Evaluating Expected Performance and Graceful Degradation in Distributed Spacecraft Missions

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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

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 unweighted product of the factors I, U, Q, and S.

\[ V = B \times A = (I \times U \times Q \times S) \times A \]

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]

Source: https://www.nap.edu/catalog/21789/continuity-of-nasa-earth-observations-from-space-a-value-framework
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 $T_{\text{life}}$.

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 $i$ is $\pi_i$.

Transition rate of changing from a state $i$ to a state $j$ is $\lambda_{ij}$.

$$
\frac{d}{dt} \Pi(t) = A \Pi(t) \\
\Pi(t) = e^{At} \Pi_0
$$

$\Pi_0$ is the initial state vector. And $\Pi(t)$ is vector of $\pi_i$ at $t$.

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

Where $\rho_i$ is the performance of the system when it is in state $i$ and there are $n$ states of the system.

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

$$
\delta_{12} = \frac{E[\rho]_{t_2} - E[\rho]_{t_1}}{t_2 - t_1}
$$
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:**
  - Perspective of the firm
  - Values is: NPV

- **For EO/Science mission:**
  - Perspective of scientists/public
  - 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

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

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

\[ u(t) = f(\alpha, \sigma_m, \sigma_t) \]
\[ C(T_f) = f(C_{RDTE}, C_{prod}, \sigma_r, \sigma_m, \sigma_t) \]

\[ \alpha : \text{application type/mix (will impact$/$bits etc.)} \]
\[ \sigma_m : \text{market volatility (subscriber base/demand)} \]
\[ \sigma_t : \text{technology obsolescence} \]
\[ \sigma_r : \text{spacecraft reliability over } T_f \]
\[ C_{prod} : \text{total production costs (function of } N_s) \]
\[ C_{RDTE} : \text{R,D,T&E costs of system} \]

Adapted from: “Saleh, J., et. al. “To Reduce or to Extend a Spacecraft Design Lifetime?”, Journal of Spacecraft and Rockets, Vol 43, No. 1, Jan-Feb 2006”
Conceptualizing mission value

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

\( V(T_f) \): 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?)
\( \omega \): $ per data unit?
\( T_f \): operating life time

\[ u(t) = f(\alpha, \sigma_i, \sigma_r) \]
\( \alpha \): application type/mix (will impact bits/time etc.)
\( \sigma_i \): instrument/application related variability
\( \sigma_r \): 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.
TAT-C Analysis concepts

Architectures (x) on pareto front

Lifecycle Cost [$ M]
Total Science Return [GB]

Mean Revisit Time of POI
Number of failed spacecraft

Number of failed spacecraft
Coverage Fraction [%]

Cost per unit data [$/GB]
Number of failed spacecraft

NPV
Architectures

x1 x2 x3 x4
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 occurrence 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 ($\omega$)
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>
<thead>
<tr>
<th>Orbit</th>
<th>Market</th>
<th>Application</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEO</td>
<td>Fixed Satellite Services (FSS) (C-, Ku-band)</td>
<td>Traditional regional data and voice comm. (fixed voice, cable TV)</td>
<td>Intelsat, PanAmSat</td>
</tr>
<tr>
<td>GEO</td>
<td>Direct Broadcast Satellite (DBS) Services (Ku-band)</td>
<td>Satellite TV communication</td>
<td>DirecTV, Echostar</td>
</tr>
<tr>
<td>GEO</td>
<td>Broadband Data Services (Ku-, Ka-, V-, Q-band)</td>
<td>High-speed data communication (Internet service, streaming video, video conferencing)</td>
<td>SkyBridge, Teledesic</td>
</tr>
<tr>
<td>GEO</td>
<td>Digital Audio Radio Service (DARS) (S-band)</td>
<td>Satellite radio communication</td>
<td>Sirius, XM Satellite Radio</td>
</tr>
<tr>
<td>LEO</td>
<td>&quot;Big LEO&quot; (1-2 GHz)/Mobile Satellite Services (MSS) (L-band)</td>
<td>Global voice and data communication (satellite telephony and messaging)</td>
<td>Iridium, ICO, Globalstar, Thuraya, Connexion</td>
</tr>
<tr>
<td>LEO</td>
<td>&quot;Little LEO&quot; (&lt;1 GHz) Telecomm Systems</td>
<td>Low-data-rate comm. (e-mail, two-way paging, asset tracking)</td>
<td>ORBCOMM</td>
</tr>
<tr>
<td>LEO</td>
<td>Remote Sensing Systems</td>
<td>High-resolution Earth imaging</td>
<td>Space Imaging, DigitalGlobe</td>
</tr>
</tbody>
</table>

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 $E[NPV]$, $\sigma[NPV]$