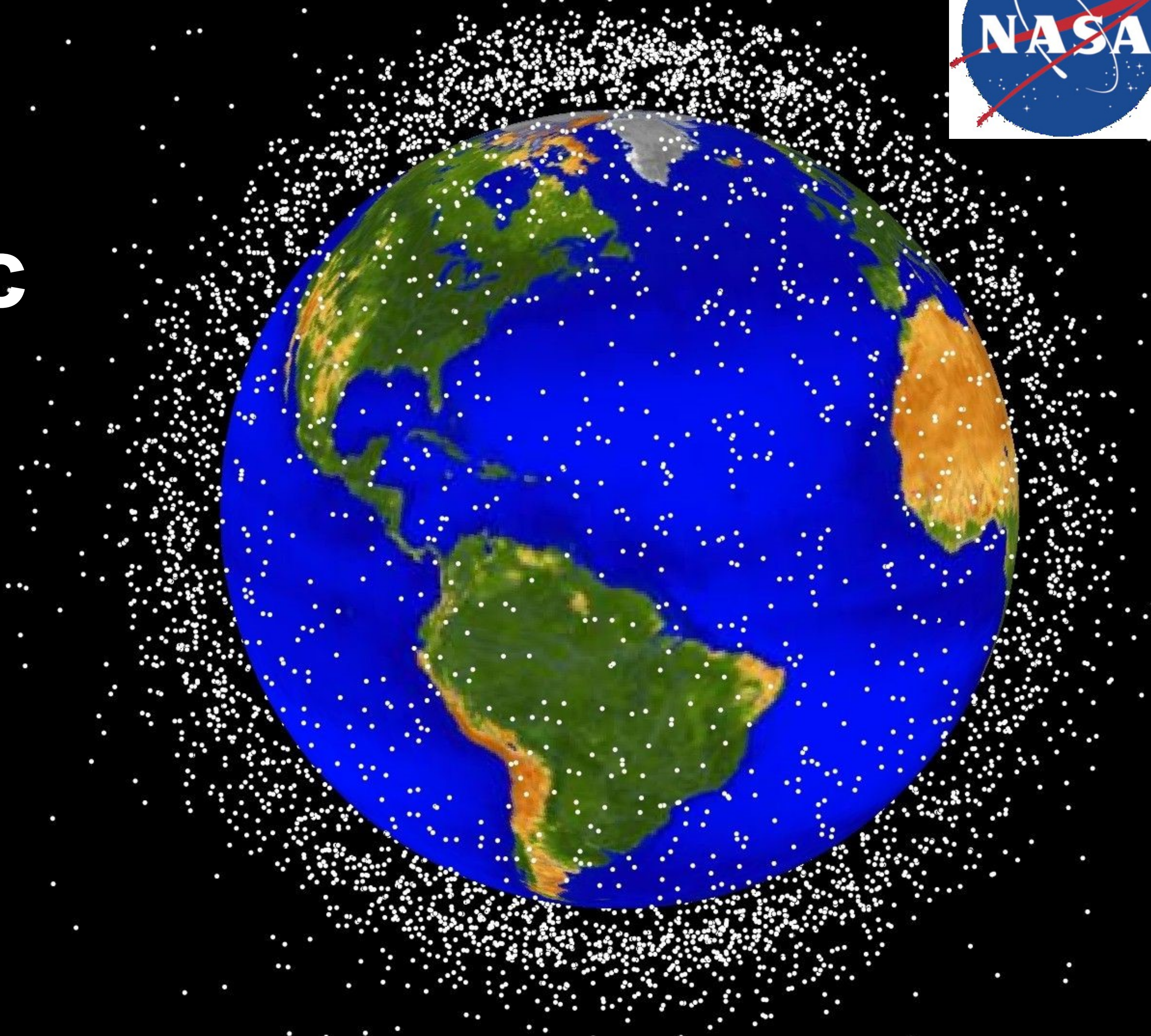
32nd AIAA/USU Conference on Small Satellites

A Concept for Civil Space Traffic Management

Applying the NASA Unmanned Aircraft System Traffic Management Architecture to Space Traffic Management



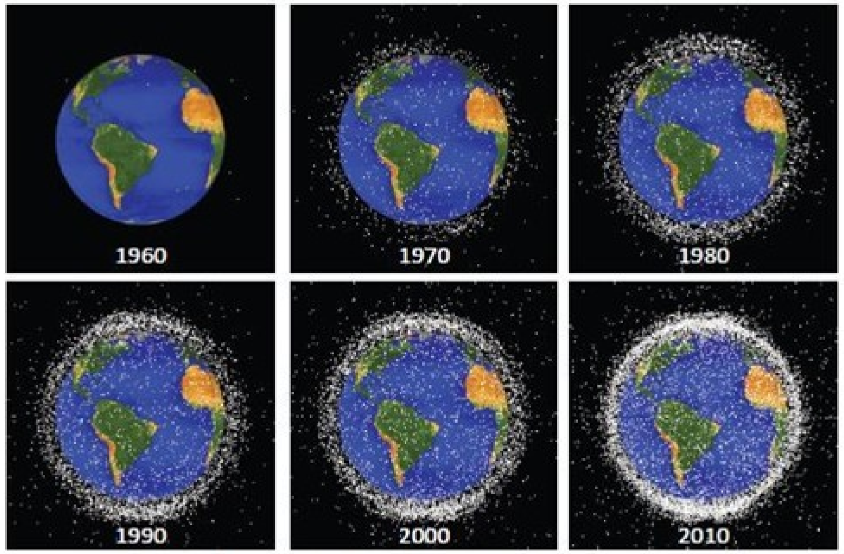
August 6, 2018

What is Space Traffic Management (STM)?

- “Space traffic management means the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and return from outer space to Earth free from physical or radio-frequency damage.” – IAA Cosmic Study (2006)
- “[P]lanning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment.” – Space Policy Directive 3
- We are focusing on physical deconfliction first.

Why is STM critical for the continued usability of space?

- Today
- 1,700 active satellites
- 23,000 tracked objects (>10 cm)
- Increases to traffic/mega-constellations.



Satellites and debris in low Earth orbit, 1960-2010. Courtesy NASA.

- Collision with *any* tracked object (> 10 cm) looks like this (or worse):

- NASA/DoD DebriSat Test Video (April 2014)

- 600 gram projectile impacting a 50 kg spacecraft model at 7 km/s, kinetic energy of 14.7 MJ (similar energy to anti-aircraft missile warhead). Produced over 200,000 fragments larger than 2 mm.

- Debris producing more debris: “Kessler Syndrome”
- Uncontrolled growth will *severely* affect future space operations

STM is a major focus of the current administration

Space Policy Directive 3 (Signed June 18, 2018):

- “The Secretary of Commerce, in coordination with the Secretaries of State, Defense, and Transportation, the NASA Administrator, and the Director of National Intelligence, **shall develop standards and protocols for creation of an open architecture data repository to improve SSA data interoperability and enable greater SSA data sharing.**”
- **Transition Civil STM** from Department of Defense to Department of Commerce
- The United States should continue to **make available basic SSA data and basic STM services** (including conjunction and reentry notifications) **free of direct user fees** while **supporting new opportunities for U.S. commercial and non-profit SSA data and STM services.**

The Ames STM project directly supports these objectives of SPD-3

*SSA = Space Situational Awareness

Current U.S. Smallsat Regulatory Environment

Launch & Re-entry	Non-Federal Spectrum Use (including debris mitigation as condition of spectru use)	Commercial Remote Sensing	International Traffic in Arms Regulations (ITAR) Export Control	Export Administration Regulations (EAR) Export Control

There is no U.S. government body with regulatory authority to conduct on-orbit space traffic management.

Current SSA/STM State of Art

Government	Non-profit	Commercial
• Basic SSA Information • Anomaly Resolution • Basic Emergency Conjunction Assessment • Basic Emergency Collision Avoidance • Advanced Services with SSA Sharing Agreement ***(All Free)***	• Conjunction Assessment, Maneuver Planning Validation • Radio Frequency Interference Mitigation/Geolocation • Database of Member Contact Information • Legal and Technical Safeguards to Protect Proprietary Information • Cooperative Member Ephemeris Information for Higher Accuracy	• Commercial Non-Cooperative SSA Information Acquisition using Various Sensors and Sensor Types • Orbit Determination • Conjunction Warning & Assessment • Anomaly Detection and Resolution

An Emerging Need for Enhanced Cubesat SSA/STM

Mission Class	Maneuverability	SSA/STM Needs	Altitudes	Deorbit Mechanism
Typical Current Cubesat (non tech demo)	No propulsion (maybe drag maneuvering)	• Post-deployment identification • Orbital Trajectory for passes and antenna pointing • Conjunction messages are not very actionable	LEO (<~600km)	Un-augmented atmospheric drag
Novel Cubesat Mission Concepts (SSA, satellite inspection)	Propulsion needed	• Same post-deployment and communications needs • Conjunction messages are actionable • Higher consequences if collision occurs	GEO, HEO, higher altitude LEO	Technical solution required for IADC guideline compliance

Example of novel cubesat mission concept:

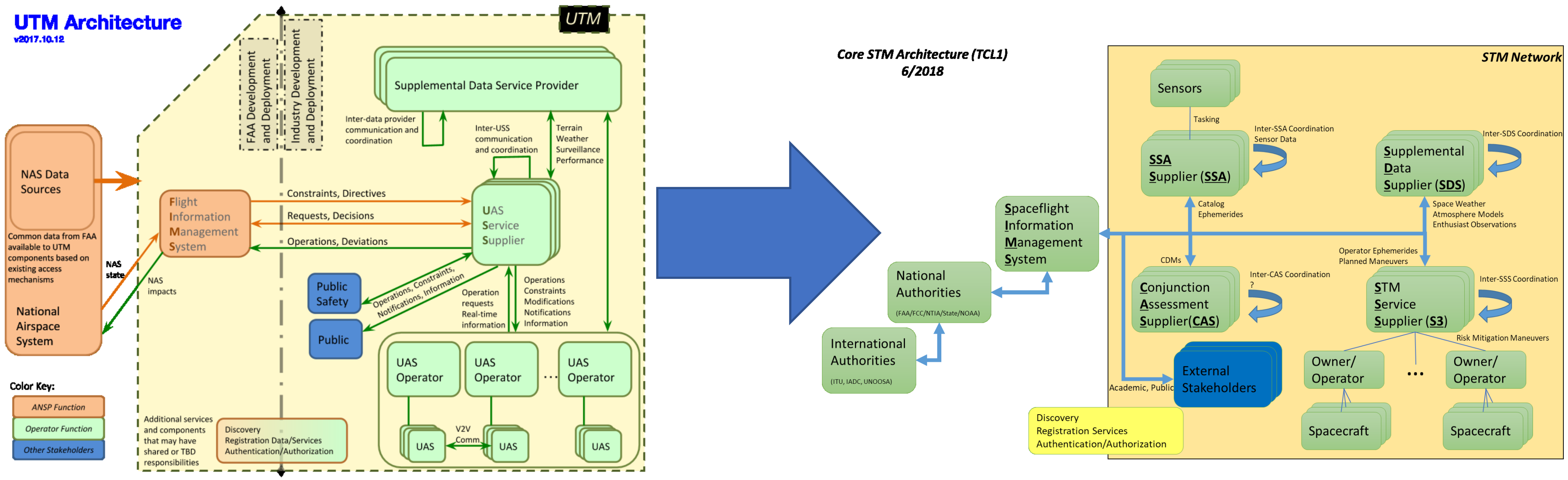
- High Earth Orbit Robotics: 6U cubesat telescope for GEO SSA
- Would need STM integration as both a user and supplier of SSA data

Some new cubesat mission concepts will require integration into an STM system.

NASA Unmanned Aerial System Traffic Management (UTM) Summary

- Collaborative effort to enable safe unmanned aircraft system operations in un-controlled low-altitude airspace.
- Pursued through joint research plan between FAA and NASA in partnership with industry.
- Developing technical ecosystem to use industry's capabilities to provide flight safety under FAA authority
- **Example:** Low Altitude Authorization and Notification Capability allows commercial UTM providers to offer api-delivered near real-time approval of access to controlled airspace (which can take 90 days via a manual process)

