled
    - 2.2.4 Formation Flyers (FF)
      - 2.2.4.1 Active Flyers (Tandem Flyers)
      - 2.2.4.2 “Tight” Formations
      - 2.2.4.3 “Loose” Formations
      - 2.2.4.4 Precision FF
  - 2.3 Temporal Relationship
    - 2.3.1 Deployment
      - 2.3.1.1 Deployed all at once
      - 2.3.1.2 Ad-hoc Missions or Missions of Opportunity
        - 2.3.1.2.1 Multi-missions
        - 2.3.1.2.2 Virtual Missions
      - 2.3.1.3 Phased
    - 2.3.2 Temporal Control
      - 2.3.2.1 “Flash Mob”
      - 2.3.2.2 Precise Correlated Measurements
- 3. Functional Configuration
  - 3.1 Functional Distribution
    - 3.1.1 Cooperative Maneuvering
    - 3.1.2 Motherships
    - 3.1.3 Drones
    - 3.1.4 Fractionated Spacecraft
  - 3.2 Autonomy
    - 3.2.1 Sensor Webs
    - 3.2.2 “Intelligent” Distributed S/C
    - 3.2.3 Remote Agent
    - 3.2.4 Autonomy
    - 3.2.5 Semi-Autonomy

DSM Terminology

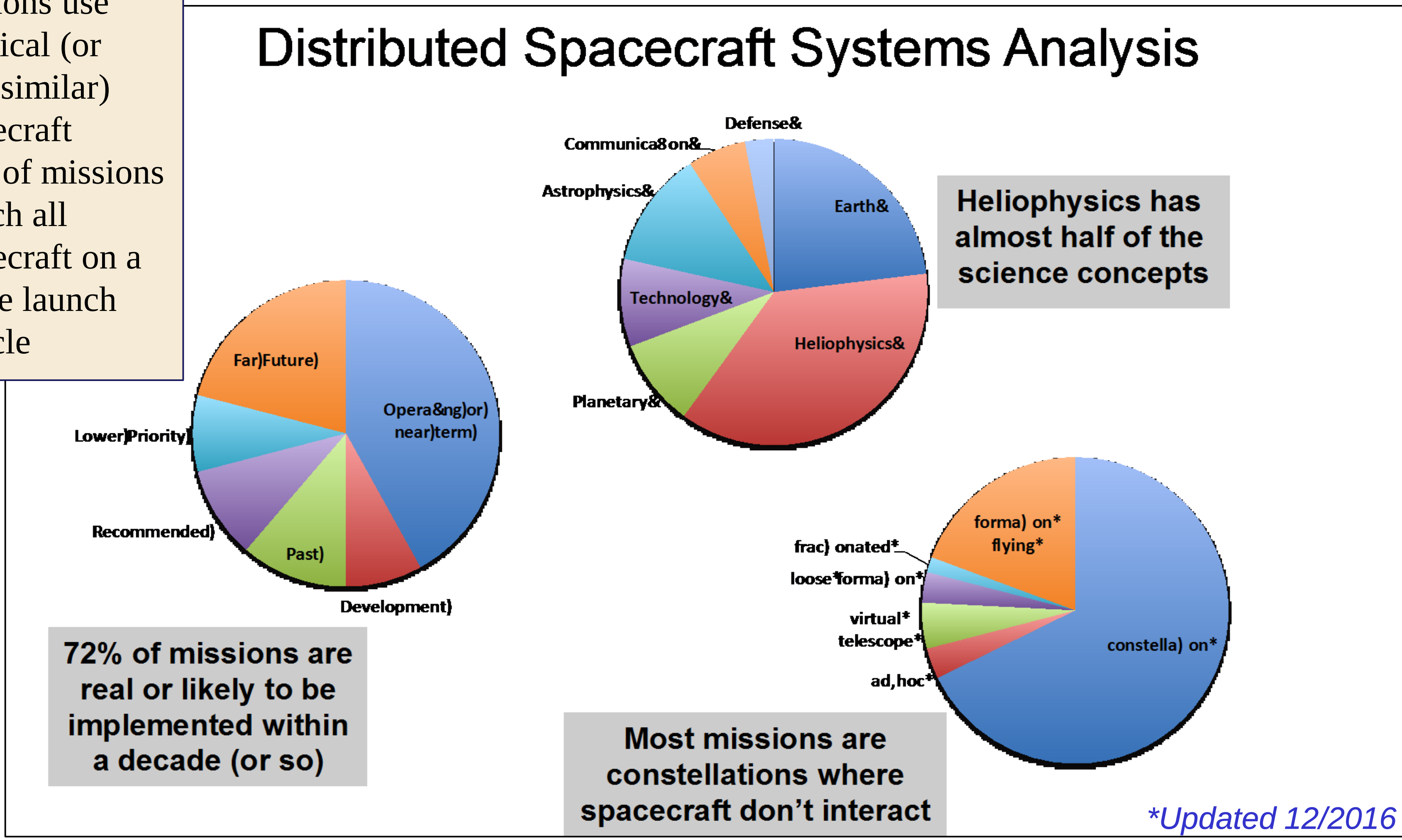
The Main DSM Categories

A *Distributed Spacecraft Mission (DSM)* is a mission that involves multiple spacecraft to achieve one or more *common* goals.

Constellation	A reference to a space mission that, beginning with its inception, is composed of two or more spacecraft that are placed into specific orbit(s) for the purpose of serving a common objective (e.g., CYGNSS, TROPICS, Iridium). A constellation can be *Homogeneous* or *Heterogeneous*.
