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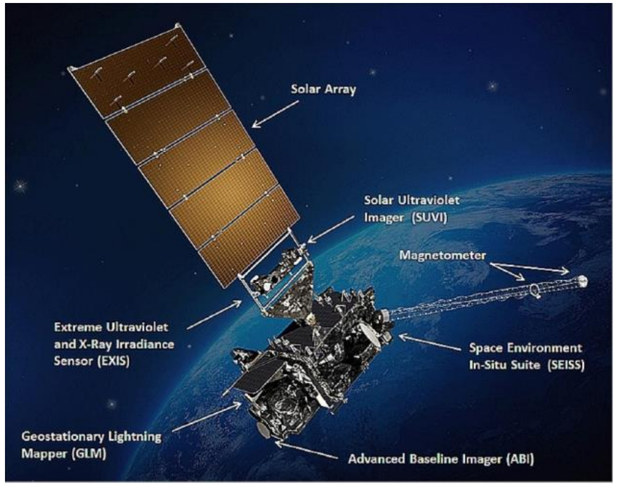
Developing Effective Space Systems with Earlier Integration, Verification, and Validation

Space Systems are Complex Systems

- Success of space system development effort = achieving the stakeholders' real-world expectations of their expected mission.
- Space systems tend towards customization, resulting in unique set of lifecycle concepts, needs, requirements, interfaces, and constraints.
- Space systems are examples of complex system development.
  – Composed of many components which may interact with each other.
  – More than the sum of their parts – they have emergent properties and behaviors.
- Development and management of a space system's needs and requirements has been shown to drive project cost, schedule, and ability to meet its technical objectives.



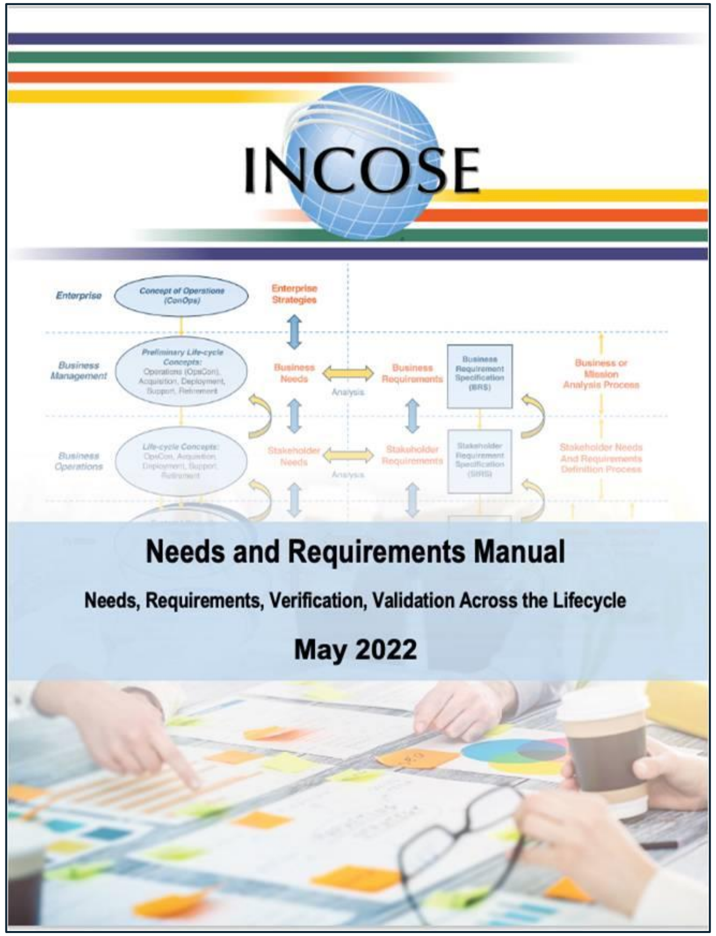
Validation of Complex Systems (Problems Observed)

- The following challenges have been identified that contribute against achieving successful system validation:
  1. Poorly defined needs and requirements result in difficulties towards design and verification
  2. Inability to pass system verification and system validation through errors in data, incomplete data, and late issues discovered during integration
  3. Inconsistent multiple sources of truth result in challenges during development and verification activities

Validation is the set of activities ensure and gaining confidence that a system is able to accomplish its intended use, goals, and objectives (i.e. meet stakeholder requirements) in the intended operational environment (INCOSE SE Handbook, v4).

Using INCOSE Resources to Address Challenges

- To address the validation challenges, concepts from the INCOSE NRM are introduced.
- By applying these concepts during space system development, the resultant effort enables earlier and confident verification and validation for the system across the lifecycle.
- The examples provided use an example space mission, FireSat II (in actuality they can be applied towards any complex mission).



INCOSE NRM Underlying Concepts

Develop the Integrated Set of Needs

Often a major focus is on the development of system level requirements, rather than first ensuring an understanding of the actual problem or opportunity, developing feasible lifecycle concepts, and defining an Integrated Set of Needs that represents the scope of the project and from which the system design input requirements will be transformed.

There is a lot of work and analysis to be done before defining the requirements.

+

Perform Integration, Verification and Validation Activities Throughout the Lifecycle

Developers will often wait until they have a realized system before addressing integration, system verification, and system validation.

This can result in risk that issues will not be discovered until late in the lifecycle.

+

Use Data-Centric Development Practices

Document-centric practice of SE, presents challenges of having multiple sources of truth.

Moving to a data-centric practice of SE results in a single authoritative source of truth.

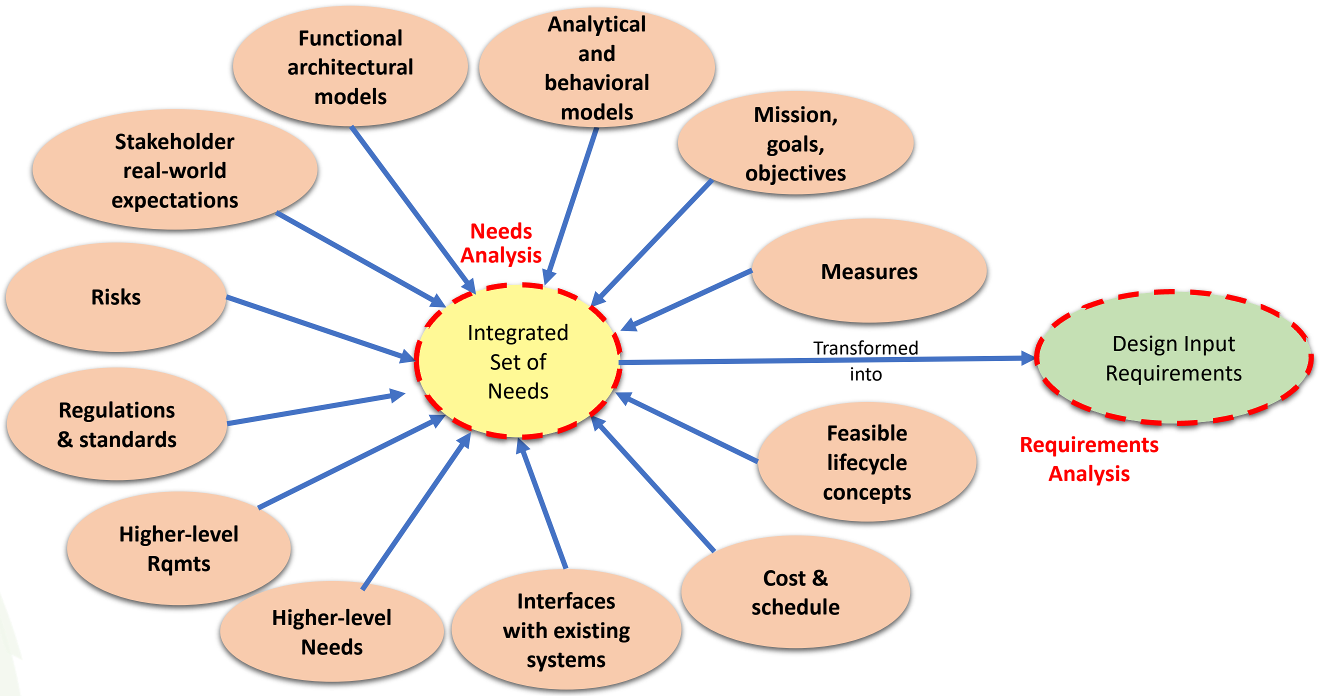
Development of a digital thread connecting SE artifacts across the lifecycle helps with effective change impact assessment.

