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MO3.R8: Distributed Spacecraft Missions: New Remote Sensing Capabilities for Earth Science II

Evaluating Expected Performance and Graceful Degradation in Distributed Spacecraft Missions

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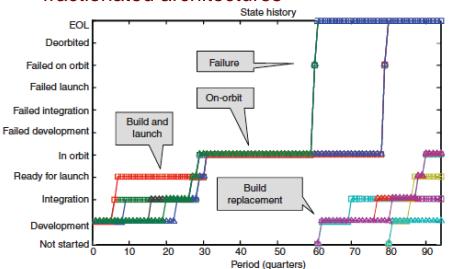NASA Goddard Space Flight Center

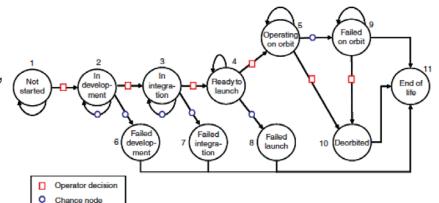# Graceful degradation is a key attribute for distributed architectures

- Graceful degradation, is defined as the gradual decline in the functionality or utility of the system due to partial failures in constituent elements or sub-systems

- **Systems that consist of multiple elements can continue to have limited functionality even when some elements become inoperative.**

- In Distributed Satellite Missions (DSM), a failure of one or more spacecraft (or instruments) in the constellation can lead to reduced performance, but it may be possible to maintain a limited (though degraded) science return from the mission.

- Evaluating graceful degradation is important for differentiating and selecting architectures for DSM
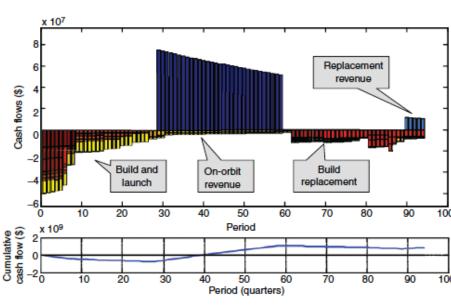
A constellation that can maintain its scientific output with greater robustness (in the presence of failures or spacecraft losses) will be more desirable

Graceful degradation enhances value of distributed space missions

- DARPA's F6 program initiated work on fractionated architectures in late 2000s

- Such architectures can allow for upgradability, scalability, incremental deployment, **graceful deterioration,** agile response, decoupling of requirements among many other advantages.

- **Value-centric design methodology was developed** to quantify life-cycle value of fractionated architectures
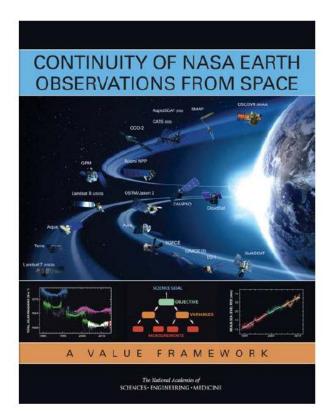
Ref: Maciuca, D., Chow, J. K., Siddiqi, A., et al. "A modular, high-fidelity tool to model the utility of fractionated space systems", *Encyclopedia of Aerospace Engineering*, Eds. Blockley and Shyy, 2010.

Value centric evaluation has been recommended for space mission selection

- "a *value-centered framework is capable of distinguishing among competing Earth measurements*" – [NRC committee]

- *Five key characteristics* define value of a measurement : *Importance (I), Utility (U), Quality (Q), Success Probability (S), and Affordability (A)*

- *Value (V) = product of Benefit (B) and Affordability (A)*;

- A useful expression of B is an un-weighted product of the factors I, U, Q, and S.

  V = B x A = (I x U x Q x S) x A

CONTINUITY OF NASA EARTH OBSERVATIONS FROM SPACE

A VALUE FRAMEWORK

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

NRC Committee Recommendation: NASA should establish a value-based decision approach that includes clear evaluation methods for the recommended framework characteristics and well-defined summary methods leading to value assessment. [2015]

Markov models can be used for quantifying degradation

- Graceful degradation can be modeled using Markov theory, wherein a system is defined to exist within a set of finite states, and it transitions between states as a result of stochastic events (such as failures).