Formation Flying	Two or more spacecraft that conduct a mission such that the relative distances and 3D spatial relationships (i.e., distances and angular relationships between all spacecraft) are controlled through direct sensing by one spacecraft of at least one other spacecraft state (e.g., GRACE). A formation can be loose or precise/tight.
Fractionated spacecraft	A fractionated spacecraft is a satellite architecture where the functional capabilities of a conventional monolithic spacecraft are distributed across multiple modules that are not structurally connected and that interact through wireless links. These modules are capable of sharing their resources and utilizing resources found elsewhere in the cluster. Unlike constellations and formations, the modules of a fractionated spacecraft are largely heterogeneous and perform distinct functions corresponding, for instance, to the various subsystem elements of a traditional satellite(e.g., DARPA F6 System)

DSM Survey*

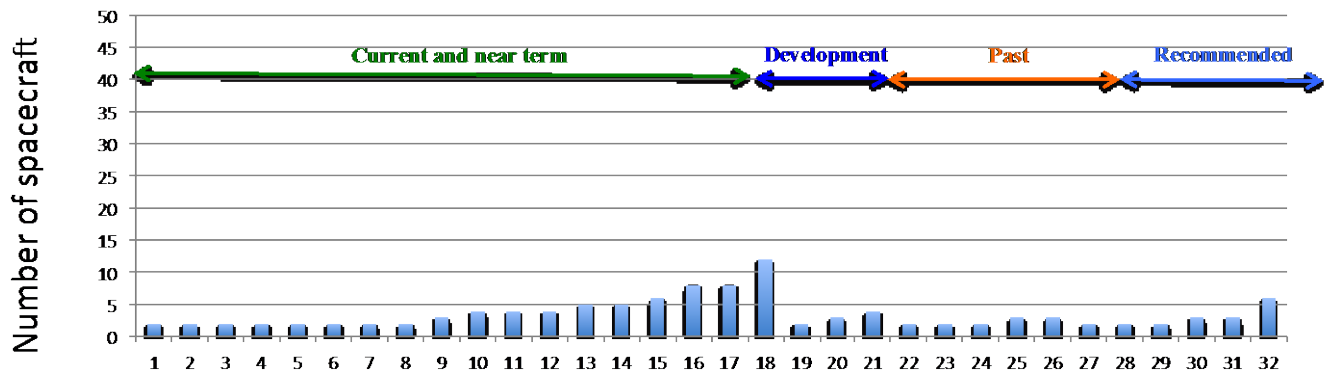
- About 73% of missions use identical (or very similar) spacecraft
- 68% of missions launch all spacecraft on a single launch vehicle



DSM Survey *(cont.)*

- Collected data on 65 missions
- Wide range of DSM:
  - Constellations
  - Clusters
  - Formation Flying
  - Virtual Telescopes
  - Fractionated Spacecraft
  - Temporal Constellations
- Wide range of applications:
  - Science (Earth, Planetary, Astrophysics, Heliophysics
  - Commercial Communications and Earth observation
  - Defense
  - Tech Demonstrations