The Solution: STM inspired by UTM

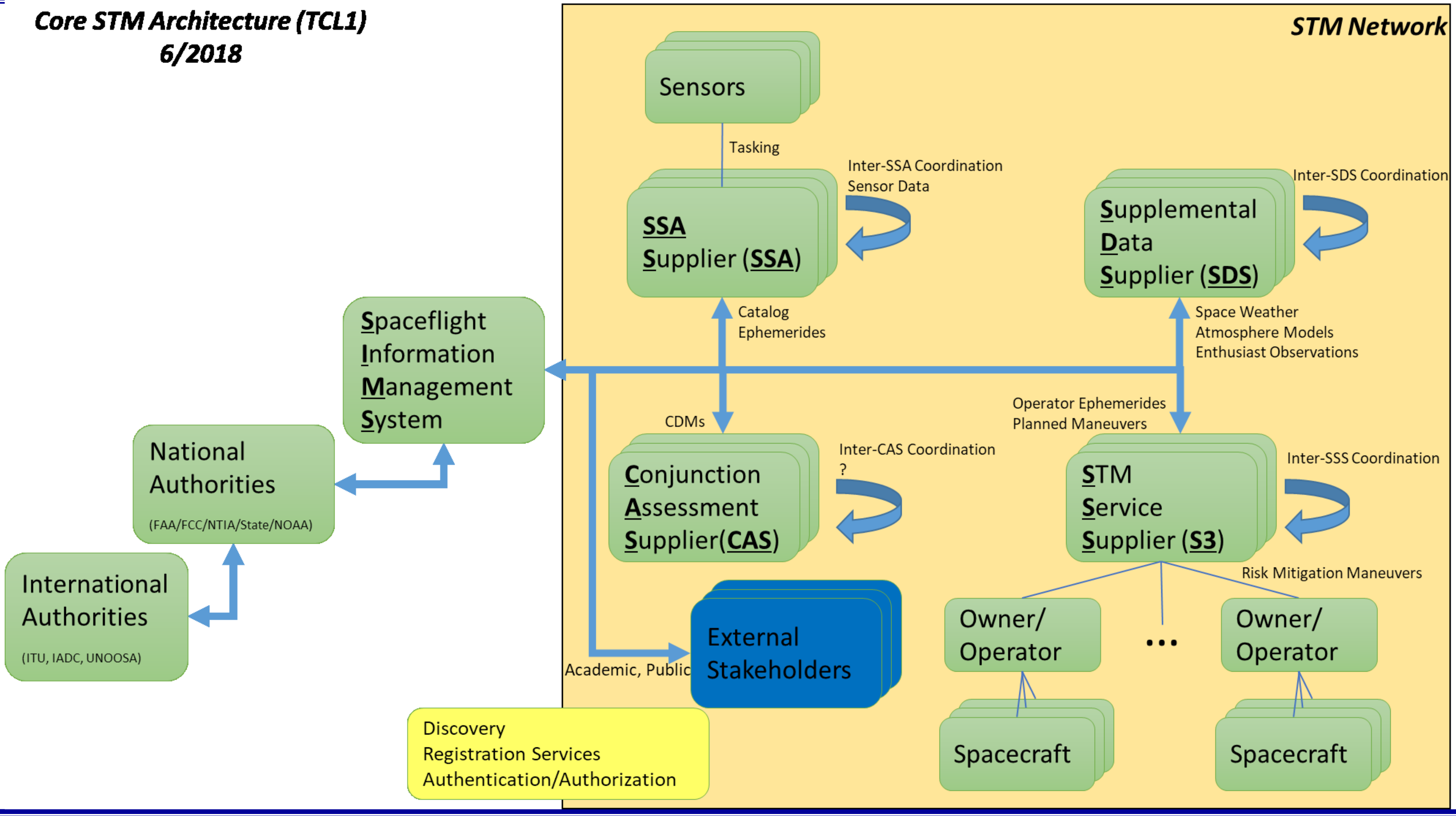


UTM architecture (left) adapted to STM (right)

Leverages successful UTM development for STM

- Enables safe operations, cooperative management with diverse participants (large, small, commercial, gov't)
- Standardized roles and machine-to-machine APIs to enable scaling
- Open architecture to empower industry & facilitate commercialization
- Service supplier network enables decentralized, highly scalable data sharing

Notional Core STM Architecture



STM Service Supplier (S3) Responsibilities

- Satellite Registration (owner/operator, key meta data, service as S3)
- Advisory/Alert Dissemination to O/Os
- Collision Risk Assessment
- Collision Avoidance Maneuver Development
- Maneuver Intent Sharing, Negotiation, Coordination (with other S3s)
- Information Gathering/Archiving for Regulatory Compliance
- Serve as STM Point of Contact for Satellites Under Supervision

Collision Avoidance Example

- Assume one spacecraft is small-sat (with or without propulsion), the other is a larger satellite (with propulsion)
- Both O/Os have well-known position for their spacecraft
- Each spacecraft has a different S3, but both participate in the STM architecture
- Timing is notional, will vary significantly based on orbital mechanics, standard practices, and entities involved

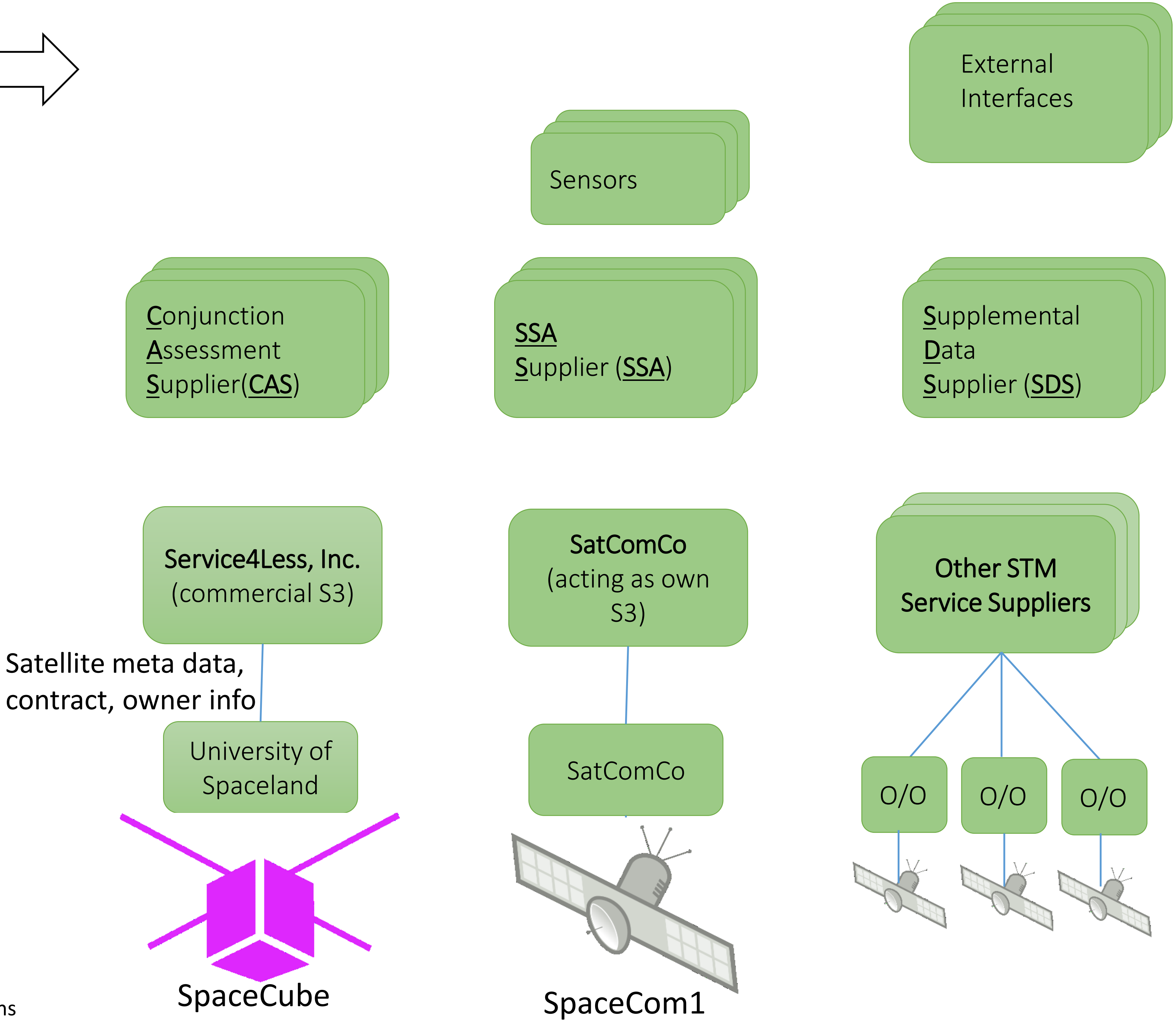
Example Data Flow: Registration (1/1)

Time

Time 0

Registration Steps

1. U. of Spaceland registers with Service4Less, an STM service supplier (S3), and provides its contact info, SpaceCube satellite metadata.
2. Service4Less updates STM system registry to indicate it oversees SpaceCube for U. of Spaceland.
3. U of Spaceland periodically provides updated tracking information to Service4Less.



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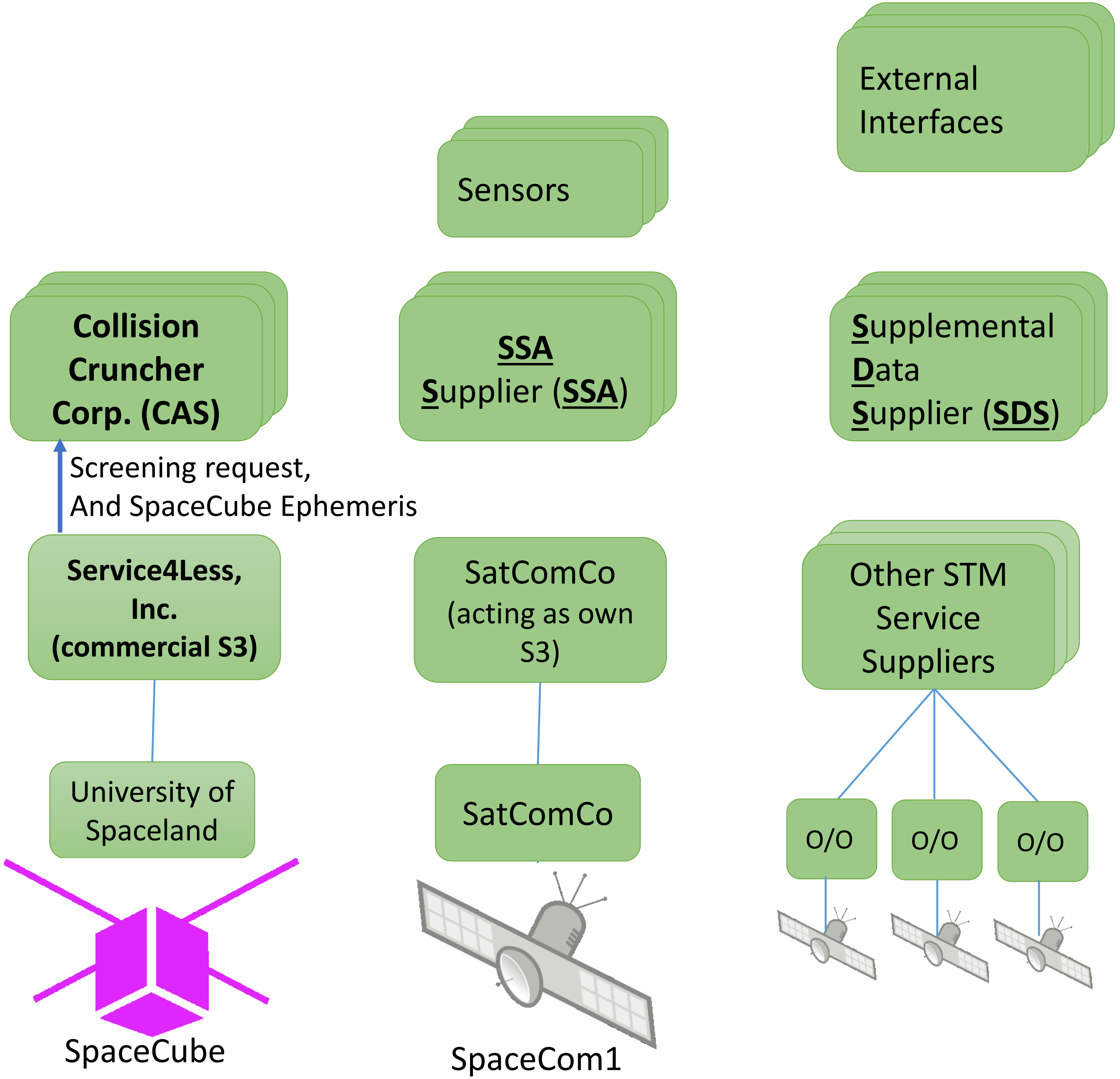
Example Data Flow: Conjunction Screening (1/5)

Time

T-7 Days

Conjunction Screening Steps

1. Service4Less periodically requests a conjunction screening for SpaceCube from Collision Cruncher Corp. and provides the latest Spacecube ephemeris.



Example Data Flow: Conjunction Screening (2a/5)

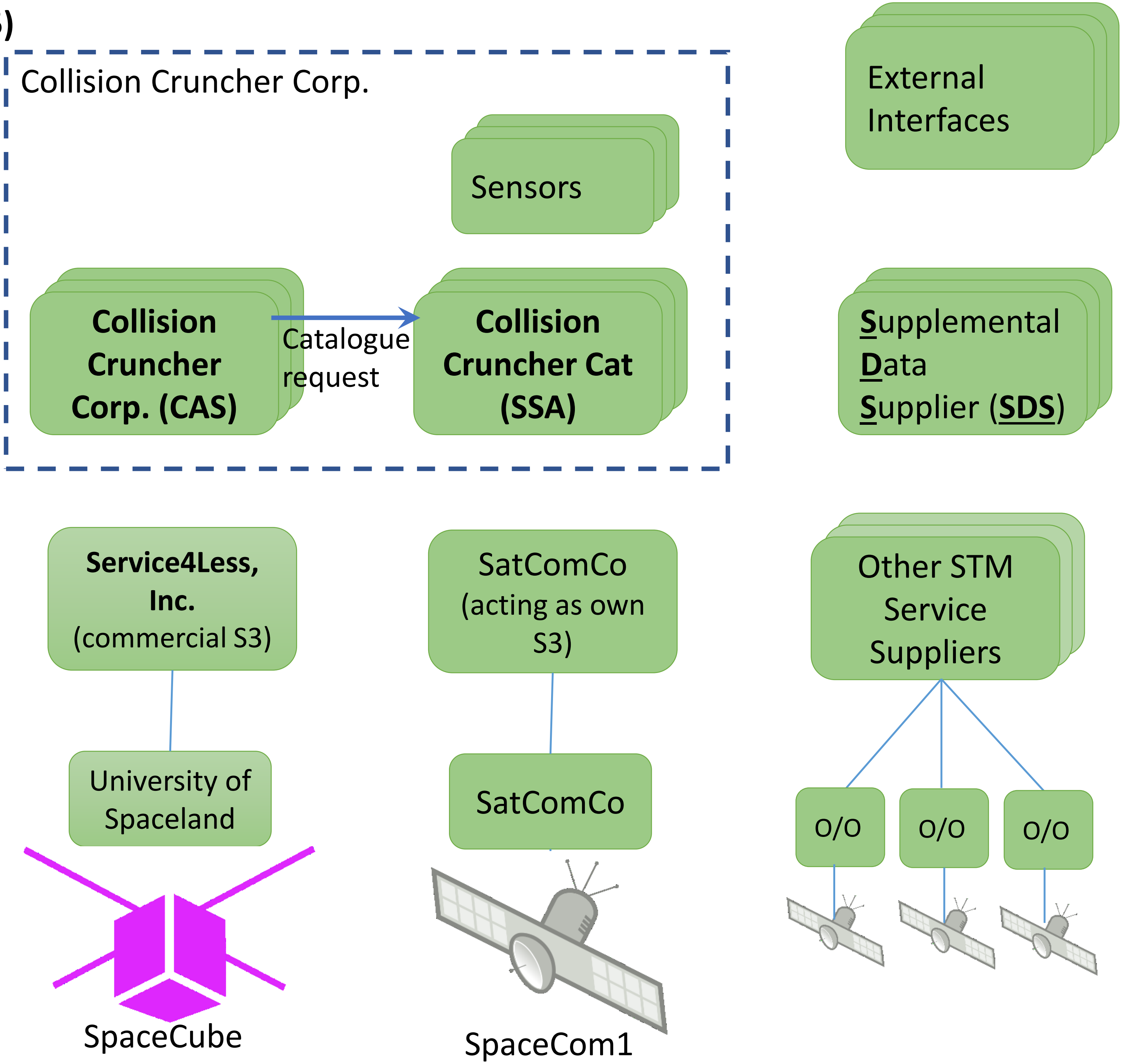
Time

T-7 Days

w/ Merged CAS/SSA

Conjunction Screening Steps

1. Service4Less periodically requests a conjunction screening for SpaceCube from Collision Cruncher Corp. and provides the latest Spacecube ephemeris.
2. Collision Cruncher Corp. queries the latest SSA information from the catalog it operates as an SSA supplier.