Developing an Integrated Set of Needs

- "Integrated Set of Needs" represent the agreed to stakeholder and customer/acquirer view of the system to be developed, addressing the question: *What do the stakeholders need the system to do that will result in their problem to be solved or opportunity to be realized within defined constraints with acceptable risk?*

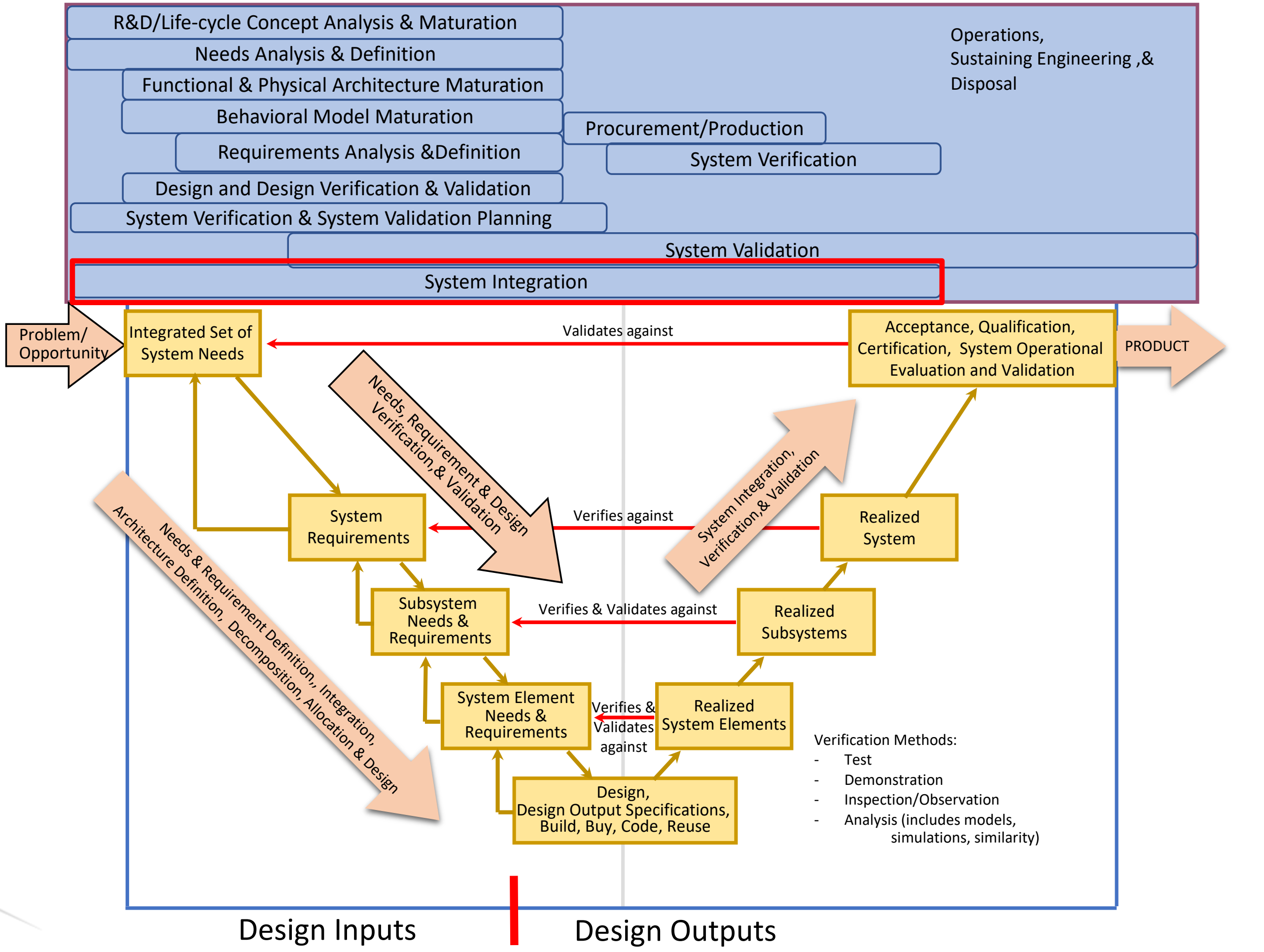
- The integrated set of needs includes the identification of drivers, constraints, lifecycle concepts, risks – it is much more than the stakeholder needs and requirements.

- System Requirements are transformed from these Needs.



Performing Continuous Integration

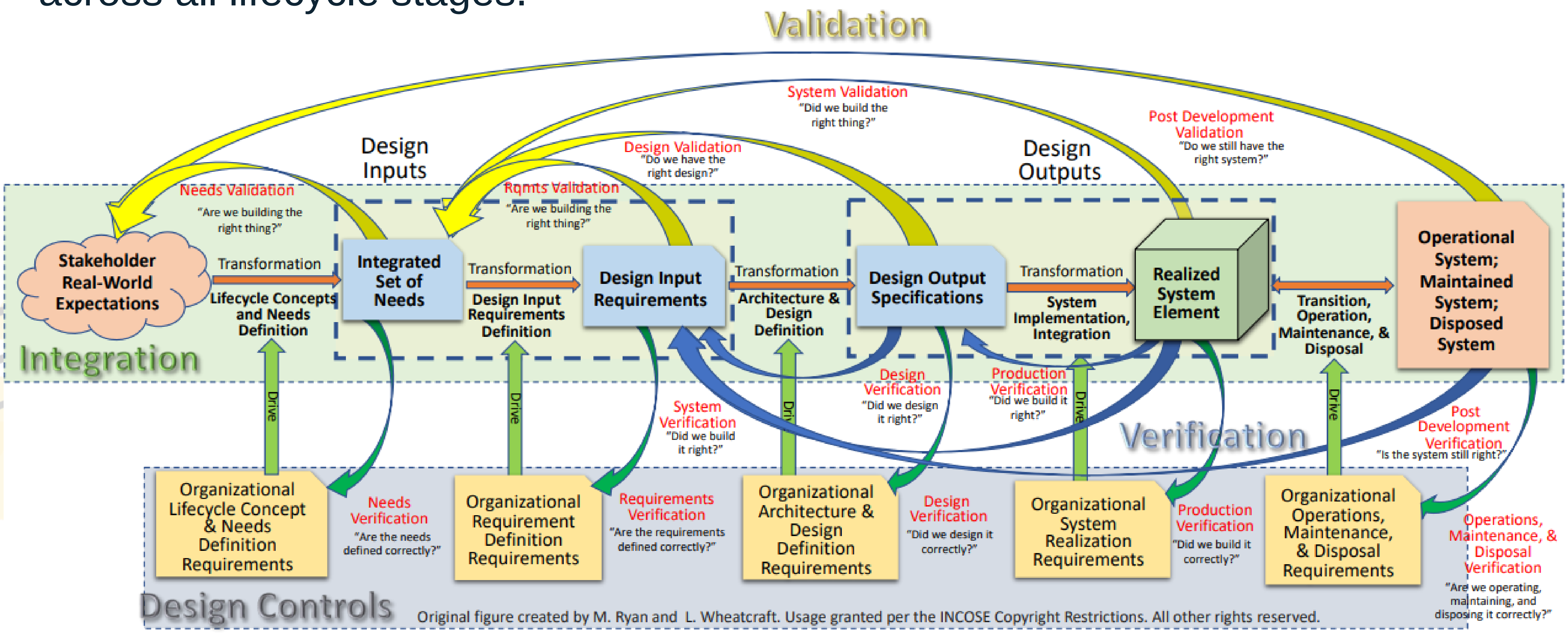
- Integration is an activity that must start at the beginning of the project
- During development, view the system as an integrated system using both the hierarchical and holistic views, not just as a sum of its parts.