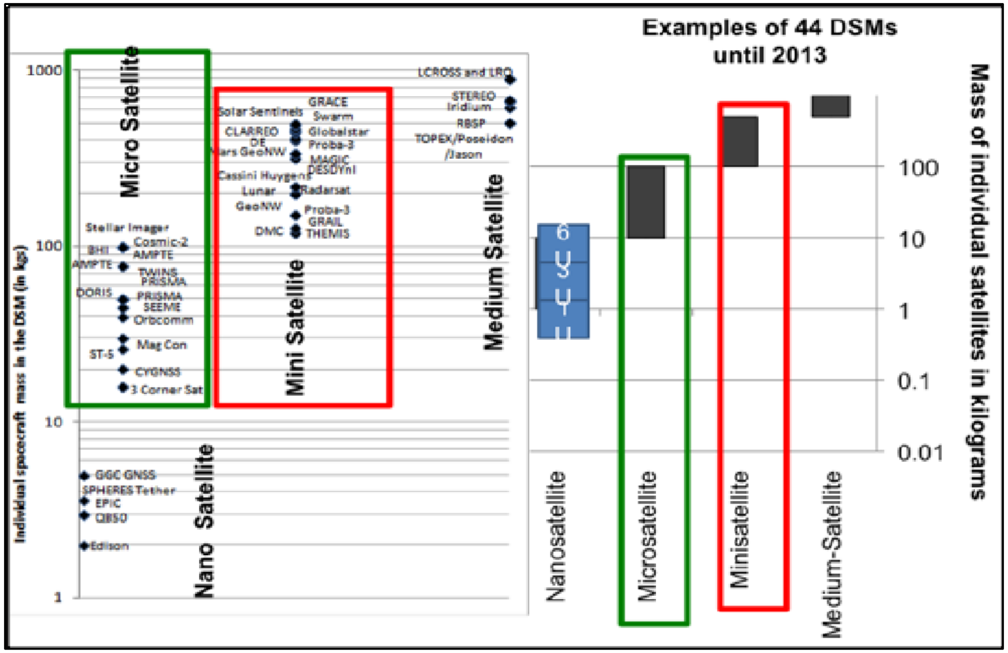
Number of Spacecraft per **Science** Distributed mission



- Mode: 2
- Median: 3
- Average: 5 (with QB50) or 3.6 (without QB50)

- Past Missions (Dynamics Explorer 1981) to far future missions such as MAXIM
- Number of flight elements from 2 to 100
- Most common type is a Heliophysics constellation of 2-6 identical non interacting spacecraft making multipoint measurements from Earth orbit

DSM Survey *(cont.)*



- May impact the perceived cost of proposed missions
- Need to derive better cost models appropriate to SmallSats and to DSM
- Need to validate new cost models using recent DSM (e.g., CYGNSS)

SmallSat Classification

Satellite Class	Mass
Femtosatellite	0.001-0.01 kg (or 1-10 g)
Picosatellite	0.01-1 kg
Nanosatellite	1-10 kg
Microsatellite	10-100 kg
Minisatellite	100-180 kg

Cost Correlations

- Did not have cost and mass information for all missions
- Little correlation observed between number of satellites and cost, when sorted by different categories
- Maximum correlation seen when sorted by size, then orbit type then distribution type

APPEARANCE	
Homogeneous	*-0.1824*
Mixed	*0.4605*
Heterogeneous	*-0.5572*
DISTRIBUTION TYPE	
Constellation	*0.5567*
Formation Flight	*0.4881*
Loose Formation/AdHoc	
SPACECRAFT SIZE	
Nanosat	*0.9921*
Microsat	*0.7461*
Minisat	*-0.0479*
Medium	*1*
Large	*-0.6731*
SPACECRAFT INTERACTIONS	
No interaction	*0.2031*
Interaction 0.912608	
FUNCTIONAL CATEGORY	
Earth	*-0.4235*
Comm/navigation	*1*
Helio/Astro	*-0.24759*
ORBITS	
LEO	*0.6087*
MEO	*-0.1877*
GEO	*1*

Goddard Science Interviews

Science Questionnaire:

Imagine that you could do your science with constellations of satellites, from 2 or 3, up to 100, rather than with single satellites. Imagine that there would be a regular pipeline of satellites, continually being launched and replaced, and that the number of satellites could be expanded or contracted based on the science data being obtained. Imagine that a major push in shrinking instrument sizes makes much smaller satellites possible.

For some specific examples, we can assume that economies of scale have been implemented and efficient assembly lines put in place, such that, with much smaller satellites, cost is no greater than current missions (or at least no greater than the rapidly escalating cost estimates for current Decadal Survey missions).