Example Data Flow: Conjunction Screening (2b/5)

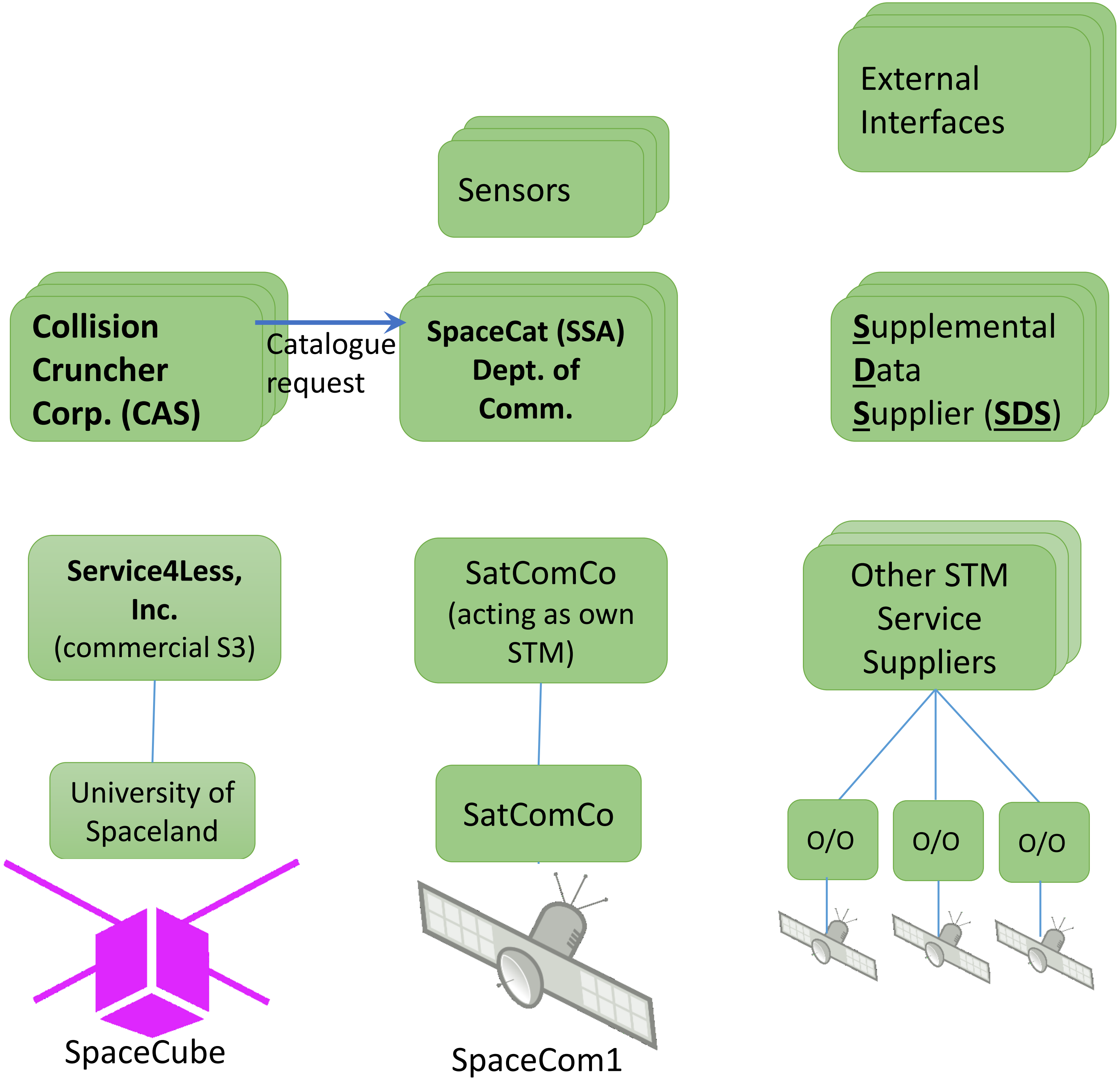
Time

T-7 Days

w/ Separate CAS/SSA

Conjunction Screening Steps

1. Service4Less periodically requests a conjunction screening for SpaceCube from Collision Cruncher Corp. and provides the latest Spacecube ephemeris.
2. Collision Cruncher Corp. queries the latest SSA information from SpaceCat, a Department of Commerce Service (or could also ask commercial SSA providers).



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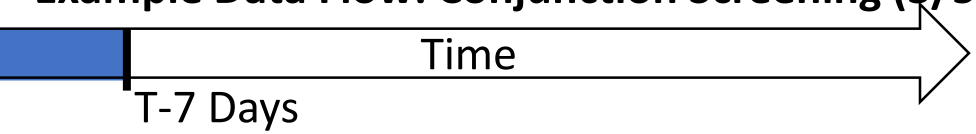
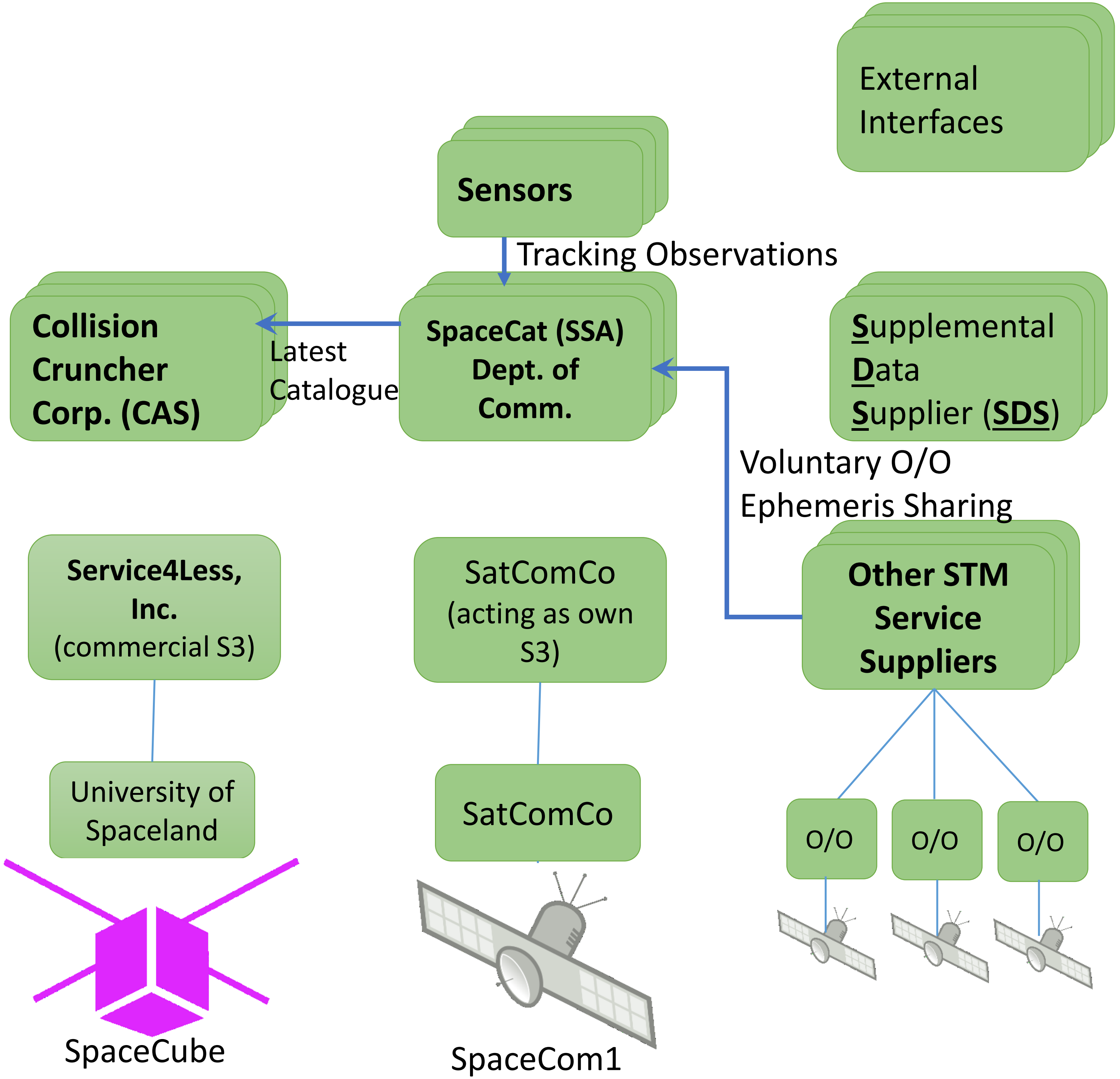
Example Data Flow: Conjunction Screening (3/5)



Conjunction Screening Steps

1. Service4Less periodically requests a conjunction screening for SpaceCube from Collision Cruncher Corp. and provides the latest Spacecube ephemeris.
2. Collision Cruncher Corp. queries the latest SSA information from SpaceCat, a Department of Commerce Service (or could also ask commercial SSA providers).
3. SpaceCat provides the catalog based on its sensors and O/O data shared with it.



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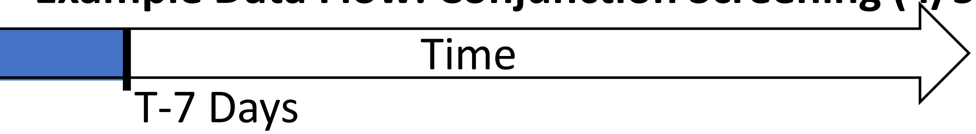
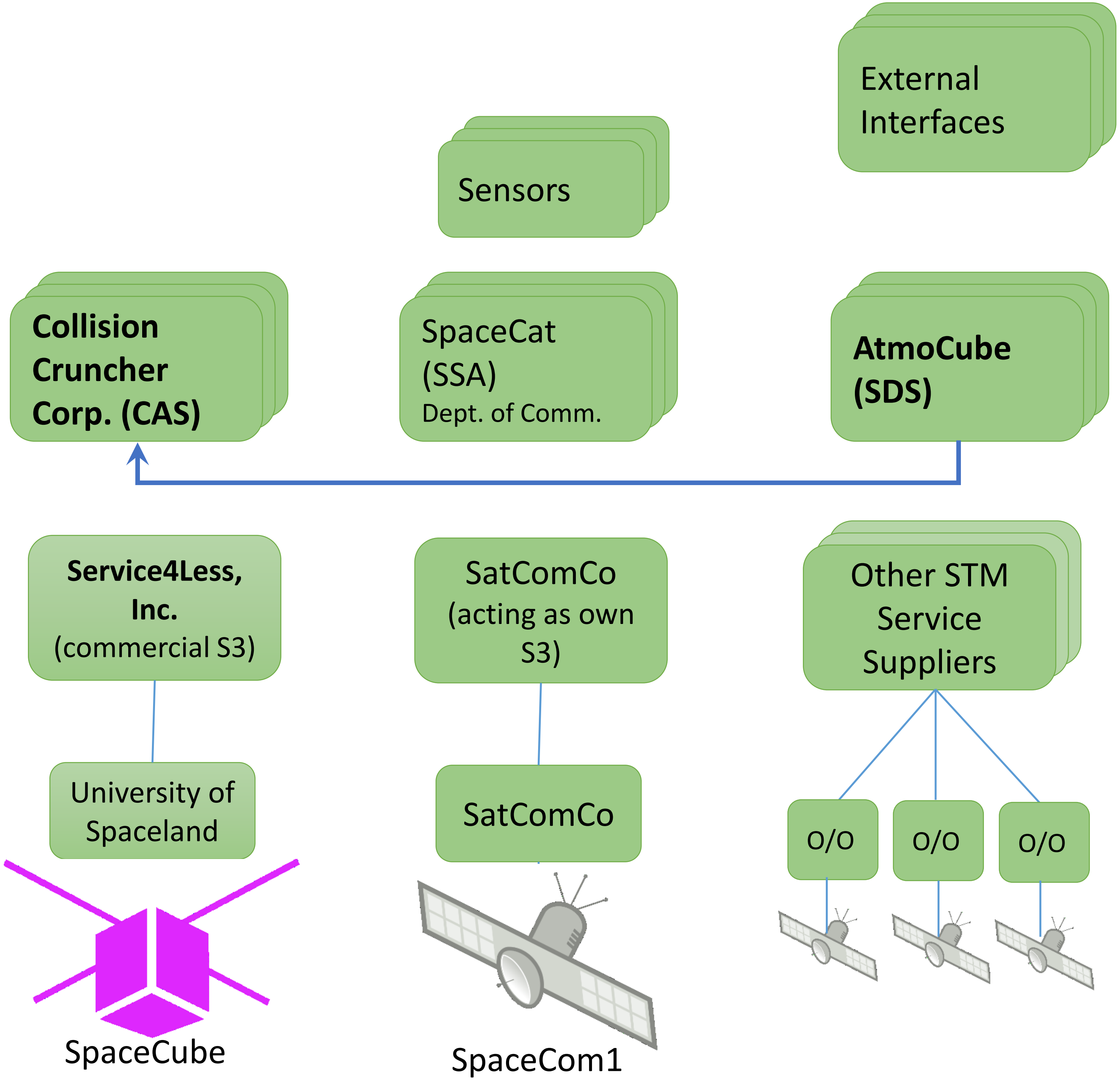
Example Data Flow: Conjunction Screening (4/5)



Conjunction Screening Steps

1. Service4Less periodically requests a conjunction screening for SpaceCube from Collision Cruncher Corp. and provides the latest Spacecube ephemeris.
2. Collision Cruncher Corp. queries the latest SSA information from SpaceCat, a Department of Commerce Service (or could also ask commercial SSA providers).
3. SpaceCat provides the catalog based on its sensors and O/O data shared with it.
4. Collision Cruncher computes potential conjunctions.