Adapted from Ryan, M. J.; Wheatcraft, L.S., “On the Use of the Terms Verification and Validation”, February 2017 and INCOSE SE HB, Version 4, Figures 4.15 & 4.19

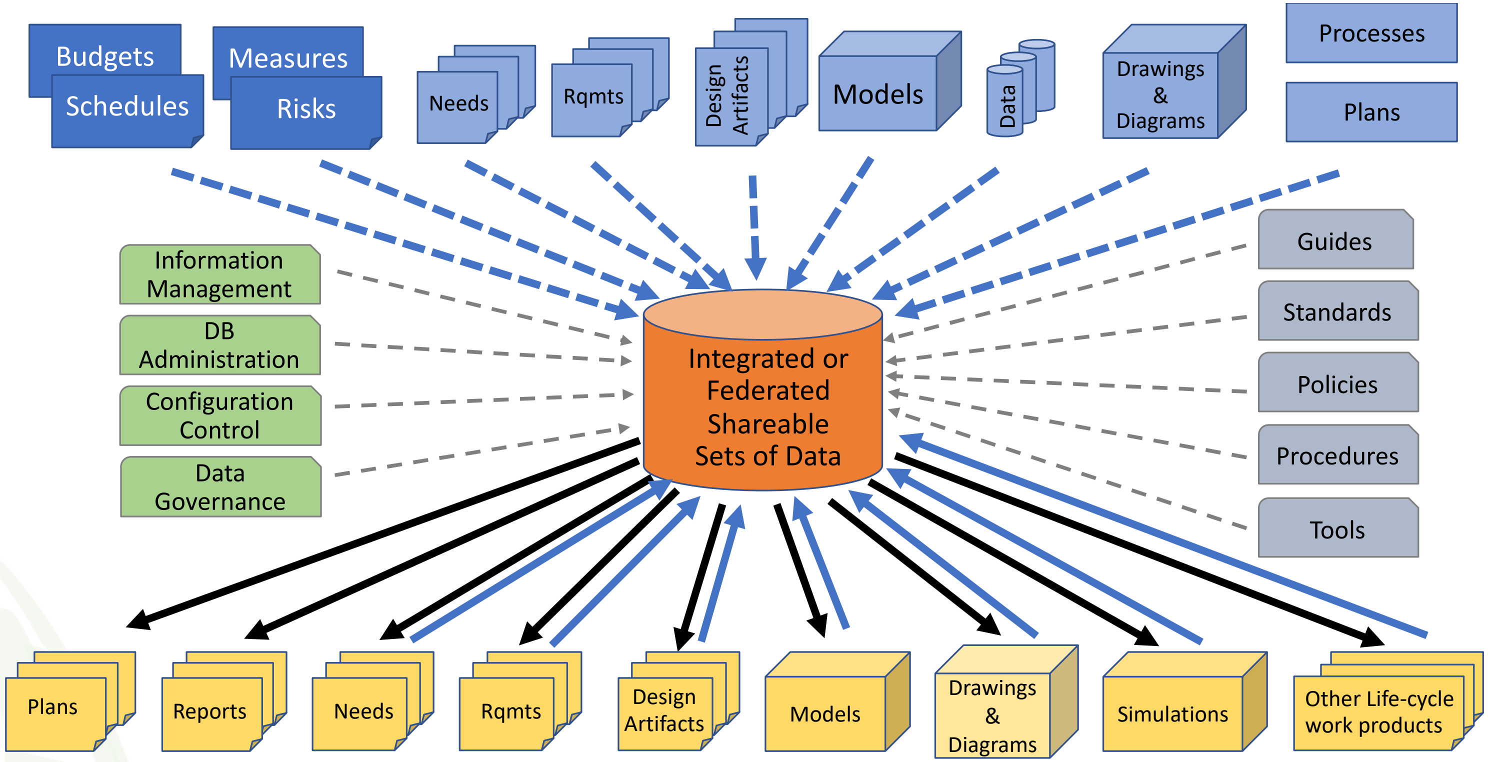
Continuous Integration, Verification and Validation

- Integration, Verification and validation are performed concurrent with architecture maturation, as they occur concurrently with the other SE technical processes across all lifecycle stages.



Data-Centric System Development

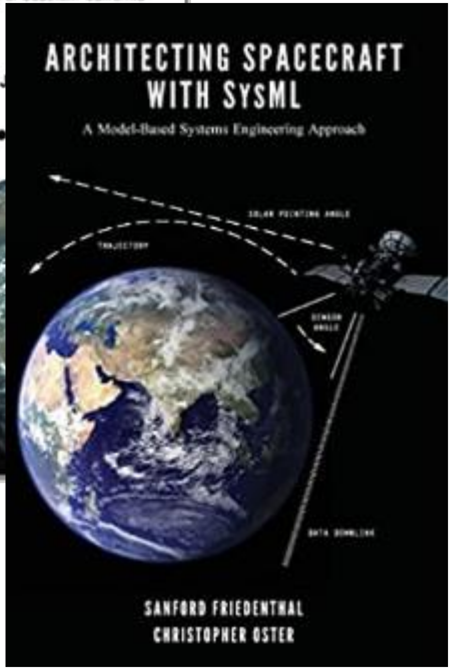
- Using a data-centric approach, needs, requirements, and other development artifacts (models, diagrams, drawings, etc.) are visualizations of an integrated data and information model of the system.
- This approach is enabled by use of an integrated set of tools which support data interoperability standards and the sharing and linking of data between tools.
- Instead of individual and separate artifacts, data and information are inter-connected (via traceability) forming digital threads across the lifecycle.



Inconsistent multiple sources of truth result in challenges during development, integration, verification, and validation activities.

