Satellite Constellation Cost Modeling: *An Aggregate Model*

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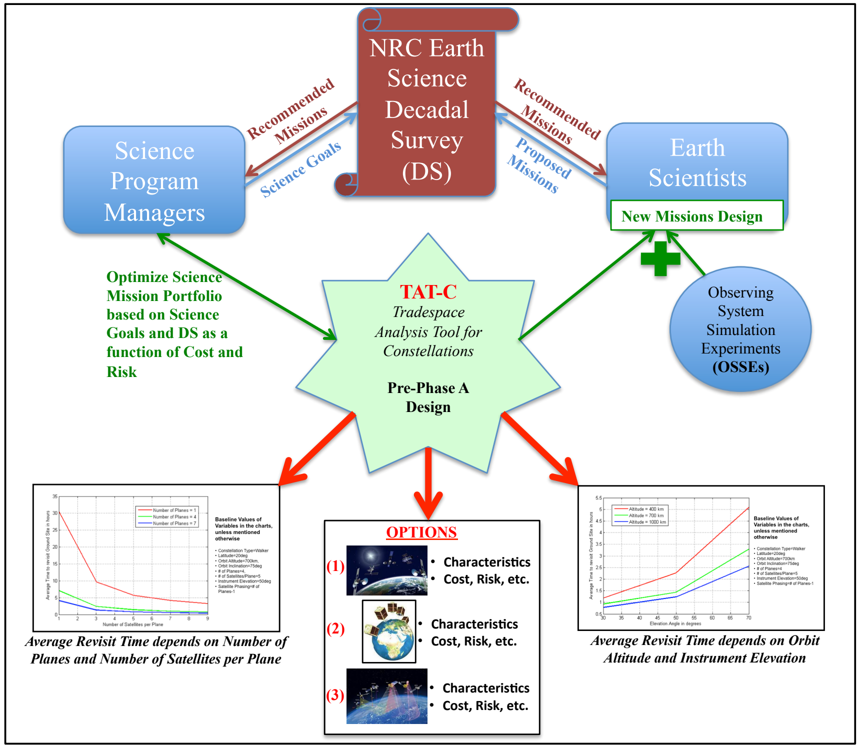
Presentation Outline

- Introduction
  - TAT-C
  - VCR Module
- Historical Context
- Aggregate model formulation
  - Motivation and Justification
  - State of the Art
  - Limitations of Existing Models
- Cost Module, Version 1
  - Implementation
  - Future Revisions
  - Impact
- Conclusions/Future Work

Tradespace Analysis Tool for Design of Distributed Missions
PI: Dr. Jacqueline Le Moigne, NASA GSFC

Objectives:

- Provide a framework to perform pre-Phase A mission analysis of Distributed Spacecraft Missions (DSM)
  - Handle multiple spacecraft sharing mission objectives
  - Include sets of smallsats up through flagships
  - Explore tradespace of variables for pre-defined science, cost and risk goals, and metrics
  - Optimize cost and performance across multiple instruments and platforms vs. one at a time
- Create an open access toolset which handles specific science objectives and architectures
  - Increase the variability of orbit characteristics, constellation configurations, and architecture types
  - Remove STK licensing restrictions