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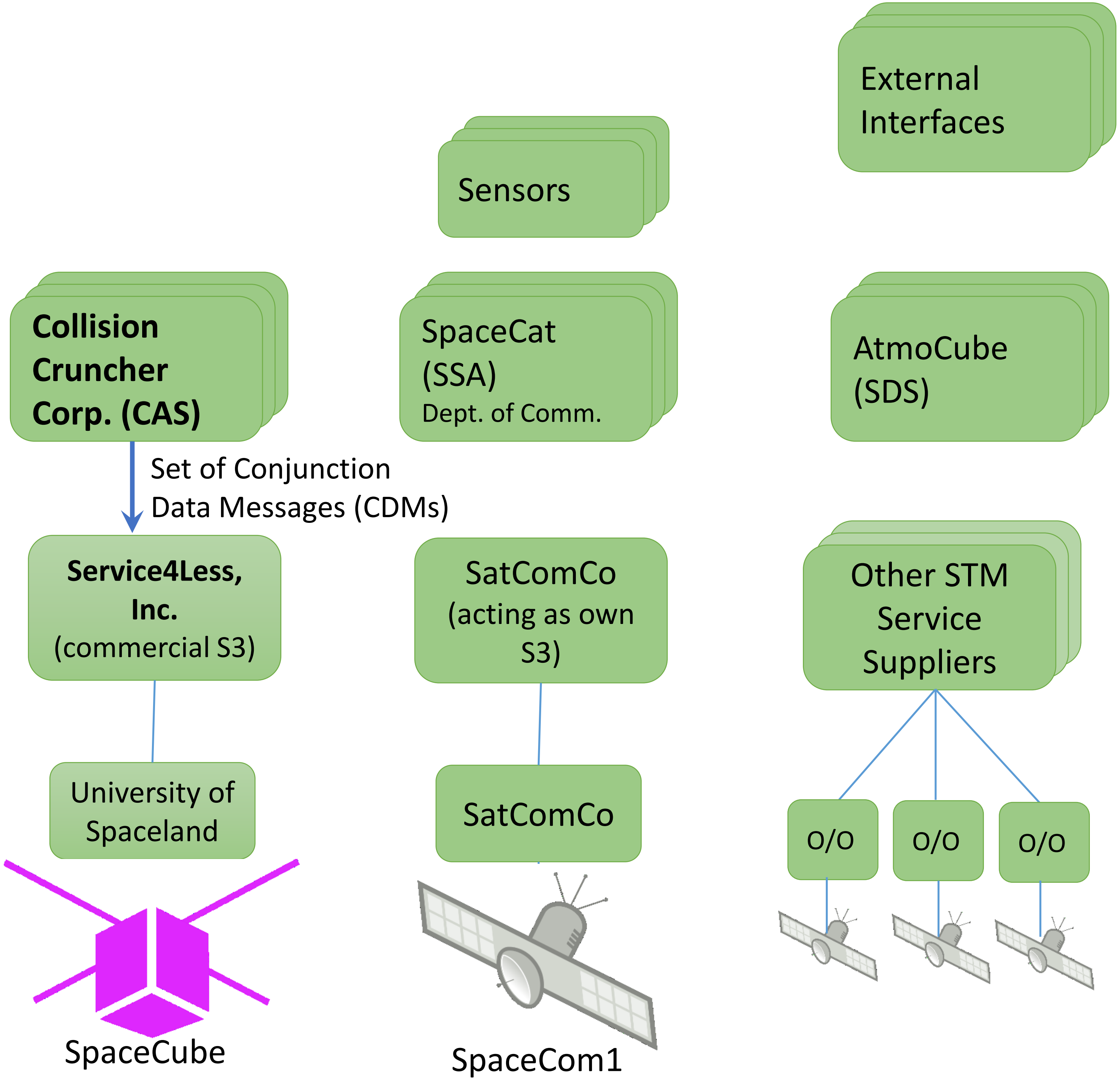
Example Data Flow: Conjunction Screening (5/5)

Time

T-3 Days

Conjunction Screening Steps

1. Service4Less periodically requests a conjunction screening for SpaceCube from Collision Cruncher Corp. and provides the latest Spacecube ephemeris.
2. Collision Cruncher Corp. queries the latest SSA information from SpaceCat, a Department of Commerce Service (or could also ask commercial SSA providers).
3. SpaceCat provides the catalog based on its sensors and O/O data shared with it.
4. Collision Cruncher computes potential conjunctions.



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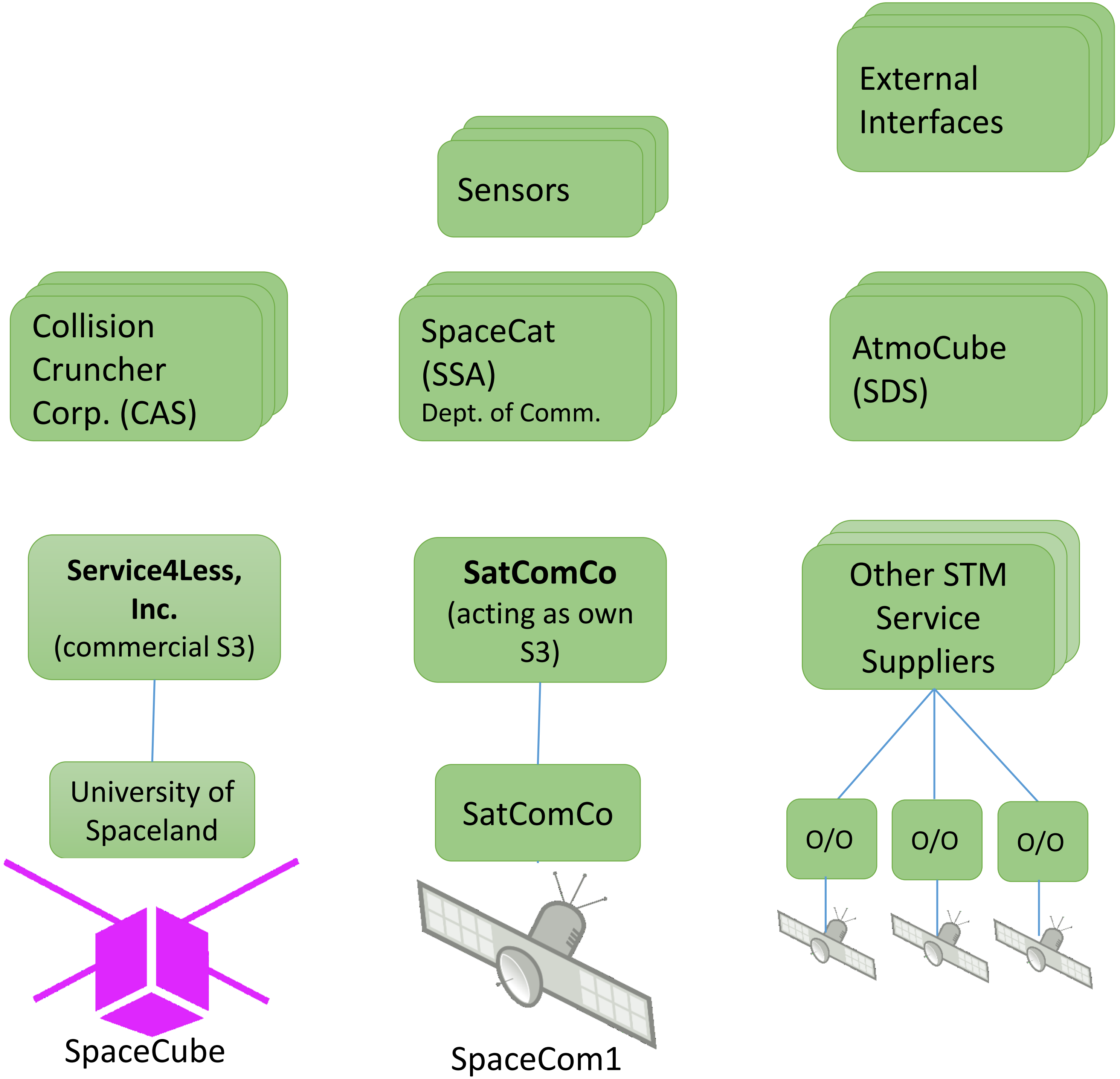
Example Data Flow: Collision Avoidance (1/7)

Collision Avoidance Steps

1. Service4Less assesses the received CDMs, clears most of them, but identifies a high risk conjunction between SpaceCube and SpaceCom1.



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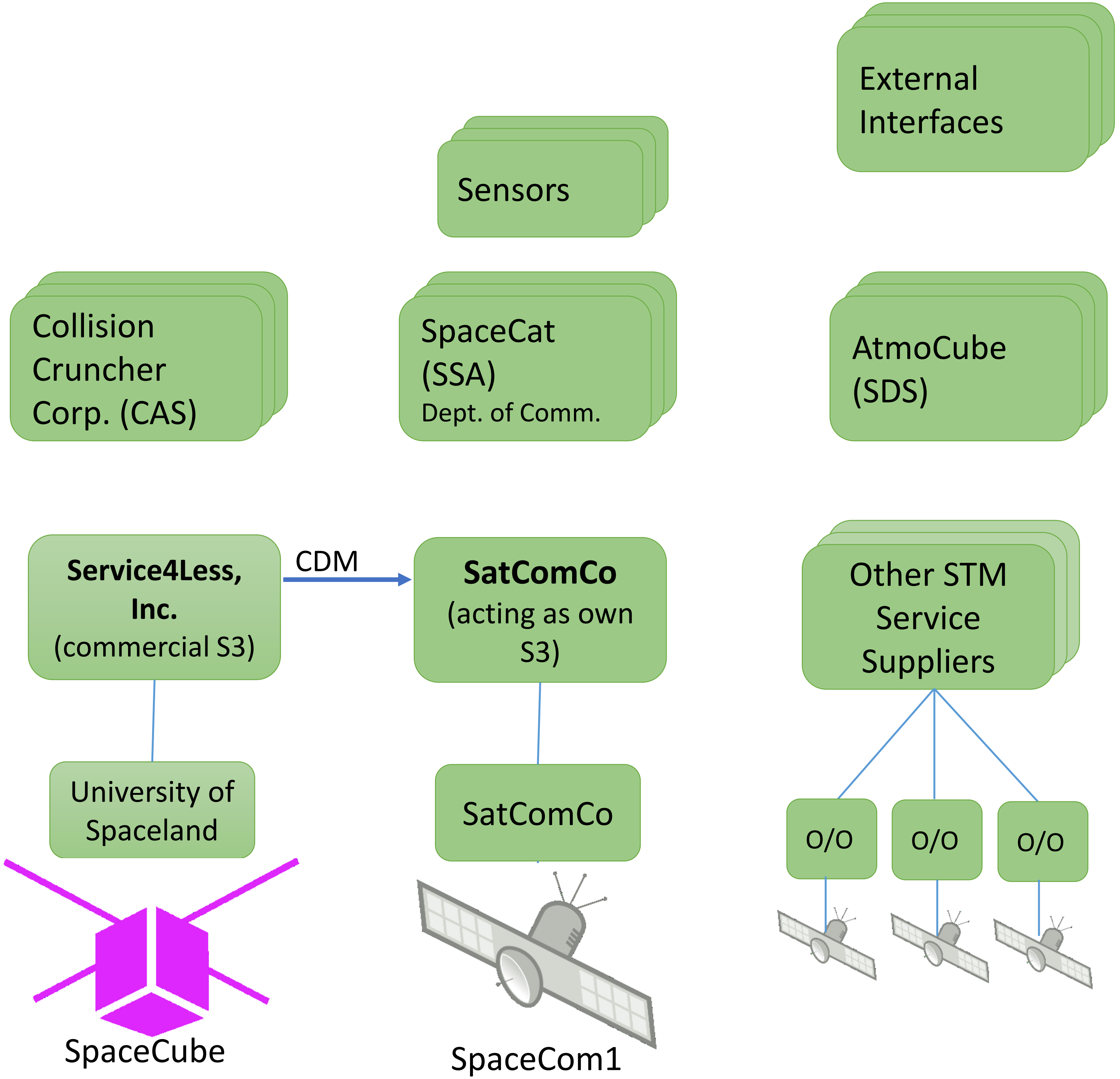
Example Data Flow: Collision Avoidance (2/7)

Collision Avoidance Steps

1. Service4Less assesses the received CDMs, clears most of them, but identifies a high risk conjunction between SpaceCube and SpaceCom1.
2. Service4Less warns SatComCo.