Space System Development Using the Recommended Approaches

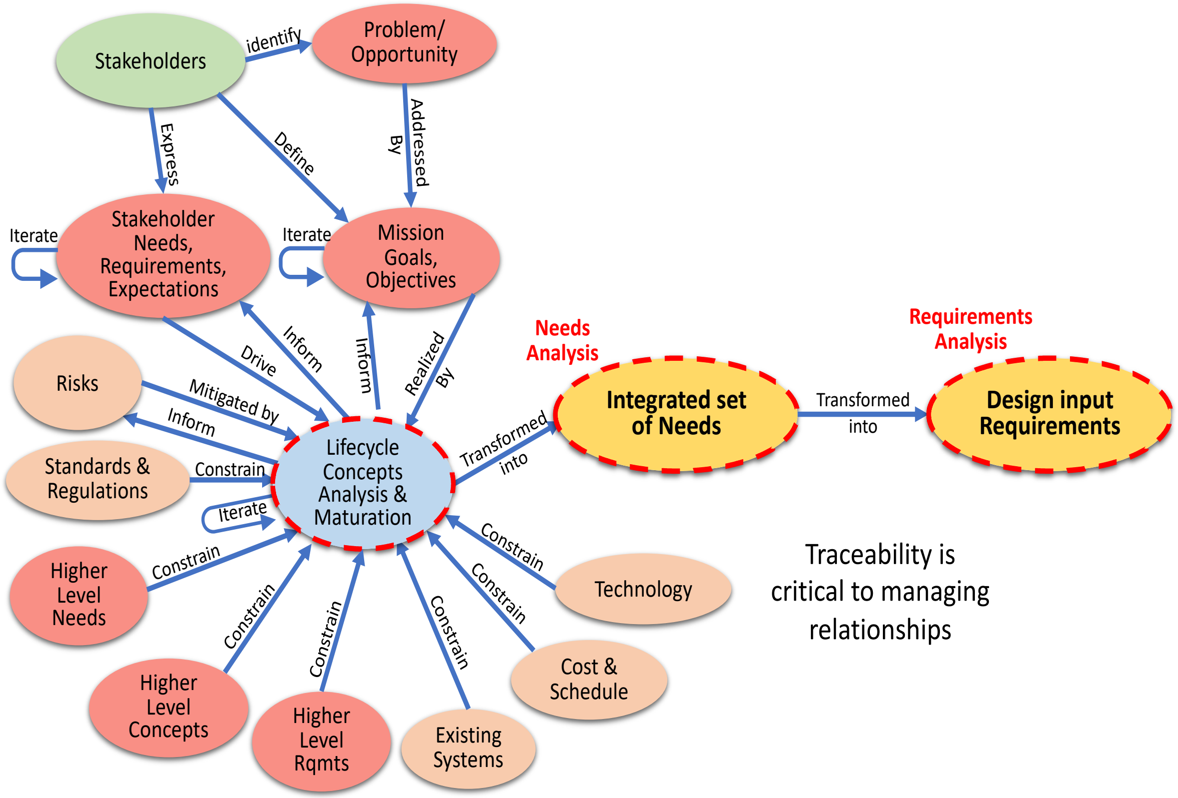
- This presentation will highlight the following set of activities from the INCOSE NRM, with application examples for development of a space system:
  - Activity 1: Develop and assess the integrated set of needs (supports challenge #1).
  - Activity 2: Develop and assess the system requirements (supports challenge #1).
  - Activity 3: Methods for early and continuous integration, verification and validation across the system lifecycle (supports challenge #2).
- Throughout, the usage of data-centric approaches will be highlighted with the examples provided (supports challenge #3).



The New SMAD (Wertz, et al, 2011) as well as the FireSat II MBSE Model from Architecting Spacecraft with SysML (Friedenthal, S., Oster, C., 2017) are used as examples throughout this presentation.

Activity 1: Develop and Assess the Integrated Set of Needs

- The integrated set of needs is developed using the approach of Systems Thinking.
- "Define the Why" by establishing the Problem, Threat, or Opportunity as well as the Mission, Goals, Objectives, and Measures (MGOs).
- "Define the Who" by Identifying External and Internal Stakeholders
- "Define What is Needed" by Eliciting Needs and Requirements from the Stakeholders
- "Establish the Boundaries" by Identifying Drivers and Constraints
- "Understand Risk to Success" by Identifying and Analyzing Risks
- Define system lifecycle concepts from several perspectives (use cases for different users).



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Example FireSat II Problem/Opportunity

- The problem statement is the first activity to address the “why” behind the space mission.

Example FireSat II Problem, derived from (Wertz, et al, 2011)

Because forest fires pose an ever-increasing threat to lives and property, have significant impact on recreation and commerce, and also have an even higher public visibility (largely because of the ability to transmit images from nearly anywhere in real time), the United States needs a more effective system to identify and monitor forest fires for other nations, collect statistical data on fire outbreaks, spread, speed, and duration, and provide other forest management data. This must be done within budget to make the system affordable to the Forest Service and not give the perception of wasting money that could be better spend on fire-fighting equipment or personnel. Ultimately, the Forest Service's fire-monitoring office, the management officers in the field, and individual firefighters and rangers fighting the fire, state and local governments, first responders, and news organizations will use the data. Data flow and formats must meet these diverse needs without specialized training and must allow fire fighters and first responders to respond quickly and efficiently to changing conditions.

Example Firesat II MGOs and Measures

- Define what is viewed as an acceptable outcome of the space mission.
- Developing MGOs sets the framework for the activities associated with defining the lifecycle concepts.
- Key measures are identified to measure success during the system development across the lifecycle.

Example FireSat II Key Program Success Measures, derived from (Wertz, et al, 2011)

- Development costs < $20M
- Ongoing Operational costs < $3M/year
- Number of users > 2500
- 10-year service life of space assets

Example FireSat II Mission, Goals, Objectives, derived from (Wertz, et al, 2011)

Mission Statement: Provide a more effective means to manage forest fire response.

Primary Goals:

- Develop an integrated ground, air, and space architecture to detect, identify, report, and monitor forest fires throughout the continental United States, Alaska, and Hawaii in near real time.
- Manage development and operation cost are within the Congressional approved budget for development and operations of the FireSat system.
- Integrate the capabilities of existing systems into a single solution.
- Maximize reusability of existing infrastructure.
- Enable autonomous identification of forest fires and reporting data.
- Distribute actionable data to users in compatible formats.

Secondary Goals:

- Demonstrate to the public and congress positive actions are underway to better respond to and manage forest fires.
- Collect statistical data on the outbreak, growth, duration, and impacts of forest fires.
- Collect other forest management data.
- Detect, identify, report, monitor forest fires for other countries.

Objectives:

- Detect a potentially dangerous wildfire in less than 1 day (threshold), 12 hours (objective).
- Provide 24/7 monitoring of high priority dangerous and potentially dangerous wildfires.
- Reduce the annual cost to fight wildfires by 10% over 2020 average annual baseline.
- Reduce the annual property losses due to wildfires by 5% from the 2020 average annual baseline.
- Reduce the average size of fire at first contact by firefighters by 20% from 2020 average baseline.
- Develop a wildfire notification system with greater than 90% user satisfaction rating.
- Provide data flow and formats in a form usable by the various users.
- Deploy a space-based asset to detect wildfires in the US.
- Cover the continental US, Alaska, and Hawaii.
- Deploy on-call UAV assets to monitor wildfires.
- Deploy an integrated wildfire command and control system to coordinate inputs from space, air, and existing ground observation assets.

Example FireSat II Stakeholders

- Identify external and internal stakeholders
- Define what is needed by eliciting needs directly from the stakeholders.
- Address multiple perspectives.