- **We can use Markov modeling to quantify change in performance measures as a result of on-orbit failures of elements within a DSM.**

- We assume that the architecture of a DSM consisting of s spacecraft is defined within a specified set of orbital parameters, and it carries payloads of given specifications, and has a design lifetime of T_{life} .

- We define a set of states of the system (the DSM) such that each state represents a condition wherein some failures have occurred in one or more of the s spacecraft comprising the DSM.

- The initial state is one where the system is fully functioning (with all of its constituent elements performing as designed), and the final state is where all of the s spacecraft have failed.

- The nature and source of failure in spacecraft can vary (ranging from failures in critical subsystems including power, attitude control, data handling and processing, or the instrument payload).

Expected performance of an architecture is evaluated using performance level and expected residence time of each state

The probability of the system to be in a state i : π_i,

Transition rate of changing from a state i to a state j : λ_{ij}
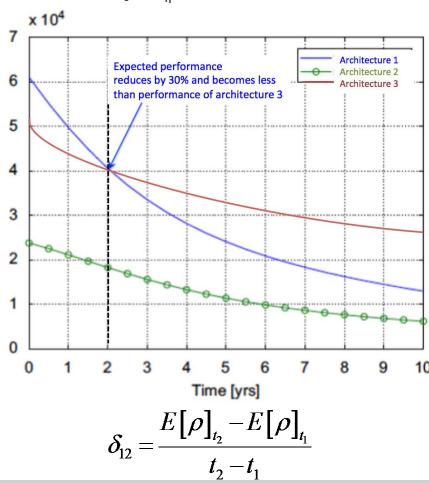
$$\frac{d}{dt}\Pi(t) = A\Pi(t)$$

$$\Pi(t) = e^{At}\Pi_0$$

Π_0 is the initial state vector
And $\Pi(t)$ is vector of π_i at t

$$\rho^T = \begin{bmatrix} \rho_1 & \cdots & \rho_i & \cdots & \rho_n \end{bmatrix}$$

Where ρ_i is the performance of the system when it is in state i and there are n states of the system

$$E[\rho] = \rho^T \Pi(t)$$

Expected performance reduces by 30% and becomes less than performance of architecture 3

Architecture 1
Architecture 2
Architecture 3

Time [yrs]

$$\delta_{12} = \frac{E[\rho]_{t_2} - E[\rho]_{t_1}}{t_2 - t_1}$$

❑ **impact on # of scenes per day metric**

    ❑ analyze how that is affected with partial failures

– (e.g. 400 scenes per day for Landsat mission, Wulder et al. 2011)

▪ **Fraction of data loss**

– (e.g. the failure of scan line corrector (SLC) on Landsat 7 led to 22% data loss, Wulder et al.).

– However data fusion and other techniques can help recover some of the losses.

▪ **Impact on down link capabilities due to satellite failure**

– a satellite loss may affect the period of contact with ground stations, and thereby cause any issues due to constraints on on-board memory and data retention.

Valuing Return of Earth Observation Missions: Expected Net Mission Value (NMV)

Value is an economic concept and varies for stakeholders of a system

- What is Value?
  - An economic concept
  - "mathematical statement of preferences," a monetized form of value is 'worth' [Collopy]

- Who's (stakeholder) point of view?
  - Designer (engineering firm), customer, etc.
  - The perspective of 'value' needs to be clearly defined to position the analysis
  - For engineering design (VCDM), the point of view needs to be from the engineering firm or organization

- **For a Telecomm mission:**   **For EO/Science mission:**
  - **Perspective of the firm**   **- Perspective of scientists/ public**
  - **Values is: NPV**   **- Value is: data -> information/knowledge**

Information or data in itself does not have inherent value. It's what can be done with the data/or what it can be used for is what lends it value.