Given these capabilities:

1. Which kind of science could you do that you cannot do now?
2. What measurement capabilities have a compelling scientific justification and are attainable only (or clearly advantageously) with a distributed spacecraft mission? Specifically, which science measurements or data would you like to collect with what temporal or spatial frequency that would be an augmentation from current capabilities and that would go above and beyond what might be recommended by a Decadal Survey?
3. Which benefits can you envision from distributed missions?
4. Generally in a mission, which capabilities would you like to have that you do not have in current missions? For example:
    a. Targeting (individual, global, collaborative) capabilities
    b. Autonomy, intelligence, onboard processing
    c. Precision/relative positioning and attitude control
    d. Distributed aperture measurements for observations
    e. Orbit, inclination, altitude
    f. Other?
5. In your mind, could constellations contribute to improved data continuity compared to single spacecraft missions?
6. Which size spacecraft would you consider? Why?
7. Which sort of missions would NOT benefit from a distributed approach? i.e., which missions must absolutely remain centralized?
8. Can you suggest a "reference mission" which would be an exemplar of the benefits of a constellation approach?

- **Interviewed 53 scientists** (15% of all GSFC scientists)
    - General Interests
    - Specific Concepts
- **General Findings** (from Interviews):
    - Helio: most advanced and most interested in DSM
        - Multi-point measurements
        - Mostly constellations; PFF for occulters, High Energy Sc.
    - Earth Science:
        - Many potential applications
        - Sampling in spatial, temporal, spectral, angular dims
        - Micro- or MiniSats rather than CubeSats
        - Data Continuity
        - Cross-Calibration
    - Astrophysics: Rising interest
        - PFF more than general constellations
        - Occulters, Virtual Telescopes, Tethered missions
        - CubeSats for tech demos
    - Planetary Science:
        - Currently, less plans on DSM
        - DSM for combined space & planetary assets
        - DSMs for minimizing communications costs
        - Multiple viewpoints for scheduling and targeting

DSM Technology Roadmap

We Start with Science …

… and End with Science

Conceive and Design, Design and Development Tools
- Pre-Phase A/Phase A DSM mission design tools
- Prototyping & Validation testbeds
- Model-based engineering tools

Build and Test Manufacturing, I&T and Assembly
- Develop/extend standards
- Integration and Testing (I&T) frameworks

Launch and Deployment
- Low-thrust propulsion
- Low-cost deployment multi-spacecraft systems

Operate Communications
- High-speed S/C to S/C comms
- Low-cost & fast SmallSats uplink/downlink

Operate GN&C
HW & SW for:
- Autonomous sensing & control
- Absolute & relative navigation
- Coordinated pointing

Operate Ground Data Processing
- Multi-spacecraft mission ops Centers and ground data systems
- Solutions for DSM “big data” operations challenge

Analyze Onboard Intelligence
- Onboard recognition of events of interest
- Onboard goal-oriented planning & scheduling
- Autonomous re-targeting and reconfigurability

Analyze and Share Science Data Processing
- Scalable data management for large DSM
- High accuracy multi-platform calibration, registration & fusion

DSM Design Reference Missions Framework

- Considering 2 DSM types:
  - DRM-C: Loose Constellation Framework
  - DRM-PFF: Precision Formation Flying Framework

- Defining DRMs Framework Requirements in terms of:
  - The 8 Technology areas defined in the roadmap, and
  - 8 DSM Science Mission Concepts
    - 4 Constellations and 4 Precision Formation Flying

- IRAD projects in 6 Tech Areas responding to at least 1 or 2 of the 8 DSM Mission Concepts

Goddard DSM Activities: Some Critical DSM Technologies

Capability	Technology	Driver
Coordinate the simultaneous acquisition of of multiple observations	Autonomous onboard recognition of science event of interest	Enable opportunistic science Mitigate orbit-to-ground latency
	Autonomous onboard data analysis for optimal science return	Enable opportunistic science Mitigate orbit-to-ground latency Reduce date volume
	Autonomous DSM S/C reconfiguration and/or instrument pointing	Enable low latency opportunistic science
	High-speed S/C to S/C SmallSat communications	Enable autonomous, low latency distributed science
	Autonomous on-board navigation	Reduce operations cost by minimizing ground tracking
Precision Formation Flying (PFF) Capabilities	Autonomous precision relative spacecraft positioning to a state-of-the-art SmallSat level of accuracy	Enable distributed telescope architectures
	Autonomous precision pointing to a state-of-the-art SmallSat level of accuracy	Enable virtual telescopes Enable collaborating spacecraft/sensors
	High-speed S/C to S/C smallsat communications	Enable collaborating/cooperating spacecraft/sensors