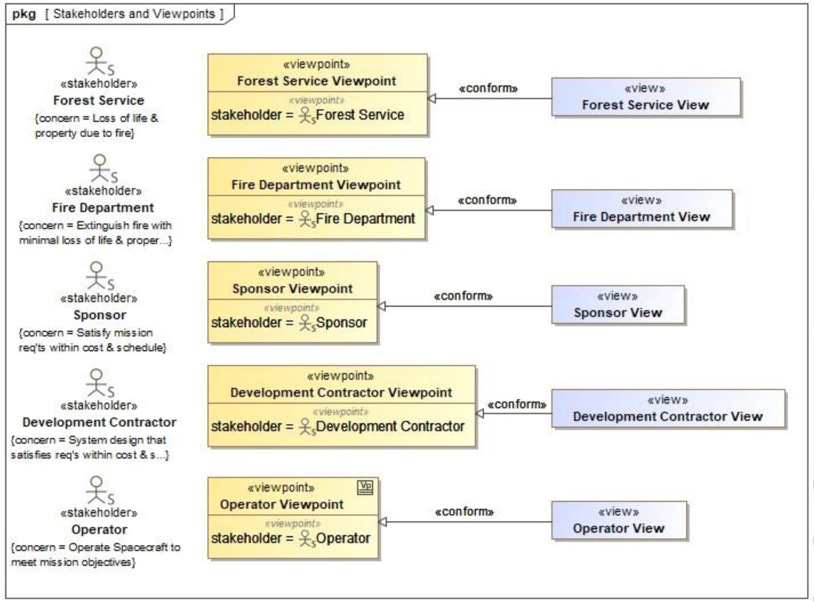


Figure from Friedenthal, S., Oster, C. (2017).

Stakeholder	Internal/ External Involvement	Desired Outcome (Need)
Supplier Company Executive	Internal, Corporate Sponsor, Gate review approval, Source of Development Funding	Meet agreed to MGOs and measures
Supplier FireSat Program Manager	Internal, Responsible for Budget, Schedule, and Resources	Meet Budget, Schedule, and Technical Goals, Objectives, and measures
Customer FireSat Program Manager	External, Responsible for Budget, Schedule, and Resources	Meet Budget, Schedule, and Technical Goals, Objectives, and measures
Supplier UAVs, UAV operators	Supply UAVs and operators, maintain UAVs	Early notification of forest fires, data collection, and transmission to FireSat Program communication network
Supplier, launch vehicle and launch base services	Supply launch vehicle(s) and launch base services	Successfully launch FireSat spacecraft into desired orbit.
Primary Customer US Forest Service	External, Source of Operational funding	Detect and monitor forest fires within budget and schedule constraints
Secondary Customer Congress	External Source of Operational funding	Demonstrate to the public that actions are being taken and government funds are spent wisely
Primary State Governments	External, providing resources and aid to the Forest Service and those impacted by the fire	Quick and effective detection, identification, reporting, and monitoring forest fires.
Primary Local Governments and First Responders	External, managing evacuations, proving local fire, ambulance, police support	Quick and effective detection, identification, reporting, and monitoring forest fires.
Secondary Home, Business, and Landowners	External, protecting property and evacuation	Quick and effective detection, identification, reporting, and monitoring forest fires.
End Users - Firefighters, Fire Detection Personnel, governments, news organizations	External, users of end product	Obtain data, easy to operate equipment, automated alerts, reliable
Mission Operations (space assets, air assets, ground communication network)	Internal, executes mission and oversees system functions	Provide forest fire data to the end user, archive data, monitor and maintain health and safety of space, air, and ground assets.
Regulatory Agency (space and air assets, FAA, FCC)	External, Provide Certification, Qualification, Acceptance	Safe for Users and Environment

Example FireSat II Drivers, Constraints, Risks

- Identify things outside the project's control that constrain or drive the solution space.
- Identify and analyze risks to the development effort and the mission.

Example Risks for FireSat II [derived]

- Management Risk: Change in Administration (funding risk)
- Development Risk: Sensor Technology Maturity, lack of traceability of development artifacts.
- Integration Risks: Lack of knowledge of existing systems, lack of definition to interact with existing systems and other constituent systems within the SoS.
- Production Risks: Ability to produce the hardware and software within cost and schedule, supply chain issues.
- Compliance Risks: Failure to meet all regulatory requirements and show evidence regulatory re-quirements have been met.
- Operations Risk: Sensor failure, attitude control propellent, orbital debris, Cyber security threat in op-eration (operations risk)

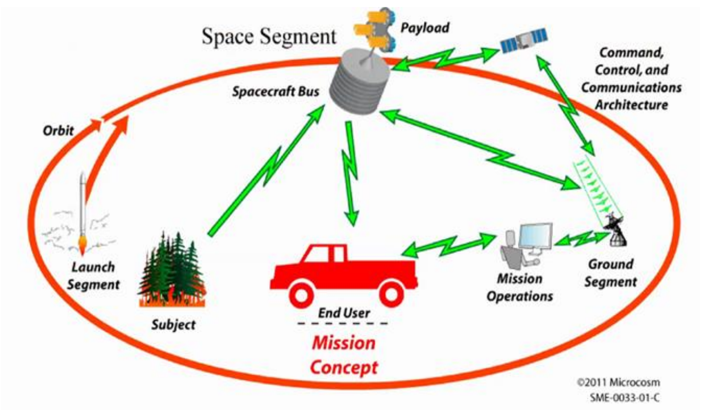
Requirement	Factors which Typically Impact the Requirement	FireSat II Example
Constraints		
Cost	Manned flight, number of spacecraft, size and complexity, orbit	< $20M/yr + R&D
Schedule	Technical readiness, program size	Initial operating capability within 5 yrs, final operating capability within 6 yrs
Regulations	Law and policy	NASA mission
Political	Sponsor, whether international program	Responsive to public demand for action
Environment	Orbit, lifetime	Natural
Interfaces	Level of user and operator infrastructure	Comm. relay and interoperable through NOAA ground stations
Development Constraints	Sponsoring organization	No unique operations people at data distribution nodes

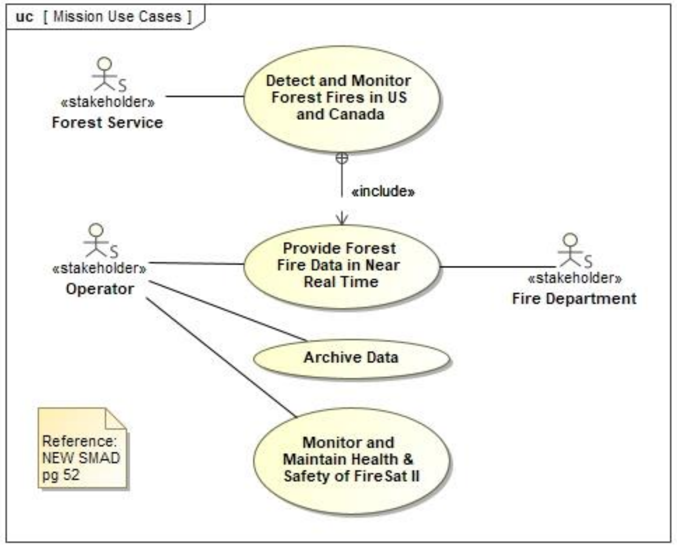
Example FireSat II space mission regulations [derived]

- Launch license (Air Force Eastern/Western Range Safety Requirements, FAA)
- Orbit Debris Mitigation (NASA, FCC, NOAA)
- RF Communication (FCC)
- Licensing of Private Remote Sensing Space Systems (NOAA)