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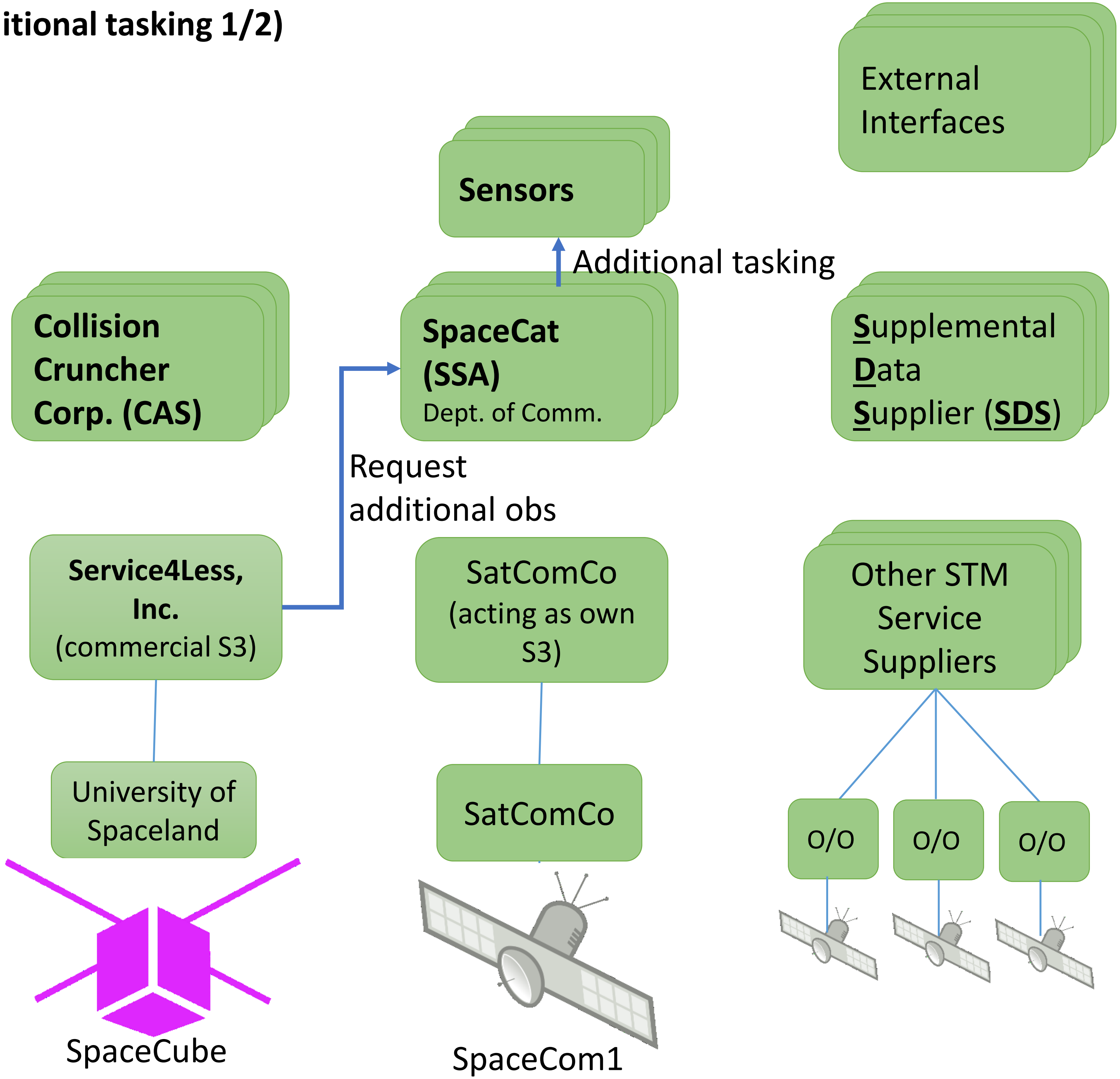
Example Data Flow: Conjunction Assessment (additional tasking 1/2)

Time
T-3 Days

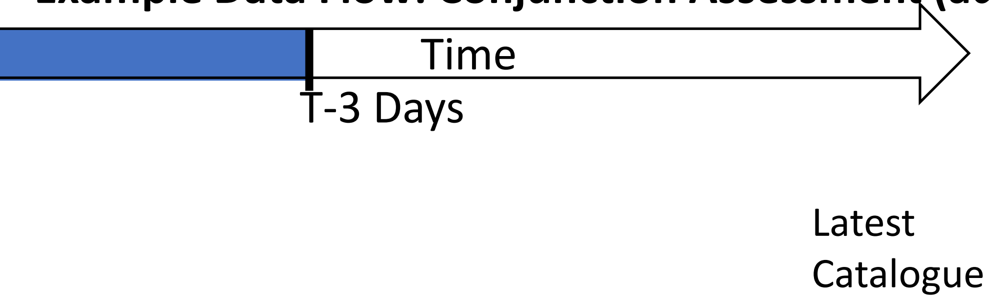
Latest Catalogue

Conjunction Assessment Steps

1. Service4Less can request additional observations from one or more SSA suppliers to reduce covariance and potential clear false positive events (optional).

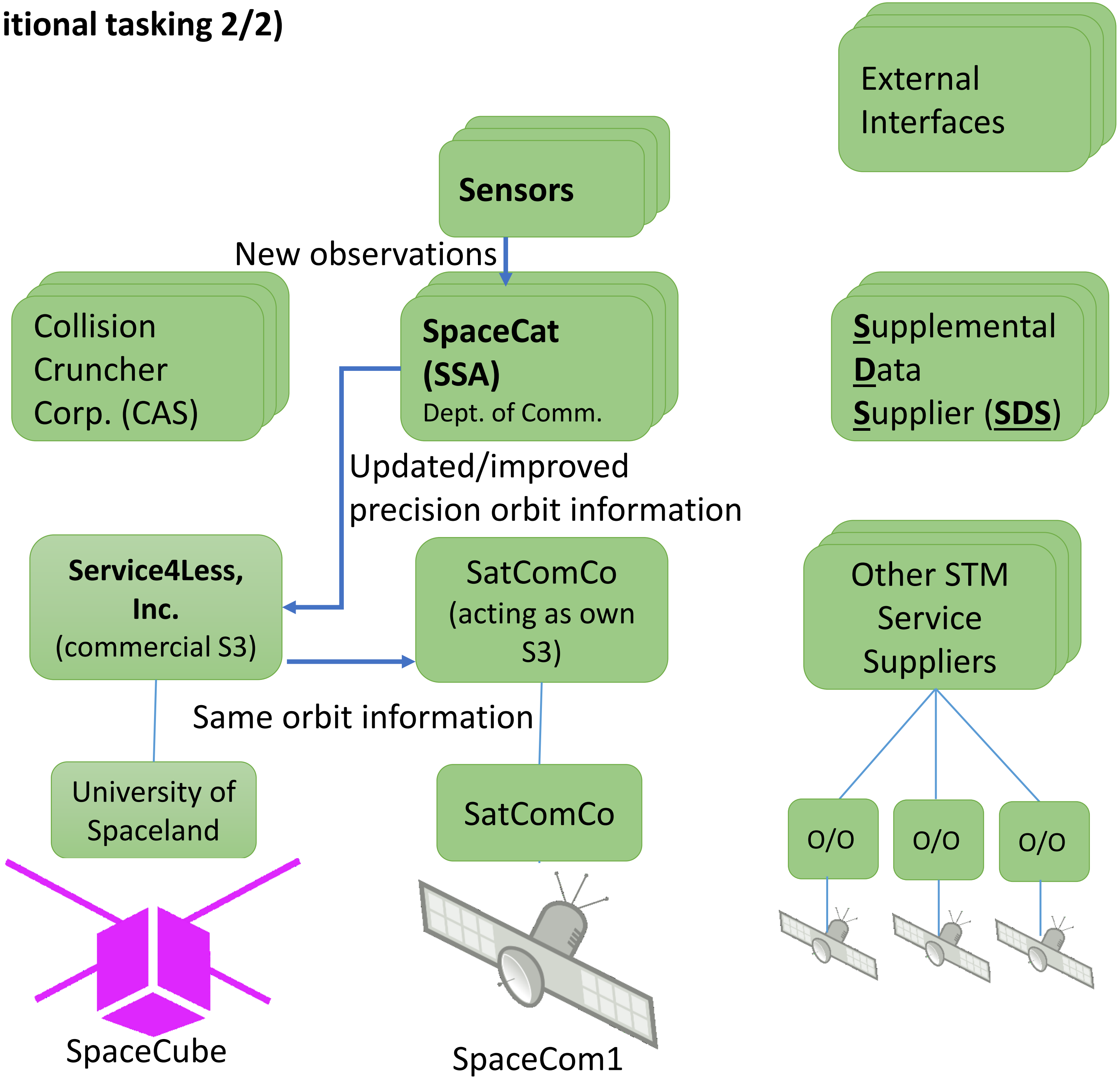


Example Data Flow: Conjunction Assessment (additional tasking 2/2)



Conjunction Assessment Steps

1. Service4Less can request additional observations from one or more SSA suppliers to reduce covariance and potential clear false positive events (optional).
2. SpaceCat conveys updated orbital information to Service4Less, with a smaller covariance from the latest observations. The event is confirmed as meeting Service4Less and SatComCo's respective criteria for a collision avoidance maneuver.



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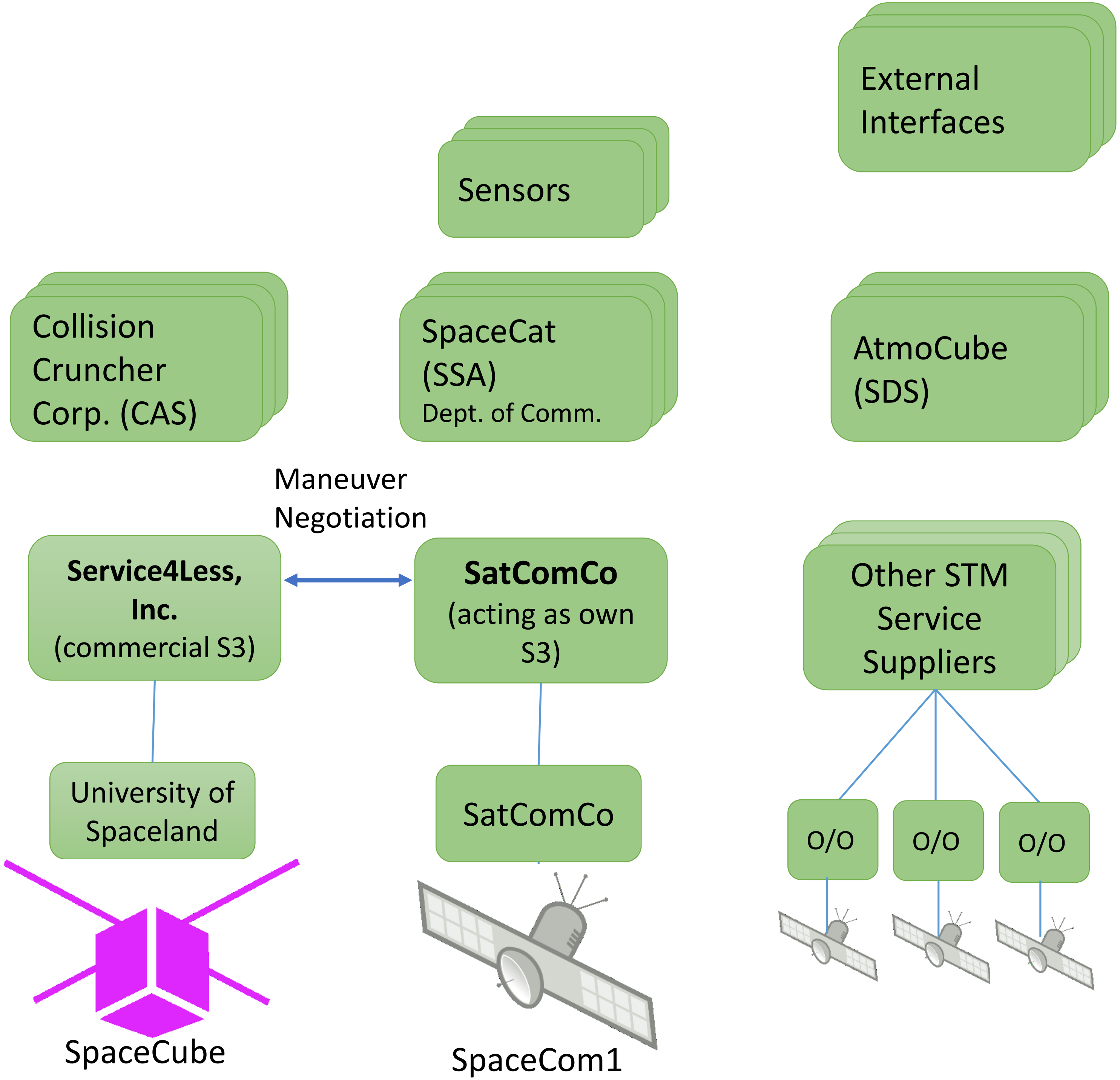
Example Data Flow: Collision Avoidance (3/7)