Net Present Value (NPV) for Commercial Applications

$$V\left(T_f\right) = \left[\int_0^{T_f} \{u(t) - \theta(t)\} \cdot e^{-rt} dt\right] - C\left(T_f\right)$$

$\underbrace{\phantom{\int_0^{T_f}\{u(t)-\theta(t)\}\cdot e^{-rt}dt}}$ discounted benefit $\quad \underbrace{}$ cost

$V(T_f)$: present value over time horizon $[0\ T_f]$
$C(T_f)$: development, deployment, replenishment/expansion costs over $[0\ T_f]$
$u(t)$: revenue per unit time
$\theta(t)$: operating costs per unit time
r : discount rate
T_f : operating life time

$$u(t) = f\left(\alpha, \sigma_m, \sigma_t\right)$$

$$C\left(T_f\right) = f\left(C_{RDTE}, C_{prod}, \sigma_r, \sigma_m, \sigma_t\right)$$

α : application type/mix (will impact \$/bits etc.)
σ_m: market volatility (subscriber base/demand)
σ_t : technology obsolescence
σ_r : spacecraft reliability over T_f
C_{prod}: total production costs (function of N_s)
C_{RDTE}: R,D,T&E costs of system

Conceptualizing mission value

$$V\left(T_f\right) = \left[\int_0^{T_f}\left\{\omega\left[u\left(t\right)-\theta\left(t\right)\right]\right\}\cdot e^{-rt}\,dt\right] - C\left(T_f\right)$$

$V(T_f)$: present value over time horizon [0 T_f]
$C(T_f)$: development, deployment, replenishment/expansion costs over [0 T_f]
$u(t)$: total data (including observations and operations data) generated per unit time
$\theta(t)$: "operations" data per unit time
r : discount rate (question: time value of information/data?)
ω : $ per data unit?
T_f : operating life time

$$u\left(t\right) = f\left(\alpha, \sigma_i, \sigma_r\right)$$

α : application type/mix (will impact bits/time etc.)
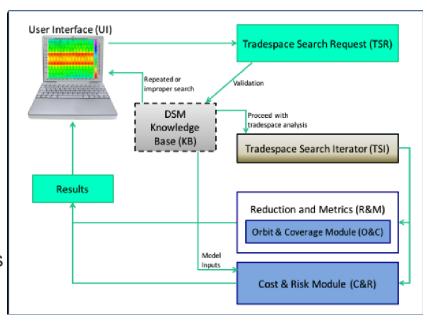σ_i: instrument/application related variability
σ_r : spacecraft reliability over T_f(?)

total data generated per unit time is a function of operational state of the DSM represented in a Markov model (where there maybe partial failures of instruments or spacecraft, degraded collection of information etc.)

Application:
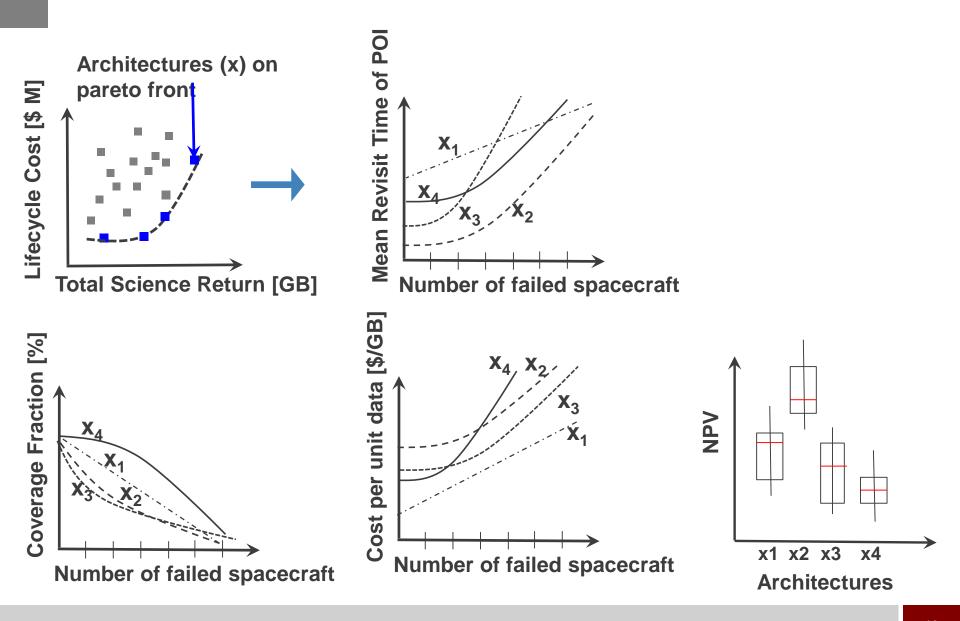# Trade-space Analysis Tool for Constellations (TAT-C)