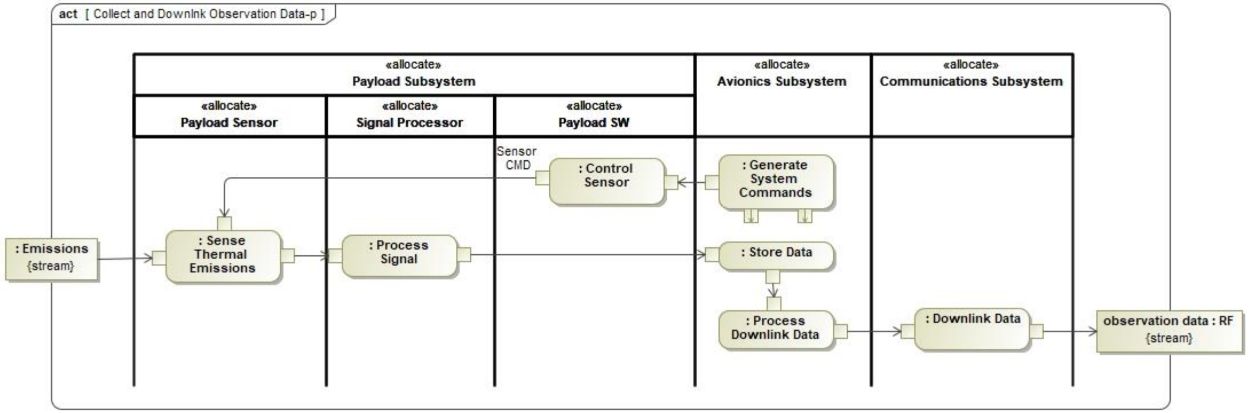
Example FireSat II Lifecycle Concepts

- Assess a series of questions about the mission.
- Define an operational view of the mission, interactions with external systems, overall concept of operations, from many viewpoints.





Element	Definition	FireSat II Example
Data Delivery	How mission and housekeeping data are generated or collected, distributed, and used	How is imagery collected? How are forest fires identified? How are the results transmitted to the firefighter in the field?
Tasking, Scheduling, and Control	How the system decides what to do in the long term and short term	What sensors are active and when is data being transmitted and processed? Which forested areas are receiving attention this month?
Communications Architecture	How the various components of the system talk to each other	What communications network is used to transmit forest fire data to the users in the field?
Program Timeline	The overall schedule for planning, building, deployment, operations, replacement, and end-of-life	When will the first FireSat II become operational? What is the schedule for satellite replenishment?



Figures from Wertz, J., Everett, D., & Puschell, J. (2011) and Friedenthal, S., Oster, C. (2017).

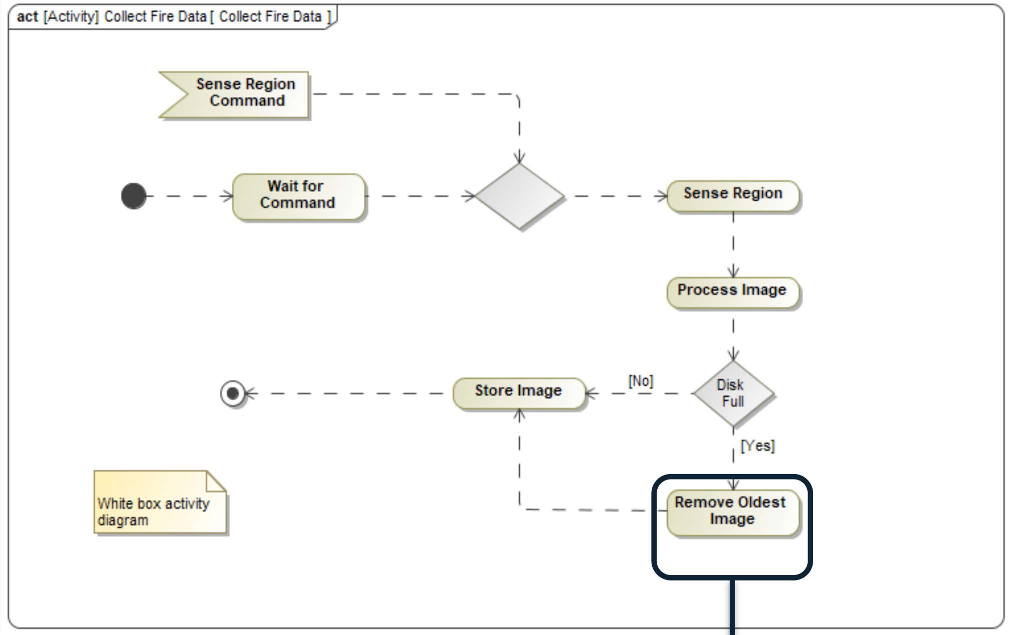
Example FireSat II Integrated Set of Needs

- Transform the data from prior analysis to a summary set of needs on the system, traceable to the source that drives the need; this is the Integrated Set of Needs.
- Use conventions that apply to the organization, these can be simply worded or fully formed statements.
- Need statements do not contain “shall”, they are from the perspective of the stakeholders (or source) and do not state how the need will be addressed.
- Guidance: ensure need statements are singular, clear, and contain attributes to highlight source, rationale, priority and criticality; Not all needs will be equal.
- Perform a check to ensure the need statements conform to agreed-to conventions and align with the data from the initial assessments (verify the need statement quality, validate they represent the mission objectives, stakeholder inputs, drivers, etc.)

Topic	Need	Source
Schedule to Mission	Operational within 3 years	Government input
Mission Design Life	10 years	Government input
Regulations	Orbital debris, civil program regulations	Constraints
Reliability	Probability of success >90%	Government input
System Availability	95% excluding weather 24 hour maximum downtime	Government input
Resolution	Less than or equal to 50-meter resolution	Mission analysis on detection
Geolocation Accuracy	1 km geolocation accuracy	Mission analysis on detection
Data Distribution	Up to 500 fire-monitoring offices + 2,000 rangers worldwide (max of 100 simultaneous users)	Lifecycle concept input
Data Availability	Accessible via the internet to stakeholders on demand.	Stakeholder inputs
Forest Service User Equipment	Data display with zoom and touch controls, built-in GPS quality map viewable on office and mobile devices in the field including phones, tablets, and laptops	User inputs
Environment	Operate in natural environments	Lifecycle concept input
Data Communications	Interoperable through NOAA ground stations	Constraint
Coverage	Coverage of specified forest areas within the US, Alaska, and Hawaii at least twice daily.	Mission analysis on detection
Detection	Detect an emerging forest fire within 8 hours with less than 10% false positives	User inputs
Notification	Notify end users within 5 minutes	User inputs
Commanding	Commandable within 3 min of events; download units of stored coverage areas.	Mission Operator inputs
Data Storage	Onboard data storage for 24 hours.	Derived Function from Lifecycle concept model, ensures ability to retrieve data for analysis

Activity 2: Develop and Assess the Requirements

- Transform the needs (stakeholder perspective) to requirements (system perspective) by addressing “what” the system must do to satisfy the needs.
- Further derivation of functions is also performed by functional analysis based on lifecycle concept models.



If Space Segment storage is at 90% of full capacity, the Space Segment shall delete oldest images until storage is less than 10% of capacity.

Figure from Friedenthal, S., Oster, C. (2017).