Collision Avoidance Steps

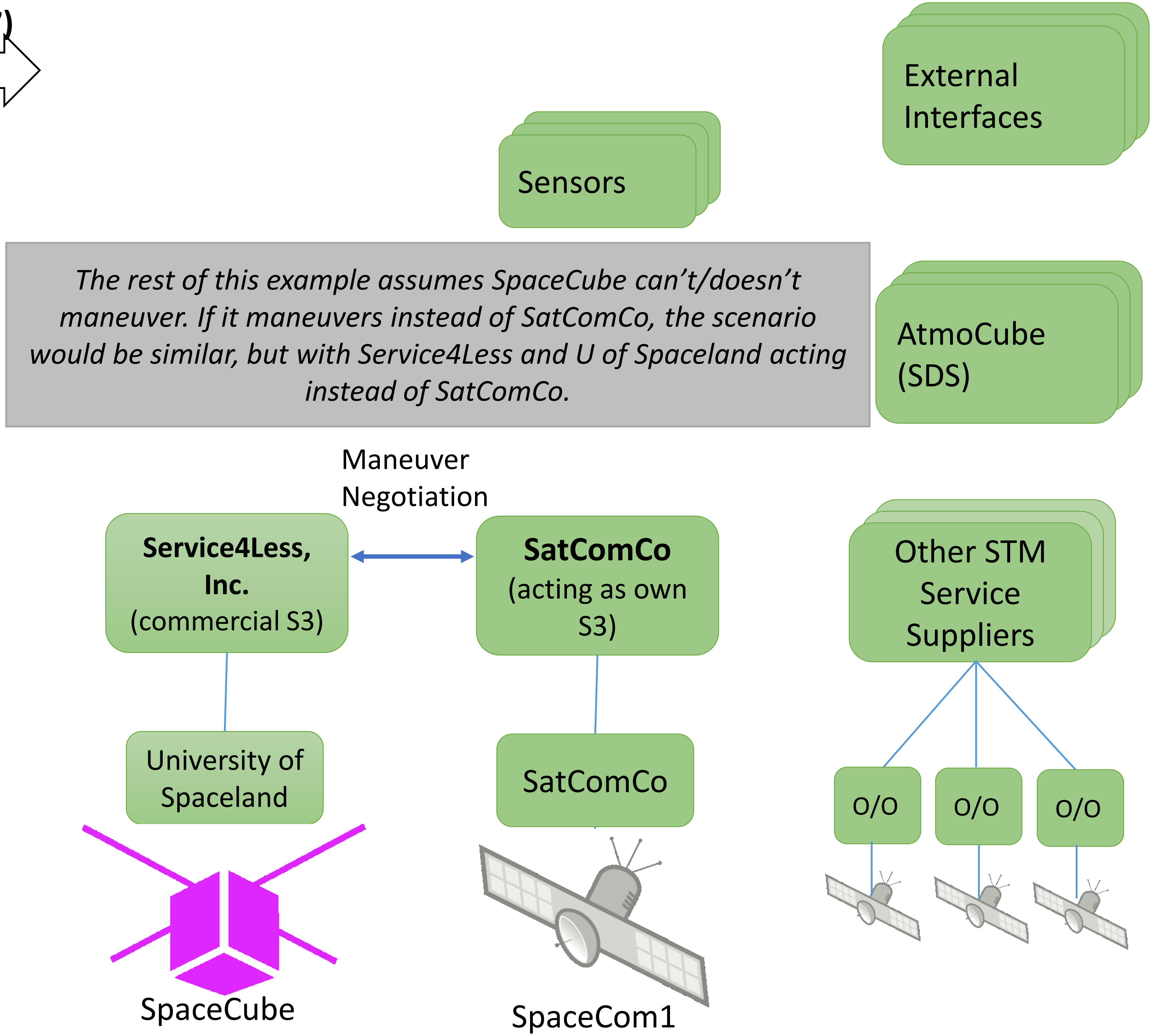
1. Service4Less assesses the received CDMs, clears most of them, but identifies a high risk conjunction between SpaceCube and SpaceCom1
2. Service4Less warns SatComCo.
3. The two S3s negotiate who will maneuver, and generate a collision avoidance maneuver.



Example Data Flow: Collision Avoidance (4/7)

Collision Avoidance Steps

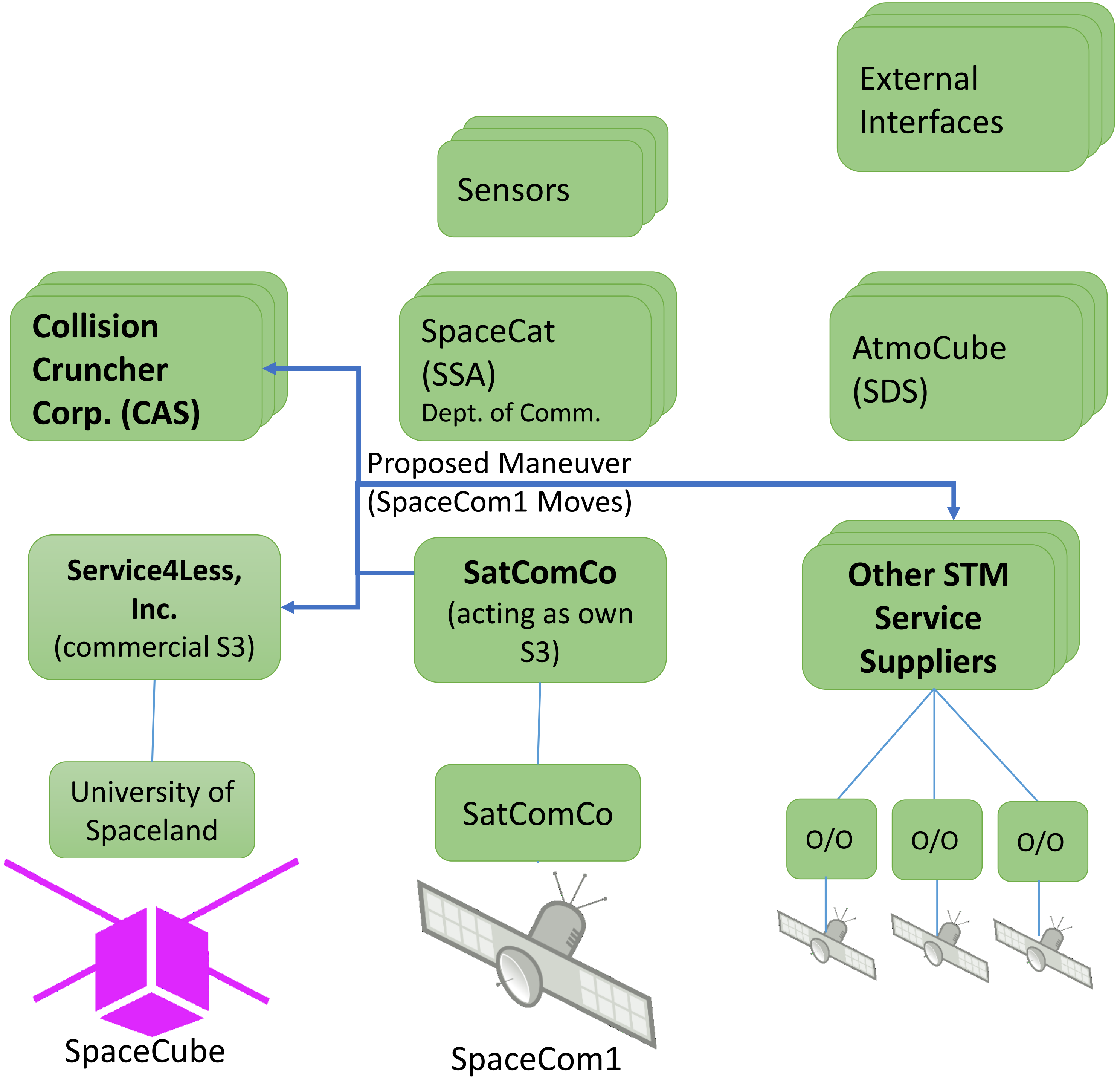
1. Service4Less assesses the received CDMs, clears most of them, but identifies a high risk conjunction between SpaceCube and SpaceCom1
2. Service4Less warns SatComCo.
3. The two S3s negotiate who will maneuver, and generate a collision avoidance maneuver.



Example Data Flow: Collision Avoidance (5/7)

Collision Avoidance Steps

1. Service4Less assesses the received CDMs, clears most of them, but identifies a high risk conjunction between SpaceCube and SpaceCom1
2. Service4Less warns SatComCo.
3. The two S3s negotiate who will maneuver, and generate a collision avoidance maneuver.
4. They share with the STM network, and validate with a CAS.



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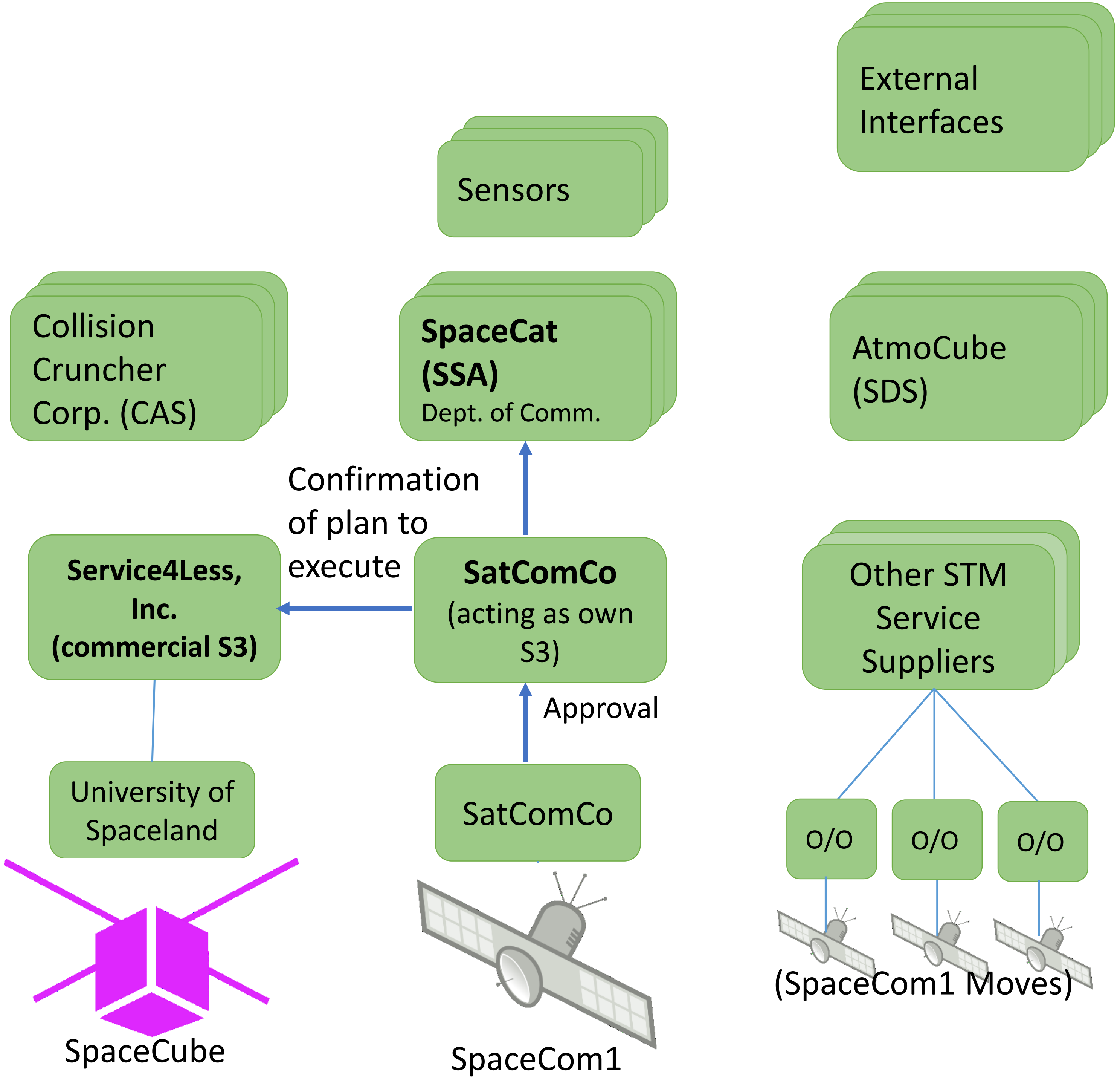
Example Data Flow: Collision Avoidance (6/7)

Time

T-2 Days

Collision Avoidance Steps

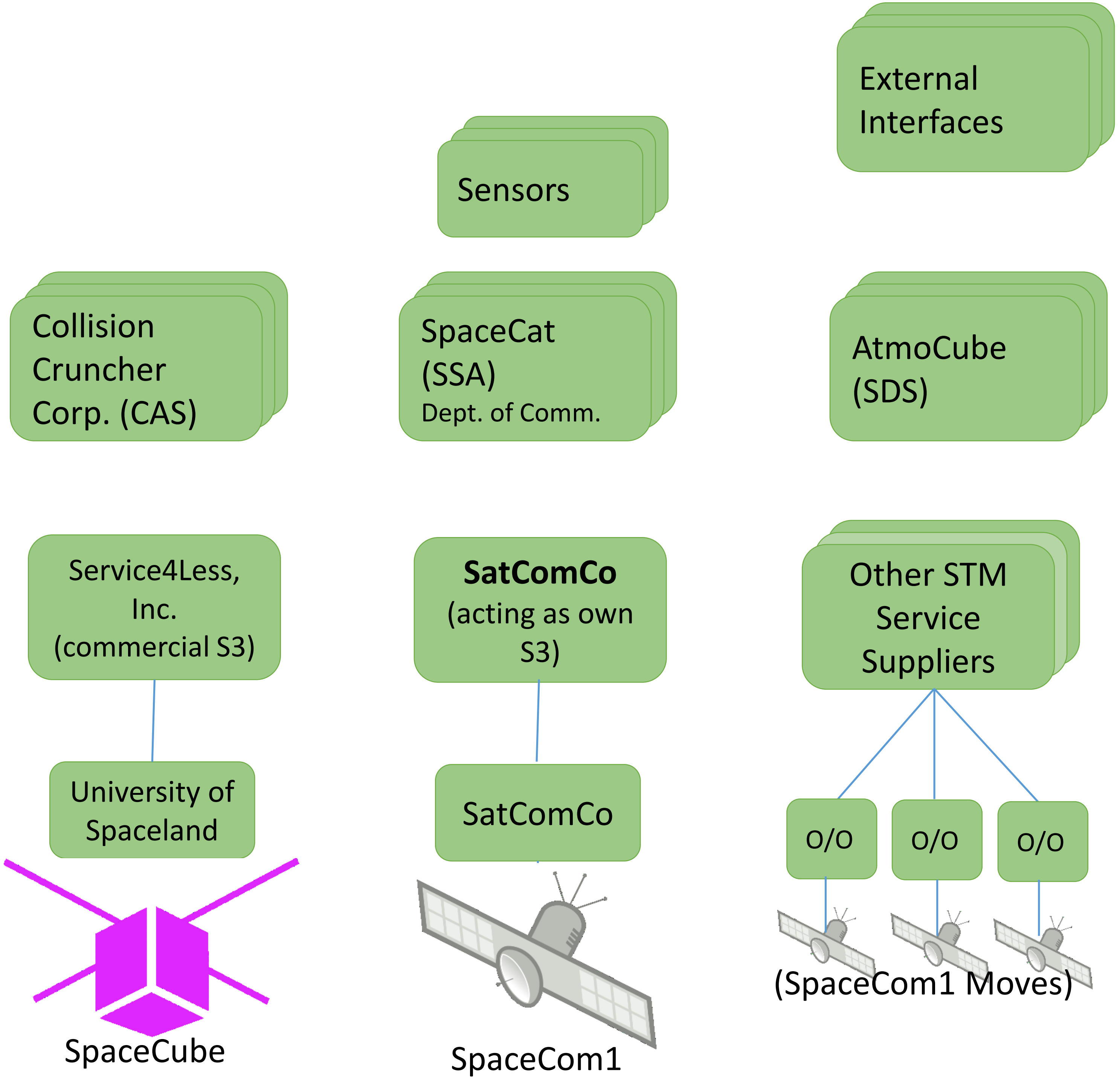
1. Service4Less assesses the received CDMs, clears most of them, but identifies a high risk conjunction between SpaceCube and SpaceCom1
2. Service4Less warns SatComCo.
3. The two S3s negotiate who will maneuver, and generate a collision avoidance maneuver
4. They share with the STM network, and validate with a CAS.
5. O/O of the moving sat approves plan. S3 shares intention.