Value, Cost, and Risk Module

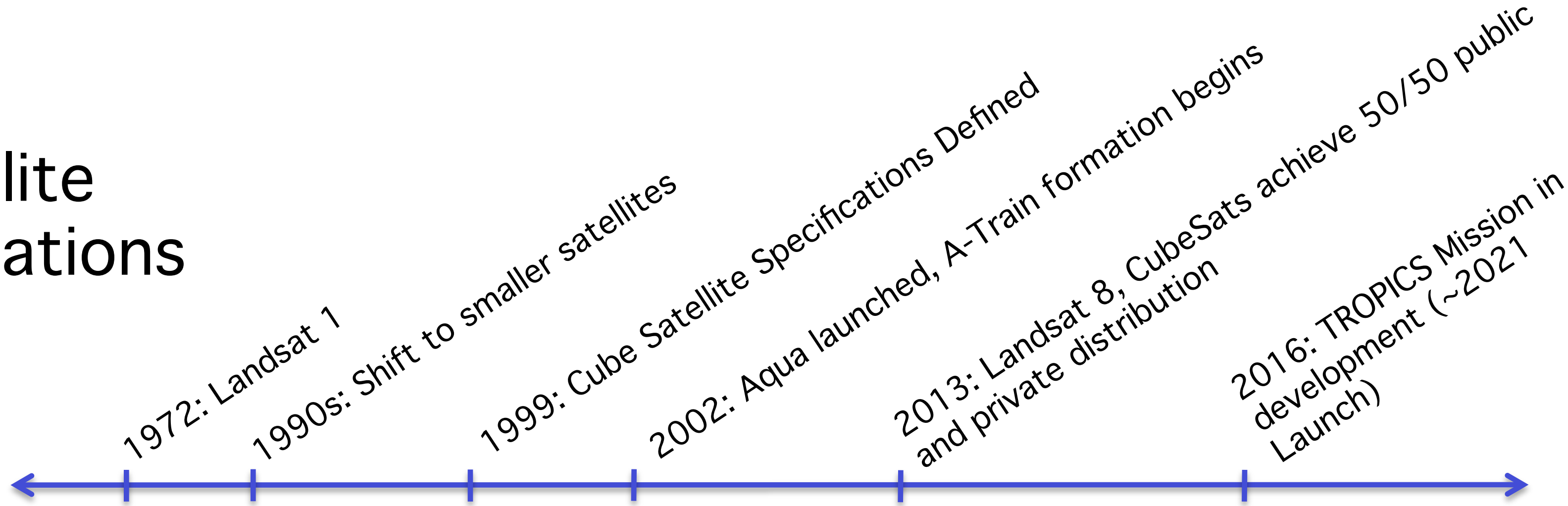
- Addresses the TAT-C Objectives that require cost and risk evaluations; given a satellite constellation architecture, the VCR module will provide estimates of:
  - Value, expressed in dollars or utility
  - Cost, life cycle cost (RDT&E, manufacturing, launch, operations)
  - Risk, profile of the system technical and cost risk

- VCR Module will enable trades between performance and value/cost/risk more readily

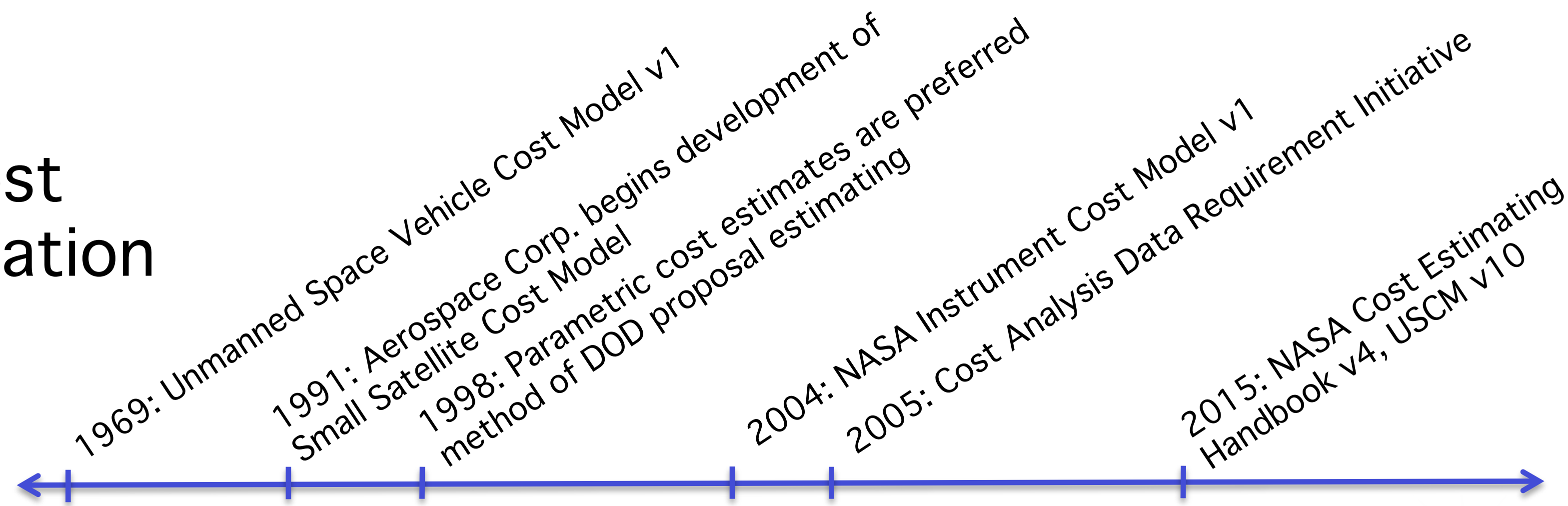
> This presentation addresses the need for an automated, integrated cost model for constellation mission design and the associated cost estimating challenges.