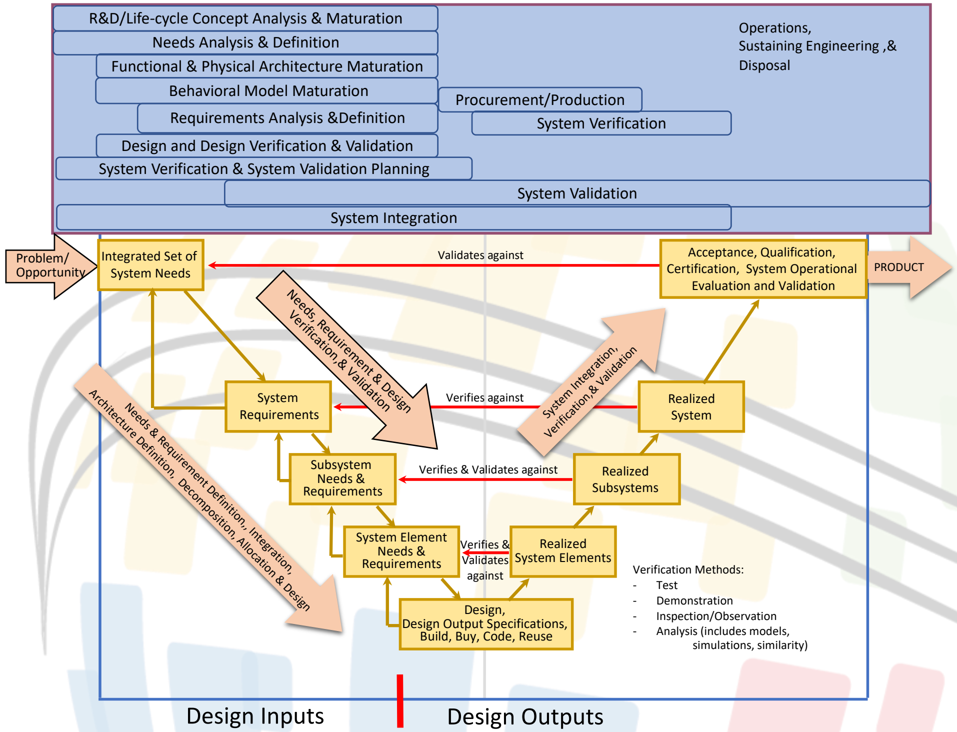
Example FireSat II System Requirements

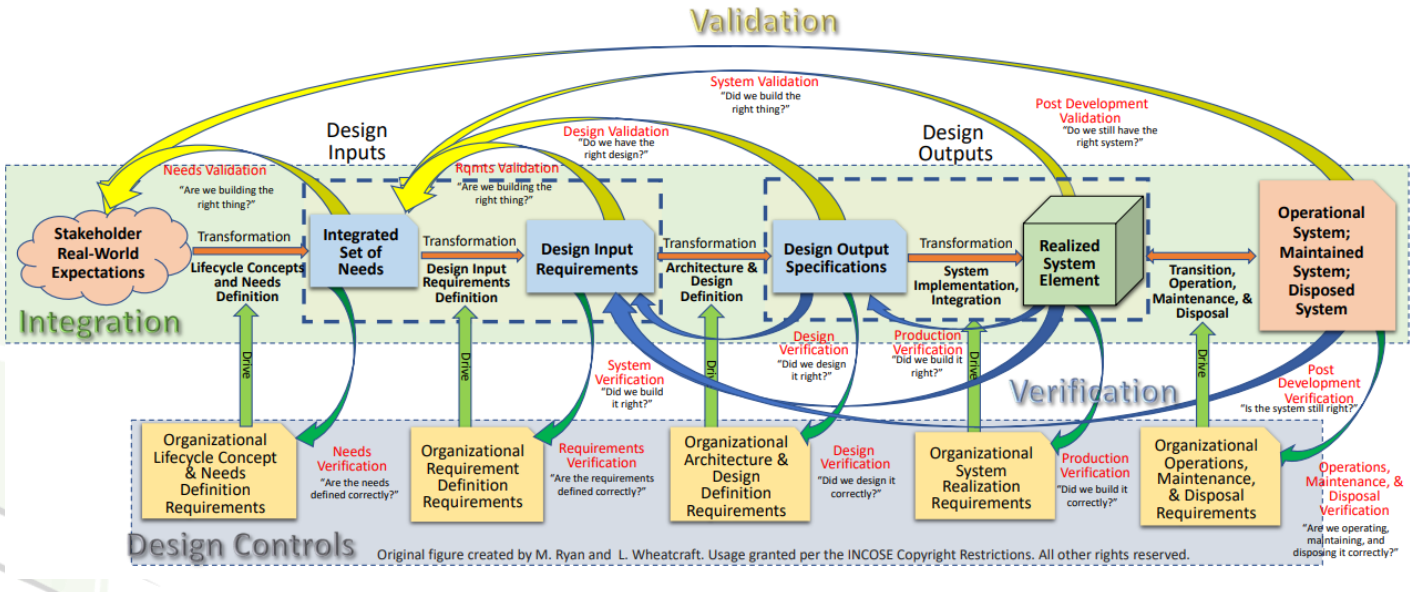
- Unlike the need statements, requirements are phrased using "shall“.
- The INCOSE Guide to Writing Requirements (GtWR) defines the structure and characteristics of well-formed requirement statements (and the set of requirements) along with a set of rules to help achieve those characteristics.
- Perform a check to ensure the requirement statements conform to agreed-to conventions and align with the Need they were transformed from (verify the requirement statement quality, validate they represent the Need).

Topic	Requirement	Rationale	Trace to Need
Target Resolution	Ground sampling distance shall be less than or equal to 40 meters.	Calculated value based on radiometric analysis to ensure needed resolution.	Resolution
Field of View.	The Space Segment shall scan with a minimum field of view of +/- 3 degrees.	Calculated value based on radiometric analysis to ensure data collection achieved for coverage and resolution needs.	Coverage, Resolution
Position Knowledge	The Space Segment shall provide a real-time GPS derived position knowledge of 500 m (3σ) in the radial, along-track, and cross-track directions.	Calculated value based on total budget for geolocation accuracy.	Geolocation Accuracy
Data Rate	The Space Segment data rate shall be a minimum of 8 Megabits per second.	Calculated value based upon number of data users and amount of data collected.	Data Distribution
Data Storage	The Space Segment shall provide 24-hour storage of fire data.	Stakeholder Need for ability to retrieve data for analysis	Data Storage
Data Storage	The Space Segment shall check if the storage is within 90% of full capacity prior to writing additional data.	Derived function based on lifecycle concept for data storage.	Data Storage
Data Storage	If Space Segment storage is at 90% of full capacity, the Space Segment shall delete oldest images until storage is less than 10% of capacity.	Derived function based on lifecycle concept for data storage.	Data Storage

Activity 3: Methods for Early and Continuous Integration, Verification and Validation across the System Lifecycle

- Space mission needs and requirements are developed iteratively and recursively, with integration, verification, and validation occurring concurrently with the other technical processes across all lifecycle stages.
- Performing verification and validation throughout the lifecycle ensures that data is provided early to highlight any flaw in the design.