Example Data Flow: Collision Avoidance (7/7)

Collision Avoidance Steps

1. Service4Less assesses the received CDMs, clears most of them, but identifies a high risk conjunction between SpaceCube and SpaceCom1
2. Service4Less warns SatComCo.
3. The two S3s negotiate who will maneuver, and generate a collision avoidance maneuver
4. They share with the STM network, and validate with a CAS.
5. O/O of the moving sat approves plan. S3 shares intention.
6. SatComCo executes maneuver.



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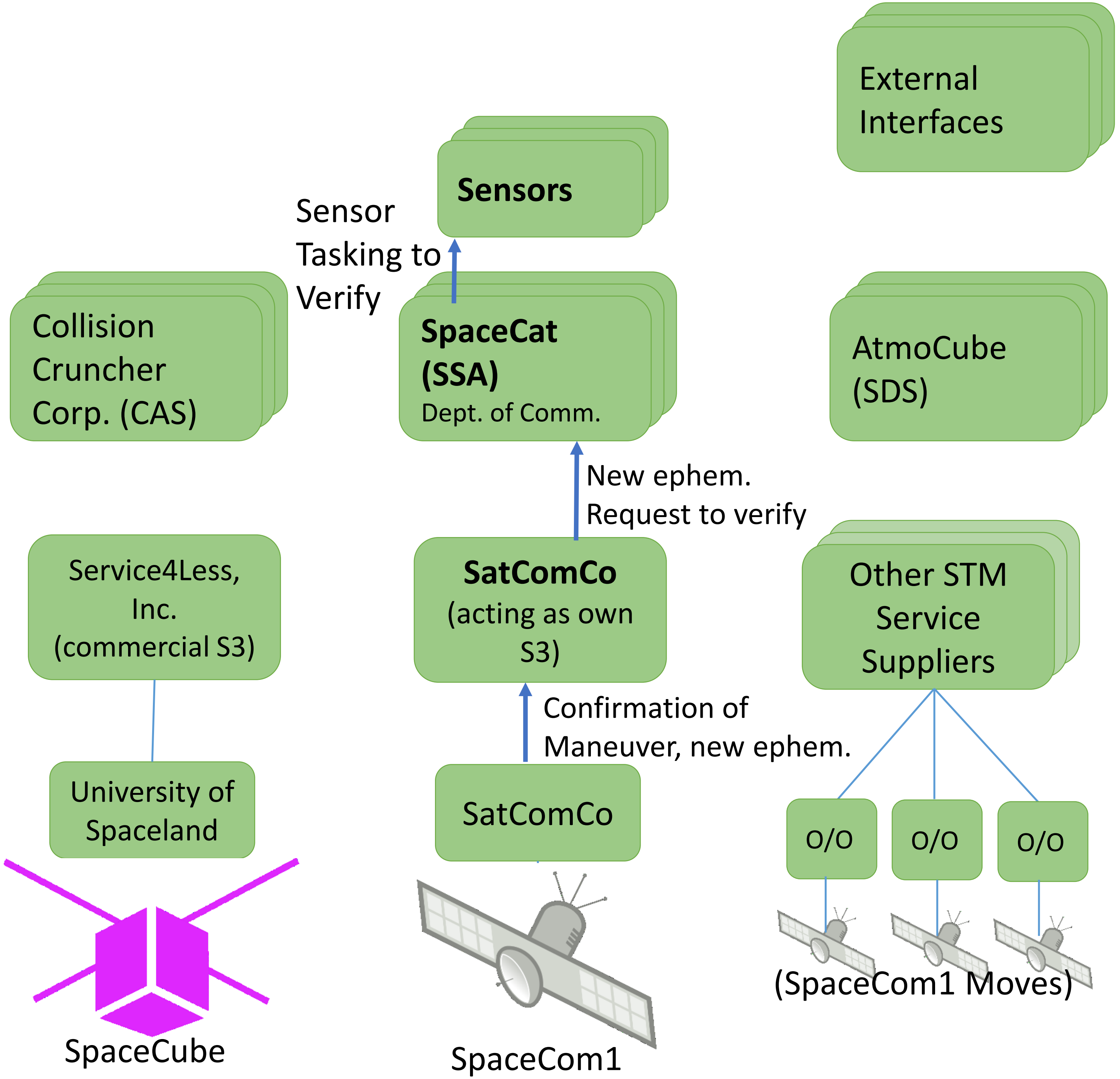
Example Data Flow: Verification (1/2)

Verification Steps

1. SatComCo requests that an SSA provider verify the maneuver was completed correctly. SpaceCat tasks its sensors accordingly (optional).



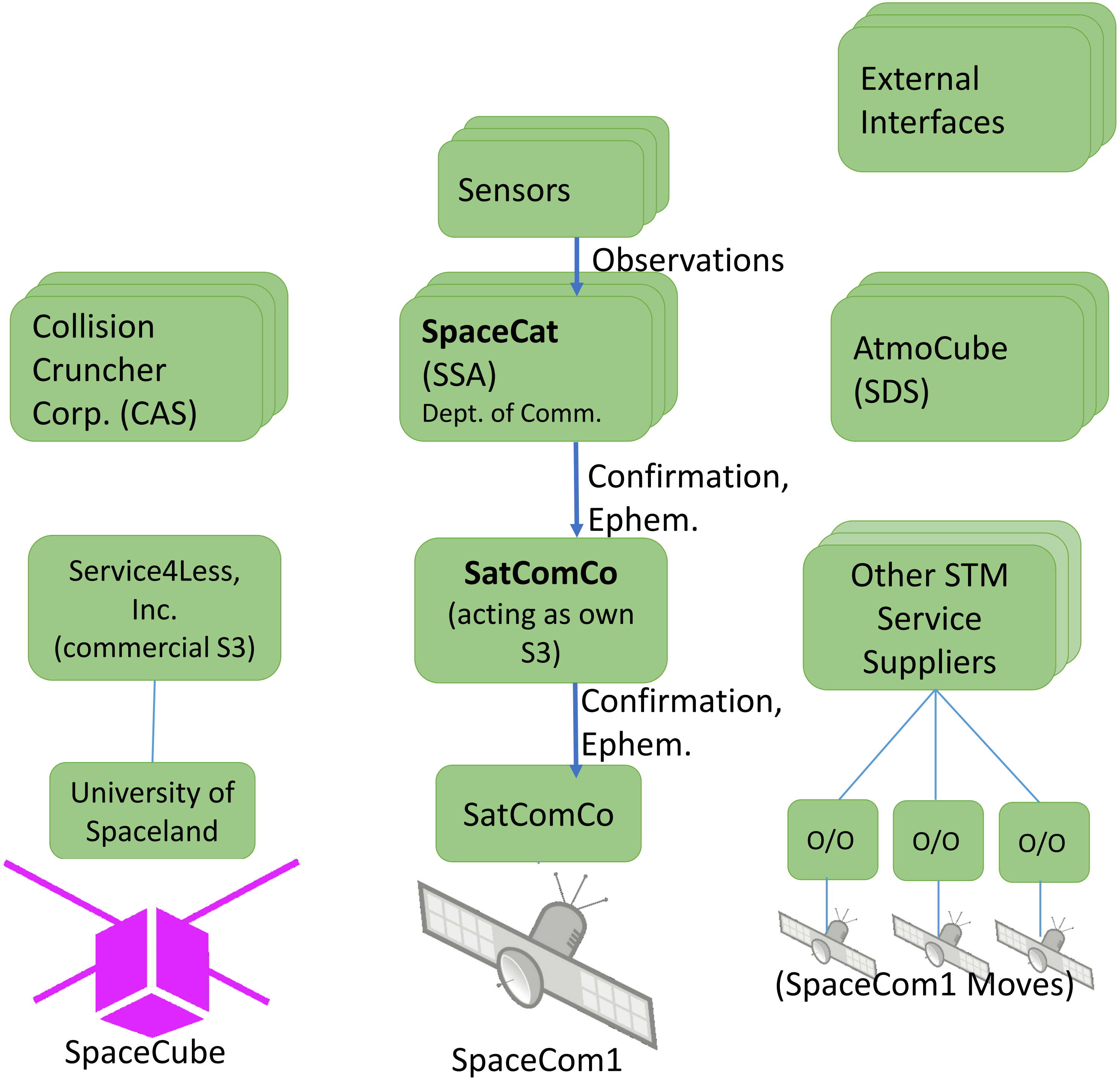
Example Data Flow: Verification (2/2)

Time

T-1 Days

Verification Steps

1. SatComCo requests that an SSA provider verify the maneuver was completed correctly. SpaceCat tasks its sensors accordingly (optional).
2. SpaceCat provides confirmation to SatComCo along with its assessment of orbital information for SpaceCom1.



STM Architecture Benefits for Smallsat Operators

1. Get ahead of regulation
2. Reduces the STM burden for smallsat owner/operators
3. Makes it easy to be a good citizen
4. Fosters market opportunity for smallsat-generated STM services

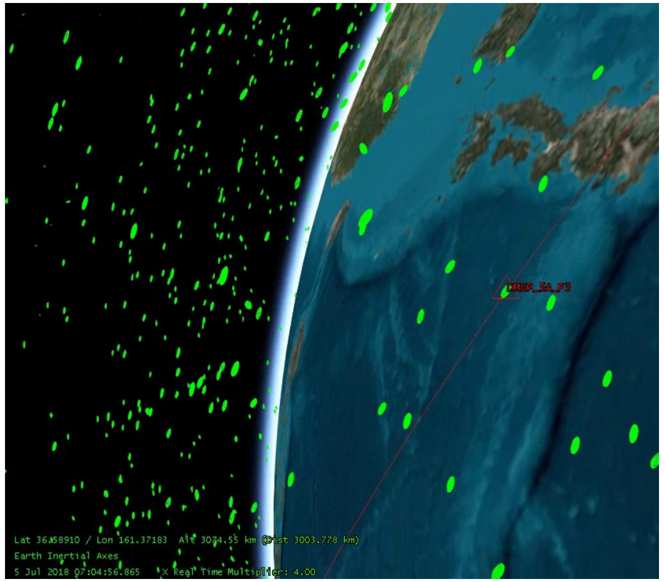
Current STM Development at Ames

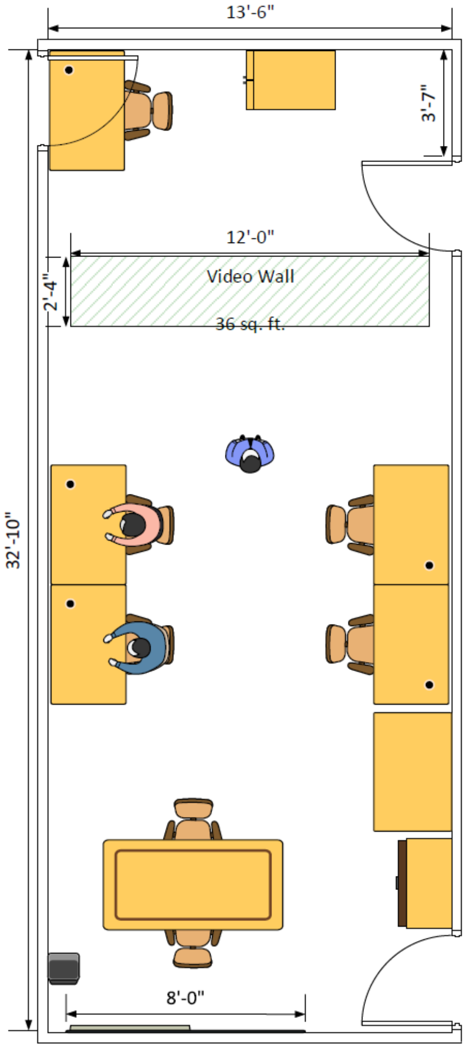
- Developing STM architecture
  - Defining APIs, roles, functions
  - Roadmap with TCLs

- Finding industry, academic, government partners
  - Consensus finding, developing user community, defining interfaces

- Developing research environment (NASA Ames N243 R237)
  - Implement strawman STM ecosystem
  - Visualization environment