Recent DSM R&D Activities

- **Design and Modeling Testbed**
  - *Autonomous Rotorcraft as a 6DoF Spacecraft Emulator*
  - *Model-Based System Engineering Applied to Distributed Spacecraft Missions*
  - *Trade-Space Analysis Tool for Constellations (TAT-C)*
- **Spacecraft to Spacecraft Crosslinks**
  - *Software Bus Network (SBN) Message Routing Protocol*
  - *SmallSat Constellation Inter-Satellite Link System Simulator*
- **Communications & Navigation**
  - *Rapid Formulation of a low SWAP Integrated Communications & Navigation Terminal*
  - *Prototype Low SWaP-C Multi-Regime Integrated Communications & Navigation Terminal*
- **Coordination of Simultaneous Acquisition of Multiple Observations**
  - *Deep Learning for Constellations of SmallSats*
- **GN&C Control and Sensing**
  - *Active 2-Axis Positioning Mechanism for Detectors and Occulters*
  - *Precision Alignment Determination and Control System for a Precision Formation Flying Distributed Spacecraft Mission (DSM)*
  - *High precision relative position sensing system for formation flying spacecraft*
  - *Long Range (1 AU) Ranging & Data Comms with Small Satellite Laser Links for Deep-space Science*
- **"Big Data" Challenge for Large Constellations**
  - *Real-Time Analytics Test System for Distributed Spacecraft Missions*

DSM Architecture Characteristics

<table>
<tr><th colspan="21">DISTRIBUTED SPACECRAFT MISSIONS CHARACTERISTICS (07/26/2013)</th></tr>
<tr><th></th><th rowspan="2">MONOLITHIC</th><th colspan="19">DISTRIBUTED</th></tr>
<tr><th>CHARACTERISTICS</th><th colspan="6">CONSTELLATION</th><th colspan="5">FORMATION FLYING</th><th colspan="4">FRACTIONATED</th><th colspan="4">AD-HOC/VIRTUAL MISSION</th></tr>
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DSM Architecture Characteristics *Examples*

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Example DSM Activities

Trade-space Analysis Tool for Constellations (TAT-C)

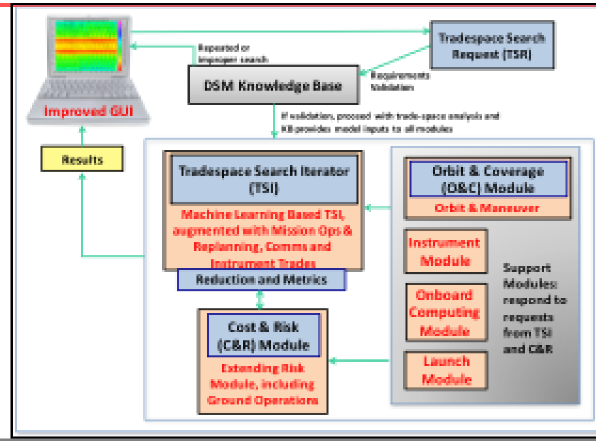
Generalizing Distributed Missions Design Using the Trade-Space Analysis Tool for Constellations (TAT-C) and Machine Learning (ML)

PI: Jacqueline Le Moigne, NASA Goddard Space Flight Center

Funded through ESTO/AIST14&AIST6

Objective

- Extend TAT-C Capabilities, *i.e.*, increase the dimension of the trade-space with:
  - Various trajectories, orbital planes, mission replanning, orbit and Maneuver Modeling, etc.
  - New trade modules (instrument, launch, onboard computing, etc.)
- Optimize the Trade-Space Exploration by Utilizing Machine Learning and a Fully Functional Knowledge Base (KB) to Efficiently Traverse a Large Trade-Space



TAT-C ML Modular Architecture. Existing modules (in blue) will be augmented by new capabilities and trade variables (orange & red).

Approach:

- Include Mission Ops in Cost Module; Develop TAT-C ML / GMAT Interface; Develop Figures of Merit (FOM) for Mission Replanning
- Include Occultors, Lidars and Bi-Static Radars; Develop New Launch Module; Leverage AIST14/French results for Onboard Proc. Trades
- Develop KB via semantic web technologies, formal knowledge representations and related taxonomies
- Machine Learning using Adaptive Operator Selection strategies (AOS) and Knowledge-Driven Optimization (KDO)
- Improve GUI and interfaces to OSSEs and MBSE