Historical Context

Satellite Constellations



Cost Estimation



Building an Aggregate Cost Model

- Motivation
  - Constellation architectures require that traditional cost estimating assumptions be challenged
  - Previous work has highlighted the limitations of existing models with respect to constellation missions
- Objective
  - Develop an automated cost estimating approach for constellation missions that will help enable early design phase trades
  - Build the approach in such a way that it is easily manipulated and highly transparent
- Challenges
  - Automated cost estimation often results in skepticism
  - Model must be able to adapt to technological innovation

Selected Approach

- Interoperable, parametric cost estimating tool to interface with TAT-C
  - Parametric estimating allows for a top down approach
    - More appropriate in early stages of design; does not require extensive design decisions
    - Cost Estimating Relationships (CERs) can be easily updated
  - Want to leverage existing and trusted techniques and apply them to Distributed Spacecraft Mission (DSM) and constellation architectures

- Allow for relative trades between cost and capability
  - Early stage mission cost estimates are relative, not absolute

- Plan to supplement the parametric approach with an analogous cost estimate to ensure model fidelity

State-of-the-Art and Existing Literature

- Many widely accepted cost estimating tools exist, including:
  - Unmanned Space Vehicle Cost Model (USCM), Version 10
  - Small Satellite Cost Model (SSCM), 2014 Release
  - NASA Instrument Cost Model (NICM), Version 7
  - QuickCost, Version 6.0
  - Programmatic Estimating Tool (PET)

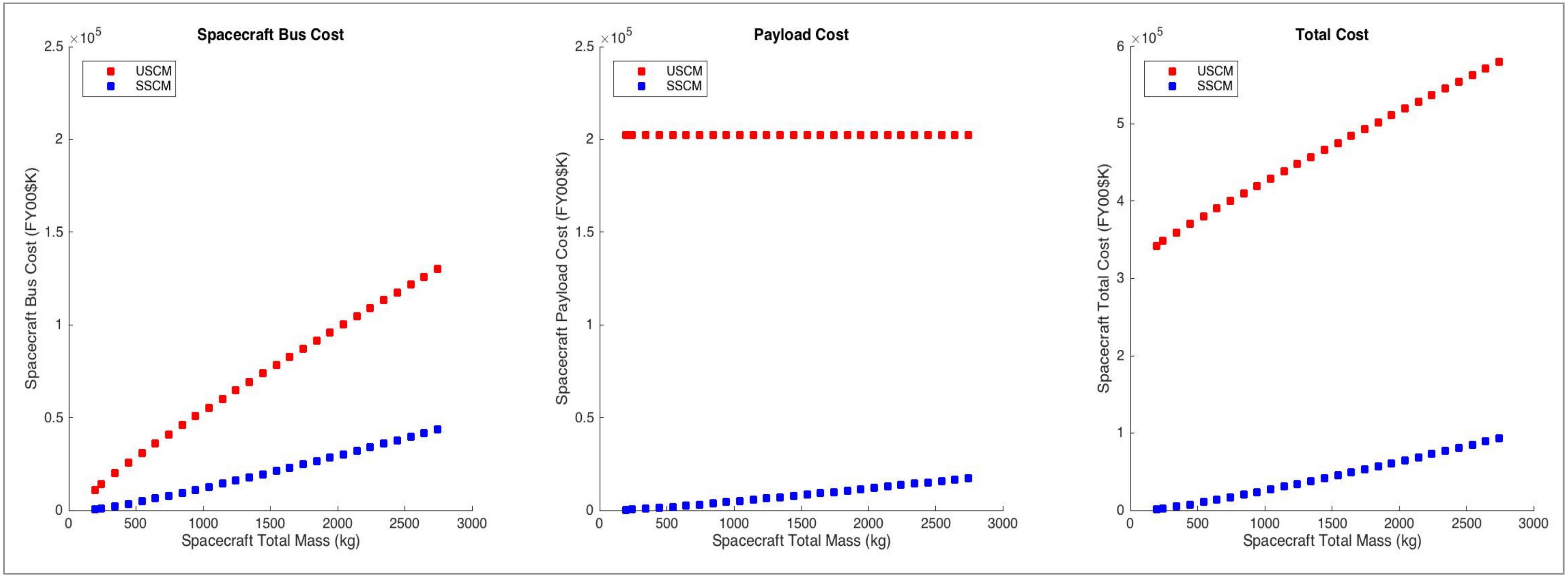
- Popular references:
  - NASA Cost Estimating Handbook, Version 4.0
  - Space Mission Analysis and Design, 3rd Edition