Ames STM Research Environment





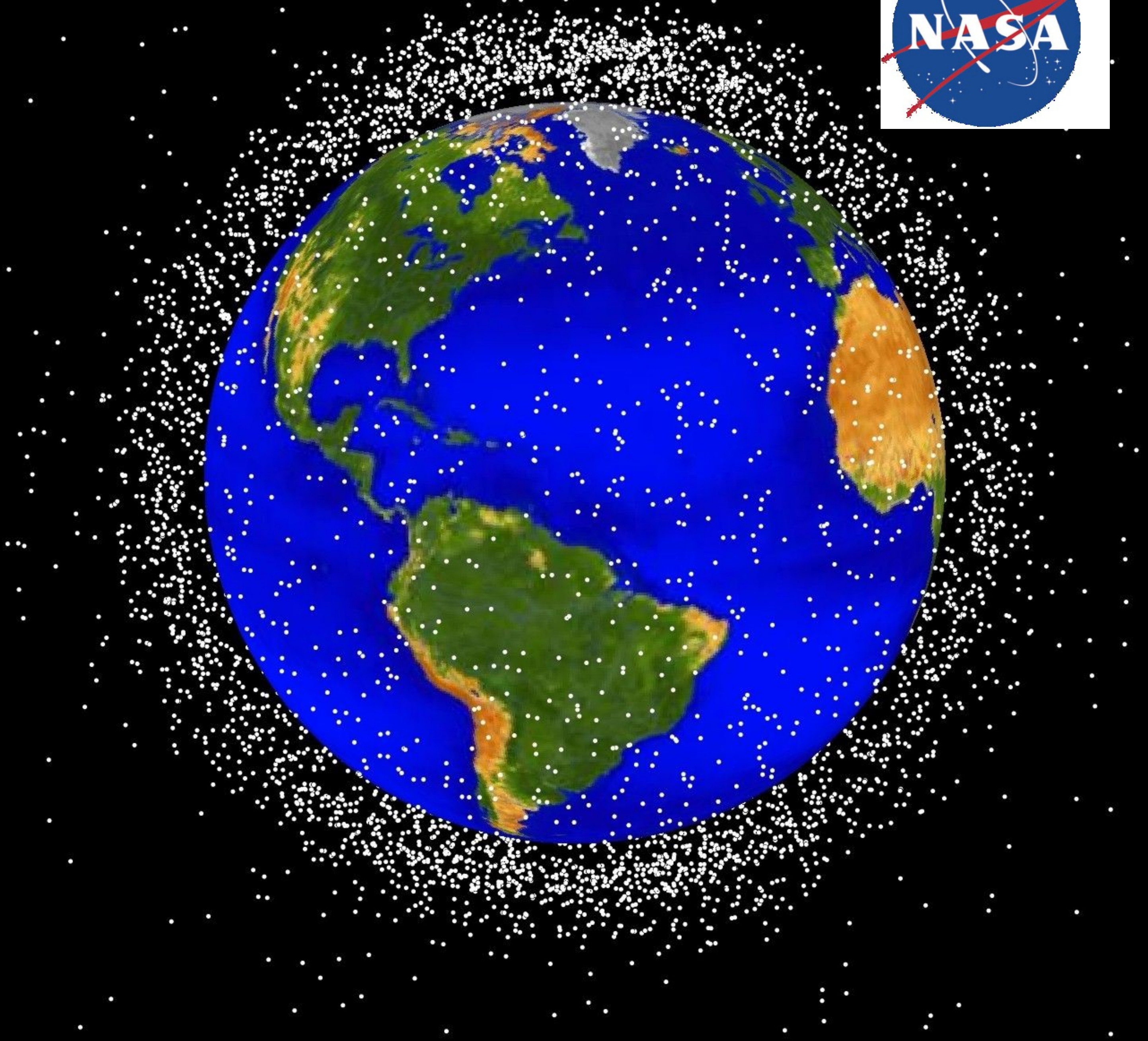
Objective: Develop and test prototypes of STM services

- Small-scale lab w/ workstations, server, hyperwall
- Focus on early partner involvement (industry, academia, gov't)
- NASA, AGI software suites
- Leverage UTM experience and codebase
  - (Potential) development using public Git repos, deployment for 'field tests' on Amazon Web Services

Conjunction Assessment Simulations

- Simulate the automation of the following functionalities required within STM:
  - Identifying high-interest conjunctions (HIC)
  - Developing and validating collision avoidance strategies
  - Performing trade analysis between maneuvers to identify the best strategy.
- Demonstrate the automation of this process through the use of existing conjunction assessment software tools:
  - ESA's DRAMA
  - AGI's STK AdvCAT
  - LightForce (in-house code)
- Expected results
  - Automation of conjunction assessment services is critical to the success of STM
  - Reduction in probability of collision and number of conjunction warnings as a result of implementing suggested maneuvers
  - Creation of a framework in which existing conjunction assessment software are utilized

Questions or Feedback?



CCDS Standards for Data Exchange

- The Consultative Committee for Space Data Systems (CCSDS) is a multi-national forum for standards development.

Relevant Standards:

- Navigational Data Messages (CCSDS 500.2-G-1)
  - Attitude Data Message (ADM)
  - Orbit Data Message (ODM) CCSDS 502.0-B-2
    - Orbital Parameter Message (OPM)
    - Orbit Mean-Elements Message (OMM)
    - Orbit Ephemeris Message (OEM)
  - Tracking Data Message (TDM) CCSDS 503.0-B-1
  - Conjunction Data Message (CDM) CCSDS 508.0-B-1
  - Space Maneuver Message (SMM) CCSDS 511.0-W-4 (proposed)

Architecture Goals

- Solve system-wide discovery issues (who do I contact about an issue with CubeSat1?)
- Enable success of commercial STM participants, lower barriers to participation and interoperability
- Enhance system safety
- Reduce the cost (time and resource) for small operators to comply with STM best practices

Value Proposition (for Department of Commerce)

- Utilizing an existing approach with proven results (UTM commercial ecosystem)
- Heavy focus on commercialization
- Reduces oversight burden (compared to traditional approaches)

STM Technical Capability Levels (TCLs)

Capability 1: Demonstrated STM for Small Sats

- On-orbit operations
- Open interface and data validation
- Civil (commerce) /commercial catalog(s)
- Small satellites S3 conjunction assessment & warning, COLA planning

Product: Overall con ops, architecture, and roles, use case

Capability 3: Mature Concept, Expanded Capabilities

- Space weather
- Single actionable catalog + data fusion
- Support for mega-constellations
- Procedures and "rules-of-the-road"

Product: mature concept incorporating regulator policy choices

Capability 2: Full Physical STM and RFI

- Autonomous maneuver planning/deconfliction (small and large satellites)
- Interaction with crewed spacecraft
- Radio-frequency Interference
- Coordination with non-participants/classified entities

•Product: Requirements, interfaces, and proof of concept for broader set of participants/services

Capability 4: Internationalization and Integration with Air Traffic Management

- Launch and reentry, sub-orbital
- Internationalization of system?
- Active debris removal/rendezvous and proximity operations
- Laser/directed energy integration

•Product: comprehensive architecture for STM covering all phases of activity, coordination with other countries

•Evolutionary approach: build capability by function and user needs

Architecture Roles

Space Situational Awareness Supplier (SSA)	Collision Assessment Supplier	Supplemental Data Supplier	STM Service Supplier (S3)	Owner/ Operator (O/O)	Space Information Management System (SIMS)
Track Resident Space Objects (RSOs)	Conjunction Detection	Additional data needed by participants (RF, micrometeoroid, atmospheric modeling, etc.)	Conjunction Assessment	Control authority	Acquire information for regulators
Determine RSO orbits, pool data	Conjunction assessment and maneuver planning/validation support		Conjunction Mitigation Plan Development, validation, and Deconfliction	Separation and collision avoidance	Disseminate regulator information to participants as required.
Propagate Orbits			Operations Archive		

Actor/Entities and STM System Roles

Service/Function		Actors/Entities						
		✓ = Primary responsibility, S = Secondary responsibility						
		Owner/Operator (O/O)	Space Traffic Management Service Provider (S3)	Conjunction Assessment Supplier (CAS)	Space Information Management System (SIMS)	Space Situational Awareness Supplier (SSA)	Supplemental Data Supplier	TBD National or International Regulators
Separation	In plane orbital separation and station keeping	✓						
Hazard/Terrain Avoidance	Radiofrequency Interference Generation Avoidance	✓	S					
	Conjunction Avoidance	✓	S	S				
Status	Satellite Information Archive	✓	S					
	Satellite Information Status	✓	S					
	On-Orbit Position Determination of Satellite	✓	S			S		
Data	Data Collection	S	S	✓		✓	✓	
	Data Pooling and Fusion		S		✓			
Conjunction/RFI Mitigation	Conjunction Detection		S	✓				
	Conjunction Notification	S	✓		S			
	Conjunction Risk Assessment		✓	S				
	Conjunction Mitigation Plan Development	✓/S	✓/S					
	Conjunction Plan Negotiation (with other parties)	S	✓					
	RFI Attribution	S	S		✓			
	RFI Mitigation	✓	S					
Maneuvers	Maneuver Intent sharing (pre-execution/during/after)	S	✓					
	Maneuver Execution	✓	S					
Operations Management	Demand Capacity Management							✓
	Space Access Management							✓
	Control of flight	✓						
	Orbital Slot Allocation & Constraint Definition		S					✓

Who maneuvers to avoid a satellite-on-satellite high interest event (HIE)?

- Some basic questions:
  - Who can move adequately within the available time to avoid the conjunction?
  - What is the impact of a maneuver on mission/consumables?
  - What if the two O/Os (and their respective S3s) have different assessments about whether an event merits a maneuver?
  - How does the maneuver plan accommodate contingencies?
- What policy rules or norms do you want to develop? Considerations:
  - Equity
  - Incentives & avoiding rent-seeking behavior
  - Effectiveness
  - Objectivity, ability to be (somewhat) automated.
  - Enforcement (or is mechanism self-enforcing?)
- Decision regimes on the next slide assume that both crafts are capable of moving to mitigate a contingency.

Methods to Decide Who Moves in a Sat-on-Sat HIE

	Description	Benefits	Harms	Considerations
Rules-based	Hierarchy of agreed-upon right-of-way rules (i.e. port over starboard, leeward over windward), prioritizing the less maneuverable craft. Regardless of rules, all have duty to avoid collisions.	• Clear standards • Equitable	• Need to be carefully designed to avoid O/Os externalizing cost of collision avoidance onto others	• Needs a unified global system to work • Need widespread adoption • Limited effectiveness if not accompanied by liability enforcement
Dual-Maneuver, Implicit Cost Split	Both craft maneuver to split cost to consumables and/or mission disruption.	• Equitable split of costs	• Difficult to quantify mission disruption. • More failure modes • Maneuvers need to be mutually planned	• Difficult to automate.
Last-Moment	Whoever is more concerned by risk first will move first.	• Simple • Self-enforcing	• High likelihood of late/no mitigation • Encourages irresponsible activity	• This really isn't a good idea…
Auction-Based	O/Os offer to move for a certain price. Whoever proposes the lower cost to move gets paid that cost by the other O/O.	• Reveals O/O economic preferences.	• Risks collision-seeking behavior. • Favors large/rich O/Os	• Monetary exchanges between countries that do not permit financial transactions. • Doesn't work when one-party can't maneuver.
Resource-Based	O/O who would experience a lower cost to move, does.	• Reduces total cost of mitigation.	• Considers relative cost only. Ignores absolute cost.	• Challenging to equate costs across different satellites

New Cubesat Mission Concepts will need STM

- To date, limited need for Cubesat SSA/STM
- Typical Contemporary Cubesat (non-technology demo)
  - No propulsion and only limited drag maneuvering
  - Minimal STM needs:
    - Post-deployment identification
    - Orbital Trajectory for passes and antenna pointing
    - Conjunction messages are not very actionable
  - Low altitudes (typically <600km)
  - Un-augmented atmospheric drag for deorbiting mechanism.
- New mission concepts at higher altitudes will need propulsion/integration into an STM system.

How do you handle coordination system-wide SSA coordination?

- Want to avoid three kinds of collisions
  - **Primary collisions** – conjunctions found during CAS computation
  - **Secondary collisions** – one or both crafts move to avoid a primary conjunction and create a second conjunction with the other craft later in the future.
  - **Tertiary collisions** – one or both crafts move and ends up on a course for a conjunction with a third-party resident space object (usually screened within a certain window).
- Challenging if proprietary concerns limit O/O ephemeris sharing. Non-cooperative methods (i.e. radar/telescopes) don’t always detect maneuvers in a timely manner.

System-wide SSA coordination (continued)

- Stakeholder consultations needed to understand propriety concerns and level of data that can be shared.
- Current thinking (to be verified by software platform testing and stakeholder discussions)
  - Small movements (i.e. station keeping) might be addressable by adequate screening volumes during initial conjunction screenings, as cost of false positives
  - Large movements need either centralized trusted agent that can warn, or global (potentially fuzzy) declaration
  - Bi-lateral positional consensus determination by S3s during collision avoidance maneuver negotiation can solve secondary conjunctions.
  - Third-party conjunctions require publication of maneuvers for screening by other S3s or centralized trusted agent.

Potential SSA Catalog Architectures

- One Master Catalog (either government or private)
  - Likely to result from concerns about sharing O/O ephemeris
- Small Number of Catalogs (semi-manual integration)
  - Manual decisions about who to trust, use to inform your SSA
- Large Number of Catalogs (highly automated integration)
  - Automated processes for assessing data sources
- Algorithmic Consensus (distributed consensus)
  - meta-catalog driven by multiparty computation that cryptographically shields contributions from each catalog

System Objectives Inform Participant Recruitment Strategy

What objective are we trying to achieve?

- Prove concept and demonstrate utility
- Refine concept and add capabilities/use cases gradually
- Create pathway towards implementation of an operational system

Build-a-little, test-a-little approach to system development

- Need enough users to test system/inform development
- But not so many users that we run into scaling issues before system design is mature
- Build confidence/support from users before attempting to transition to an operational system

Should there be a participation mandate for an operational STM system?

- Depends on natural adoption rate, value of system, effectiveness of voluntary incentives/disincentives
- Question assumes that greater participation will increase system effectiveness/flight safety
- Different niches of users respond best to different mechanisms
- More heavy-handed approaches should be narrowly employed only as absolutely necessary.

What are option to encourage system participation?

- Pure Voluntary
  - System benefits are attractive to users
- Carrots
  - Payments/discounts
  - Reduced insurance costs
  - Regulatory permission for desirable actions (i.e. operate in more congested environments, fast-track approval)
- Sticks
  - Fines
  - Operating restrictions (altitude, spectrum, etc.)
  - Increased engineering requirements (propulsion, retro-reflectors, etc.)
  - Mandate to compensate crafts maneuvering to avoid your spacecraft
- Mandate with phase-in criteria
  - Satellite mass/volume, power, orbital region, value
  - Constellation size
  - Owner type (commercial, academic, hobbyist)