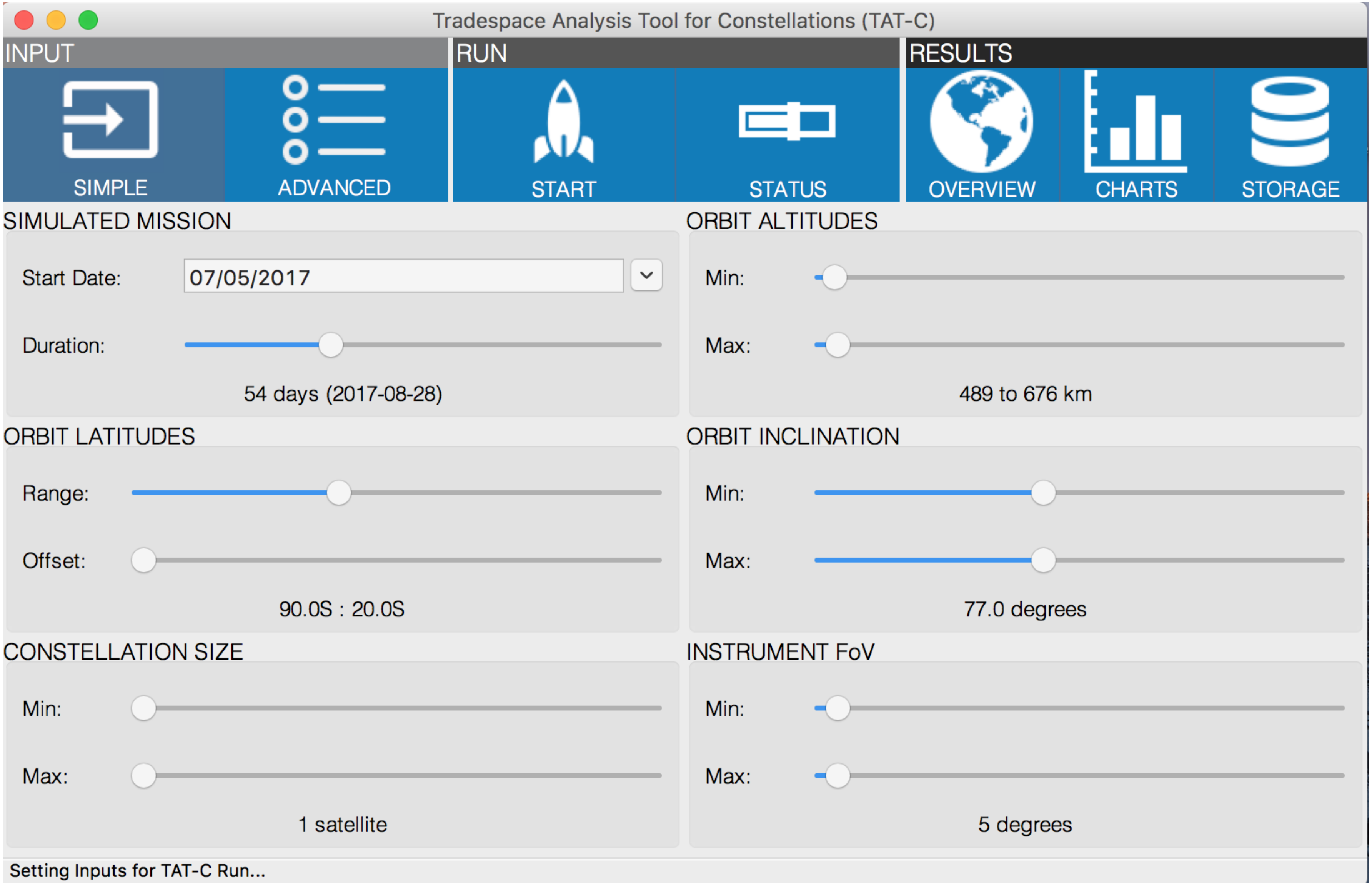
Co-I's: P. Dabney, M. Holland, S. Hughes/GSFC; S. Nag/BAERI; A. Siddiqi, V. Foreman/MIT; P. Grogan/Stevens; D. Selva, N. Hitomi/Cornell

Key Milestones

• Define SLI and TROPICS Full Requirements	11/17
• TAT-C Machine Learning Ontology Defined	05/18
• Mission Ops in Cost & Risk Module	08/18
• Instrument Models Development	11/18
• Knowledge Base and Maneuver Modeling Complete	03/19
• TAT-C ML/GMAT Interface	06/19
• TAT-C ML Validation Using SLI and TROPICS	08/19