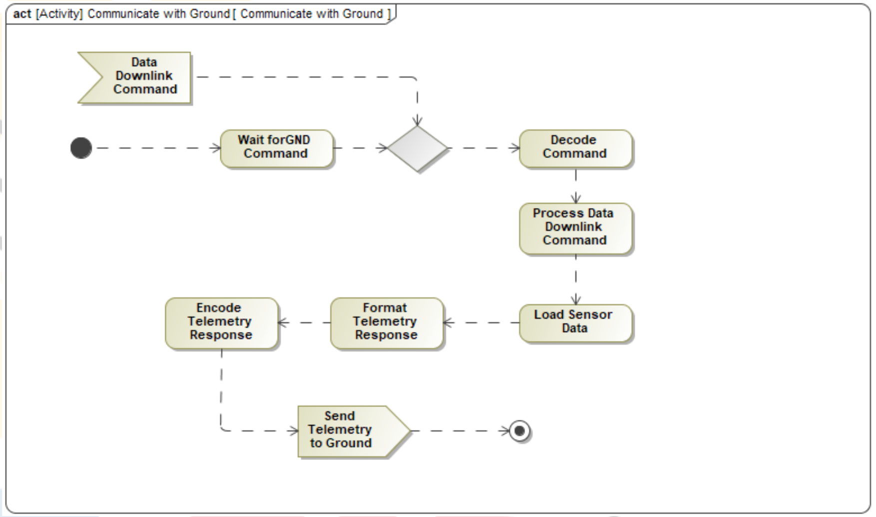
Adapted from Ryan, M. J.; Wheatcraft, L.S., "On the Use of the Terms Verification and Validation", February 2017 and INCOSE SE HB, Version 4, Figures 4.15 & 4.19

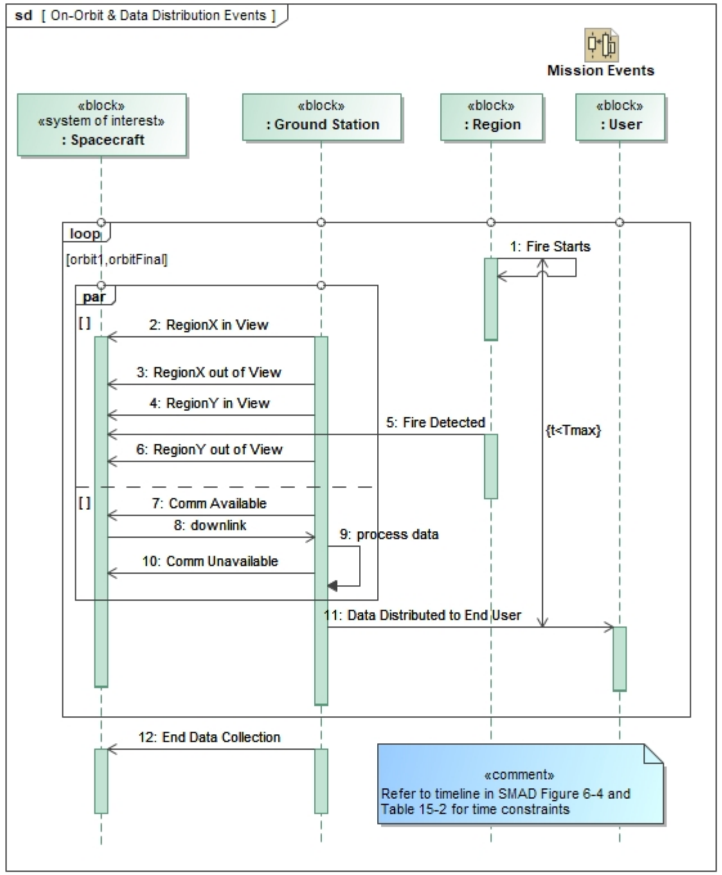
Examples of Early System Verification and Validation

- Early system verification and system validation can occur before the physical system is manufactured using the behavioral models, simulations, prototypes that were developed to mature the design.
- Examples of early system verification and system validation activities include:
  - Models and Simulations
  - Prototype testing
  - Early testing of key elements of the system
  - Life tests
- For complex projects, the use of data-centric models and simulations can be both cost effective and enable the ability to discover emergent properties and interface conflicts well before a physical system is realized.
- More and more system developers are utilizing digital twins to obtain better insight towards system behaviors and integration, reduce physical testing, and improve overall design prior to physical realization.
- The outcome of these model-based activities is a demonstration of space system integration prior to the realized system, as well as provide evidence towards early system verification and validation, minimizing risks of the solution not addressing stakeholder needs and supporting faster development.

Example FireSat II Simulation (MBSE)

- FireSat II MBSE data model during lifecycle operations enables visibility of:
  - Data interfaces across the mission elements.
  - Interactions with other constituent systems that are part of the overall System of Systems.
  - Verification of expected functions and operations (simulations of sequences for early de-sign verification, and test measurements for system verification).
  - Evidence of system validation by providing confirmation the solution meets the integrated set of needs.





Figures from Friedenthal, S., Oster, C. (2017).

Example FireSat II Simulation (Math Model)

- Creating a FireSat II integrated power system model enables simulations for a variety of mission profiles.
- Simulations can be run over mission and load changes to assess power impacts during development, including simulated fault scenarios such as battery failures, stuck switches, and solar array failures in the ascent and orbit phases.
- This type of simulation can guide the development of mission opportunities and protocols for failure cases and provide data to support integration confidence of the design solution and enable early system verification.

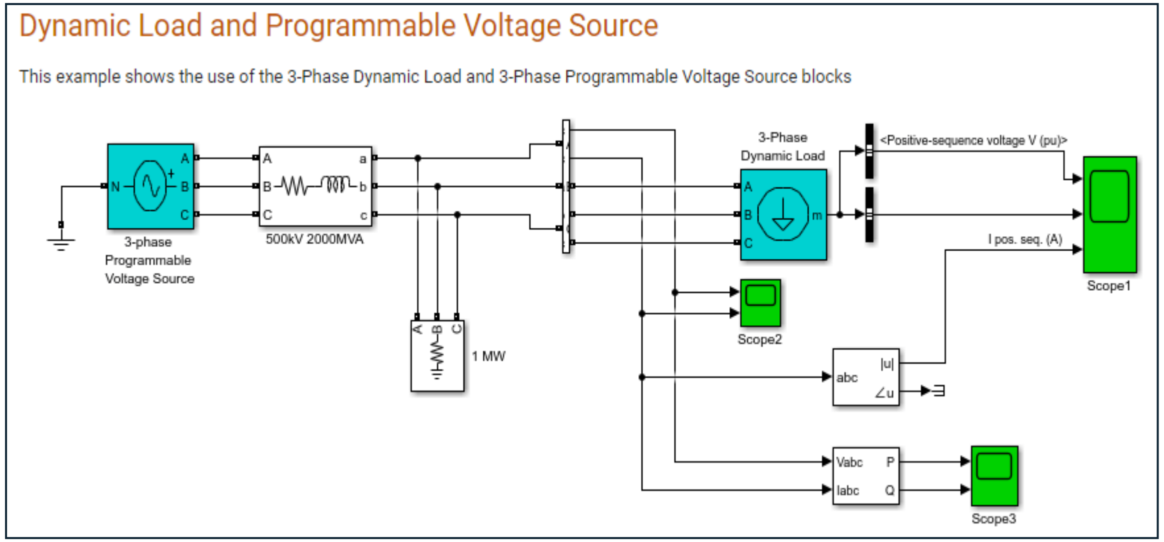


Figure from https://www.mathworks.com/campaigns/offers/model-based-design-space-control-systems.html, and https://www.mathworks.com/help/sps/ug/dynamic-load-and-programmable-voltage-source.html

Concluding Thoughts

- This paper highlighted space system development approaches which enable early integration, verification, and validation, with specific focus on addressing system validation, based on the processes from the INCOSE NRM.
- Specifically addressed are the following:
  - Ensuring the space system requirements align with a comprehensive integrated set of needs based on mission goals and objectives.
  - Ensuring the system development occurs in a way that enables earlier integration, verification, and validation of the space system across the lifecycle.
  - Ensuring the space system development maintains traceability of its data artifacts across the lifecycle by utilizing a data-centric approach to systems engineering during the development effort.
- Examples were provided to show how these activities could be implemented in development of a space system. Implementation of these techniques help mitigate current challenges of poor requirements, inability to pass verification and validation, and multiple sources of truth.

Objective of this methodology is the faster development of effective space systems meeting mission objectives while passing system validation.

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