Expected performance and value will be used as evaluation measures for analyzing architectures in TAT-C

- The Trade-space Analysis Tool for Constellations (TAT-C) is a framework for conducting pre-Phase A mission analysis of DSMs.

- It allows for modeling multiple spacecraft sharing a mission objective, and helps explore trade-space of variables for pre-defined science, cost and risk goals and metrics

- TAT-C computes performance of architectures over mission lifetime, and outputs minimum, maximum and average information across all Points of Interest (POIs), information per POI and information as a time series.

- These outputs can be combined to provide mission level measures such as percentage POI covered, revisit times etc.

Trade-space Analysis Tool for Constellations

TAT-C Analysis concepts

Merits and limitations of methodology

- Markov theory is well developed and widely used in systems analysis

- Closed form solutions for state trajectories can be obtained for given Markov models that allow for quickly computing state transitions and state residence times.

- The assumption of finite and discrete states simplifies system representation and limits the analysis

- State transitions are based on assumptions of failure rates or occurence of stochastic events for which data is typically limited or not available

Modeling Issues

- Estimating failures
  - Basic reliability theory, Common failure (beta model), Markov Monte-Carlo methods

- Estimating monetary value of data (ω)

THANK YOU!

Back up slides

Telecommunication Applications

- The value delivering function and (design) attributes can be thought through by focusing on applications of the telecommunication missions:

Table 1. Commercial Satellite Markets and Applications

Orbit	Market	Application	Example
GEO	Fixed Satellite Services (FSS) (C-, Ku-band)	Traditional regional data and voice comm. (fixed voice, cable TV)	Intelsat, PanAmSat
GEO	Direct Broadcast Satellite (DBS) Services (Ku-band)	Satellite TV communication	DirecTV, Echostar
GEO LEO MEO	Broadband Data Services (Ku-, Ka-, V-, Q-band)	High-speed data communication (Internet service, streaming video, video conferencing)	SkyBridge, Teledesic
GEO ELI	Digital Audio Radio Service (DARS) (S-band)	Satellite radio communication	Sirius, XM Satellite Radio
LEO MEO ELI	"Big LEO" (1-2 GHz)/Mobile Satellite Services (MSS) (L-band)	Global voice and data communication (satellite telephony and messaging)	Iridium, ICO, Globalstar, Thuraya, Connexion
LEO	"Little LEO" (<1 GHz) Telecomm Systems	Low-data-rate comm. (e-mail, two-way paging, asset tracking)	ORBCOMM
LEO	Remote Sensing Systems	High-resolution Earth imaging	Space Imaging, DigitalGlobe

Modeling Issues

- Estimating failures
  - Basic reliability theory,
  - Common failure (beta model),
  - Markov Monte-Carlo methods

- Estimating revenues u(t)
  - Binomial lattice models,
  - Monte-Carlo approaches

- Estimating R&D and implementation costs

Expected Net Present Value (NPV)

- "System Value" is defined as
  - Net Present Value (NPV)
    - Expenditures due to spacecraft and payload development, launch, ops …
    - Revenues generated by data from payloads (some $/GB is assumed)
  - NPV is treated as a Random Variable
    - Define uncertainties which can impact NPV positively or negatively

- Value of Distributed Systems
  - Simulation of uncertain NPV outcomes
  - Compare Architectures
  - Identify which Architectures are most favorable in terms of E[NPV], σ[NPV]