$TRL_{in} = 2$ $TRL_{current} = 2$ or 3

TAT-C Now Available through AMCE Cloud Interface



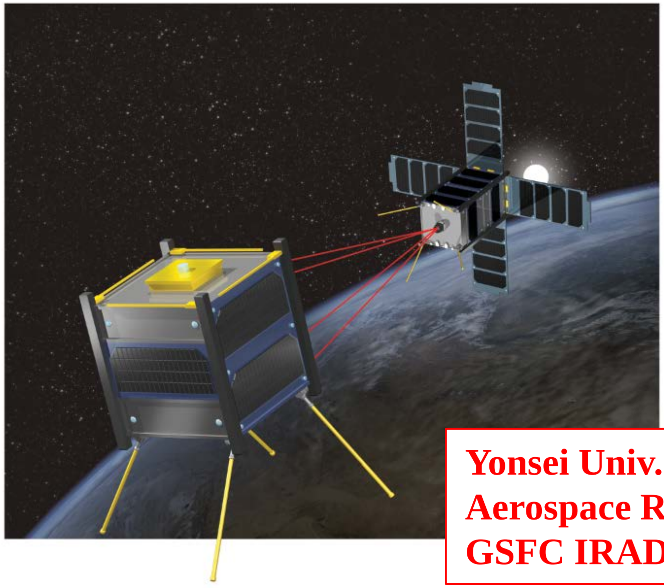
Example DSM Activities

Virtual Telescope Alignment Experiment

CANYVAL-X: The CubeSat Astronomy by NASA and Yonsei using Virtual Telescope Alignment experiment (Shah/ GSFC)

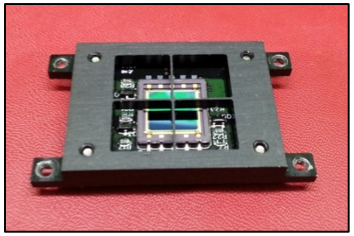
Mission Description

- CANYVAL-X : engineering demonstration using CubeSats (1U+2U)
- Validate GN&C for precise dual-spacecraft formation flight along an inertial line-of-sight.
- Solar Alignment Goals
  - Control < 1.2 deg (20 cm at 10 m)
  - Stability < 1 arc-min over 5 sec (0.3 cm at 10 m)



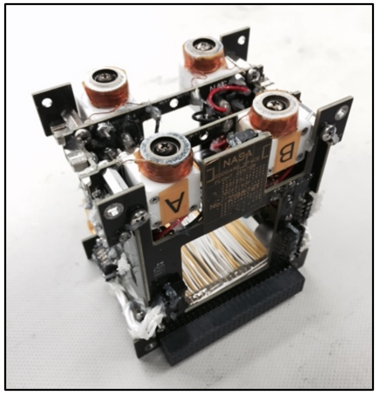
Status

- NASA & Yonsei Univ. under international agreement
- GSFC delivered: Sun Sensor (May 2015), Micro thrusters (mCAT) (Sep 2015)
- Yonsei Univ. built 2U and 1U spacecraft
- KARI performed environmental testing
- **Launched January 2018 on the PSLV-40 Mission from India.**
- ***Reached stable orbit and heard radio beacon, but current ground station issues and have not been able to command the spacecraft yet.***



Fine Sun Sensor (GSFC)

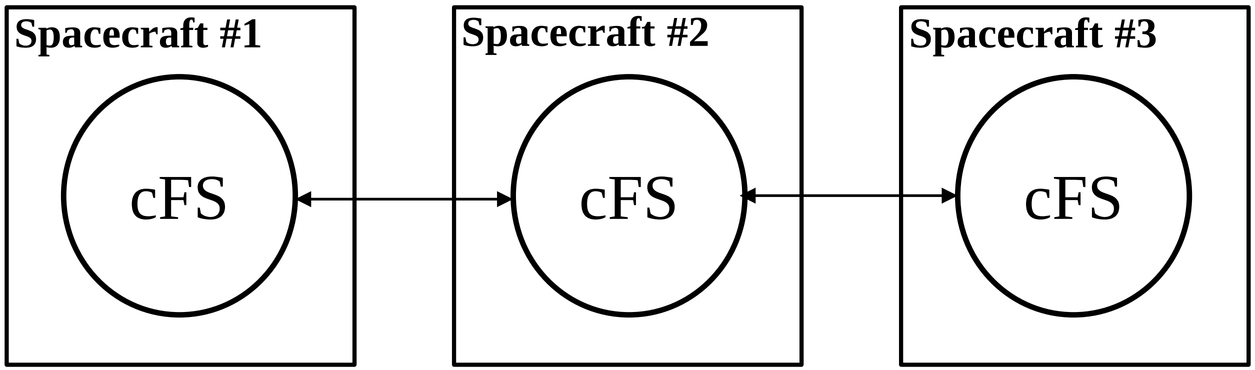
mCAT (GSFC+GWU)