- Previous work has highlighted the limitations of these tools for constellation missions:
  - Limitations of traditional cost models for high performance small satellites, motivating the SSCM [Abramson and Bearden, 1993]
  - Small satellite learning curve parameters, COTS components, technological complexity as they pertain to DSMs [Nag et al.,2014]

Model Comparison

Unmanned Space Vehicle Cost Model (USCM, Version 7) and Small Satellite Cost Model (SSCM, 1998) results for TAT-C generated spacecraft

- Spacecraft are identical, with IR Sensor payloads, except for total mass
- Payload cost differs substantially between the two models
    - Motivation for alternate payload costing approach



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Implementation

- VCR Module Cost Routine combines existing models and applies them to DSMs
  1. Assesses mission characteristics (e.g. number of spacecraft)
  2. Costs spacecraft and payloads appropriately
     - USCM for spacecraft >= 1000kg
     - SSCM for spacecraft < 1000kg

       Future work: Weighting function at crossover
       - Future work: Implementing a cube satellite specific model for < 20kg
     - NASA Instrument Cost Model (NICM) for primary payload instruments
  3. Applies existing best practices to adjust for system level cost considerations (e.g. learning curve, design heritage)
  4. Uses current launch vehicle market prices to estimate launch cost and operational support requirements
  5. Formats cost estimate and record caveats to valuation

- Shao et al. (2014) took a similar approach to Performance-Based Cost Modeling, leveraging USCM, SSCM, NICM

Sample Output

Truncated output JSON

Advantages:
- Human readable, promotes transparency
- Formatted to mimic Work Breakdown Structure
- Interoperability

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{
    "constellationCost": {
        "totalCost": {
            "estimate": 285896.029,
            "standardError": null,
            "confidenceInterval": [lowLimit, highLimit, probability]
            "caveats": "Constellation is homogeneous. Launch Vehicle was not designated, launch vehicle cost is set to 0. "
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        },
        "drivers": "Spacecraft 1, Payload. Spacecraft 1, Operations. Spacecraft 2 IA&T. ",
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Current Status

- Cost Routine Version 1 is being integrated TAT-C as a set of MATLAB functions

- Short term remaining tasks:
  - Transition model to C++
  - Cost Risk Estimation, will depend on risk methodology
  - Operations and Ground Segment
    - Future Work

- Long term:
  - Continued bench marking the model for reliability
  - Upgrade CERs to most recent formulae

Future Work

- Operational Challenges
  - Operations and maintenance can be most expensive constellation mission element
  - How reliable are existing methods for constellations and what is the impact of increasing automation?
    - Automation would increase Research and Development but decrease cost of operations

- Discontinuity at transition between USCM and SSCM
  - Weighting function (0-1) applied near transition
  - Will determine the appropriate blend of these methods during final model benchmarking

Conclusion

- Aggregate cost model leverages existing tools and applies them to DSM and constellation architectures, while addressing limitations of existing methodologies

- This approach allows for integration of cost with early tradespace exploration
  - VCR is designed for TAT-C, but the form and function will allow for interoperability
  - Promote cost estimating transparency in automated processes
  - Relative cost estimates for architecture comparison

- Continues to reveal limits of cost estimating techniques for constellations, and inform future DSM development

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Thank you for your attention!
Any questions?

Additional Slides: Key Assumptions

- Comparative, not an exact value, estimate
  - Estimate should provide an approximation that can be used for tradespace analysis
- Comparison during concept evaluation, not as direct budgeting tool
- CERs are based in historical trends; assume that the trends will hold into the foreseeable future
  - Major technological changes will impact model fidelity
  - Smallsat launchers could cause significant changes
- Prototype, not protoflight, hardware development process
- Scope creep is not considered
- Project is executed at the optimal pace

Acronyms

- CER: Cost Estimating Relationship
- COTS: Commercial Off The Shelf
- DSM: Distributed Spacecraft Missions
- DOD: Department of Defense
- IR: Infrared
- JSON: JavaScript Object Notation
- NASA: National Aeronautics and Space Administration
- NICM: NASA Instrument Cost Model
- PET: Programmatic Estimating Tool
- RDT&E: Research Development, Test, & Evaluation
- SSCM: Small Satellite Cost Model
- TAT-C: Tradespace Analysis Tool for Constellations
- USCM: Unmanned Space Vehicle Cost Model
- VCR: Value, Cost, and Risk