Yonsei Univ. funded by Korean Aerospace Research Institute (KARI); GSFC IRAD contributions

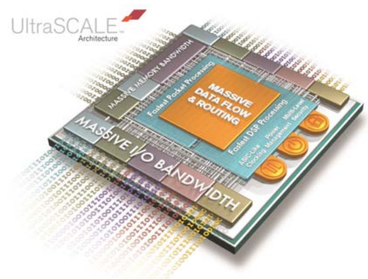
Software Bus Network (SBN)
Multi-Step Routing

- Extends the Core Flight System (cFS) Software Bus Network (SBN) application to work across processors/spacecraft that are not directly connected.
- SBN allows cFS to be used seamlessly on multiple processors/spacecraft.
- Previous versions of SBN required direct connection in order to communicate.
  - *Example below, Spacecraft 1 and Spacecraft 3 could not communicate*
- New version will allow routing through intermediate nodes.
  - *Example below: Spacecraft 1 and Spacecraft 3 can communicate through Spacecraft 2*
- Will enable cFS to be used in a wider variety of distributed architectures.
  - *Architectures with constraints on which nodes can be directly connected (due to distance, line of sight, etc.)*



Deep Learning on CubeSats
Transient Event Detection

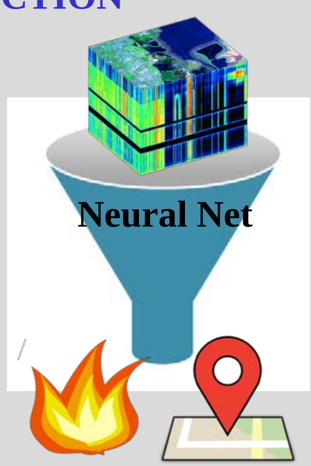
SoC/FPGAs allow for near GPU performance (high power/poor radiation tolerance) at a fraction of the power, and better radiation performance



Low Power and High Performance
Well suited for CubeSats

- **Deep learning now possible on CubeSats**
  - Advances in low-power FPGAs give the compute power necessary to run large Neural Networks
    - GPUs still useful on ground to train the networks
  - Many software frameworks make designing neural networks easy and fast
    - Software such as Google's TensorFlow or Keras
- **Combine powerful existing tools to train Neural Networks on the ground, with optimized code to deploy the trained network onto a CubeSat-like platform**

APPLICATION TO WILDFIRE DETECTION

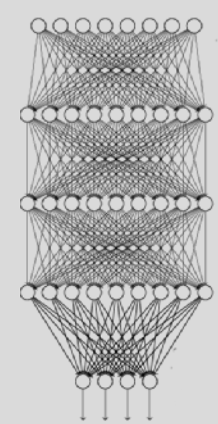


Large amount of MODIS data

Intelligent Reduction of Data

Resulting classification of data as Fire/Not Fire

Example Deep Learning Architecture



99.59 % Correct Classification Rate

ICC Movie Simulation

Summary – Next Steps

We Start with Science …

… and End with Science

Conceive and Design, Design and Development Tools
- Pre-Phase A/Phase A DSM mission design tools
- Prototyping & Validation testbeds
- Model-based engineering tools

Build and Test Manufacturing, I&T and Assembly
- Develop/extend standards
- Integration and Testing (I&T) frameworks

Launch and Deployment
- Low-thrust propulsion
- Low-cost deployment multi-spacecraft systems

Operate Communications
- High-speed S/C to S/C comms
- Low-cost & fast SmallSats uplink/downlink

Operate GN&C
HW & SW for:
- Autonomous sensing & control
- Absolute & relative navigation
- Coordinated pointing

Operate Ground Data Processing
- Multi-spacecraft mission ops Centers and ground data systems
- Solutions for DSM "big data" operations challenge

Analyze Onboard Intelligence
- Onboard recognition of events of interest
- Onboard goal-oriented planning & scheduling
- Autonomous re-targeting and reconfigurability

Analyze and Share Science Data Processing
- Scalable data management for large DSM
- High accuracy multi-platform calibration, registration & fusion

ANY QUESTIONS?