Value Variance in Constellation Architecture Studies

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Abstract

The NOAA Satellite Observing System Architecture (NSOSA) study has examined nearly 100 alternative weather satellite constellations, looking for the most cost effective arrangement of instruments, satellite orbits, and sustainment policies. Examining the cost-effectiveness of potential future satellite constellations requires quantification of each constellation's ability to provide a set of sensor capabilities that support mission functions. The effectiveness, or value, of each alternative satellite architecture depends on orbital assignments, instrument payloads, and launch frequency required to maintain given levels of constellation performance. A key complexity in the value assessment is uncertainty, we neither know the stakeholders preferences nor the alternative system's performance with certainty. Key sources of uncertainty include priority of different observation types and performance estimation of different constellation types against value measures. This paper presents several methods to assess value uncertainty of the large number of constellation examined in the NSOSA study. These methods focus on value uncertainty related to stakeholder consensus, constellation performance scoring, and stakeholder preference. The methods include approaches to resolving the strong correlations that exist between constellations because of shared satellite configurations.

NSOSA further details – see St. Germain et al. (2018)

Introduction

- NSOSA study recommends the most cost-effective constellation-level architecture for U.S. weather satellites (2028 – 2050 epoch)
- Alternative architecture ***value* (V)** based on the Environmental Data Record (EDR) value model (EVM; Maier and Anthes 2018)
  - Multi-Attribute Utility Theory (MAUT; Keeny and Raiffa 1993)
  - EVM captures the tradable range of measurement performance over ***N*** objectives (44 in NSOSA)
  - Each objective associated with measures of performance (MOPs) at three levels
  - Study Threshold (ST): < ST → no value; failure
  - Expected (EXP): Expectation of stakeholders
  - Maximum Effective (ME): > ME → no added value
  - Alternatives scored against these levels

Regional Imaging	ST: 0	EXP: 70	ME: 100
Horizontal Resolution	6 km	3 km	1 km
Update Rate	30 min	10 min	5 min
Navigation Accuracy	3 km	1 km	0.5 km

Table 1: Measures of performance at three levels for "Regional Imaging" sample objective.

- Swing weights (***w***) define the ***stakeholder priority*** of improving objective performance from ST to ME
  - Swing-weight elicitation is subjective in nature
  - Weights impart stakeholder preference on final **V**

$$\textbf{Eq. 1} \quad V = \sum_{i=1}^{N} w_i * A_i \qquad A \rightarrow \text{objective MOP score aggregator}$$

- $V_A > V_B$ → Alternative A preferred
- Focus on estimating value uncertainty

NSOSA Swing-Weight Generation

- Leadership ranked objectives by ST-ME performance swing
  - Confident in most/least important swings
  - No arguments for many steps up/down rank list
  - Much ***discussion for few steps up/down rank list***
- Eq. 2 curve models baseline swing weights based on discussed preferences (blue line Fig. 1)

$$\textbf{Eq. 2} \qquad w_i = \epsilon + \left[1 - \tanh\left(\frac{R}{N} * (i - m)\right)\right]^p$$

$$\epsilon = 0.1, R = 4.0, N = 44, m = 13, p = 1.2, i = \textit{objective rank}$$

- Curve characterized by 20:1 top-to-bottom ratio
- Overall curve shape roughly correct → Variation in objective rank assignment moves objectives a few steps up/down

Objective	Rank
Assurance of core capabilities	1
Compatibility with fixed budgets	5
Coronagraph imagery: sun-earth	10
Global ocean color/phytoplankton	15
Auroral imaging	20
Interplanet. solar wind:off sun-earth	25
Reg. RT vertical MW soundings	30
Solar EUV irradiance	35
Outgoing longwave radiation (OLR)	40
Interplanetary magnetic field at L_1	44

Table 2: Subset of objectives and ranks.

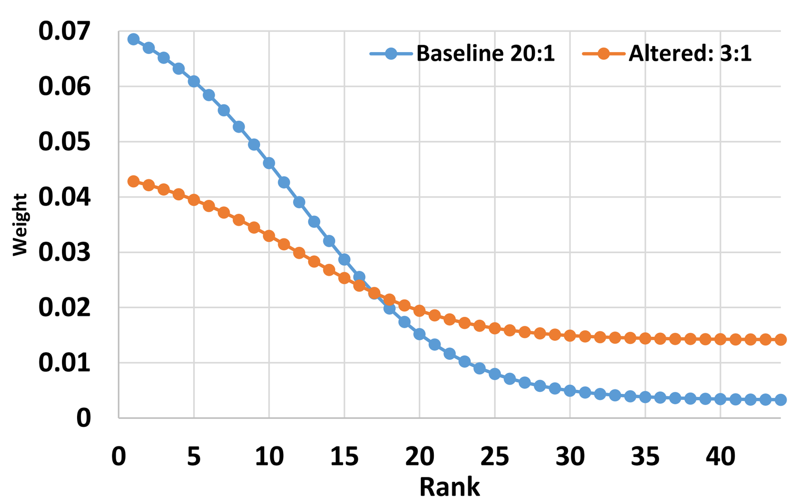

Figure 1: Baseline 20:1 (blue) and altered 3:1 (orange) swing-weight curves.

Sources of Uncertainty in Alternative Value

1. Inexact swing-weight elicitation
2. Preferences unexpressed in any single swing-weight set
3. Early performance estimates inform alternative scoring
4. Effects of unconsidered issues not captured by EVM

Swing-Weight Uncertainty: Random Variation

- 10% & 20% variation applied to baseline weights using draws from uniform distribution
- Results in rank interchanges for swing weights that ideally mimic assignment process uncertainty
- 95% confidence intervals (CIs) from 1000 Monte Carlo trials built for each constellation alternative value score

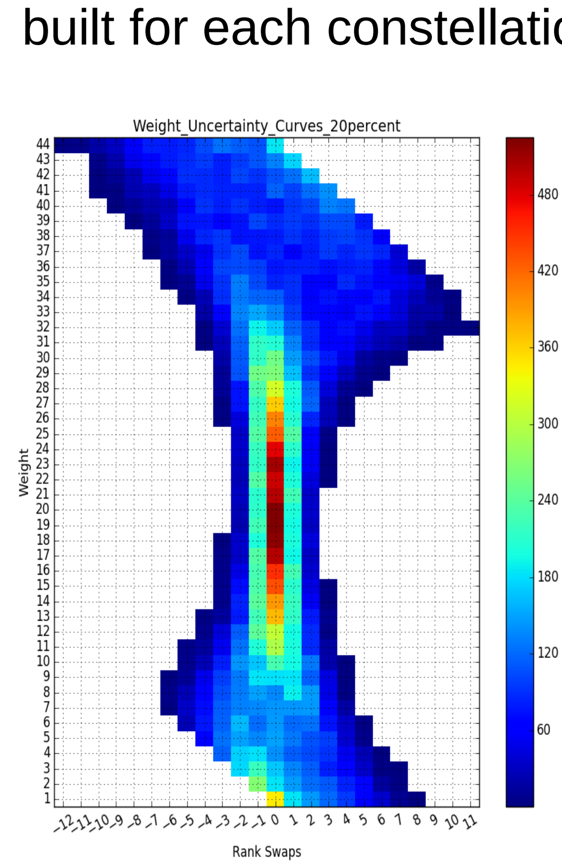

Figure 2: Swing-weight swapping with 20% uniform variation.

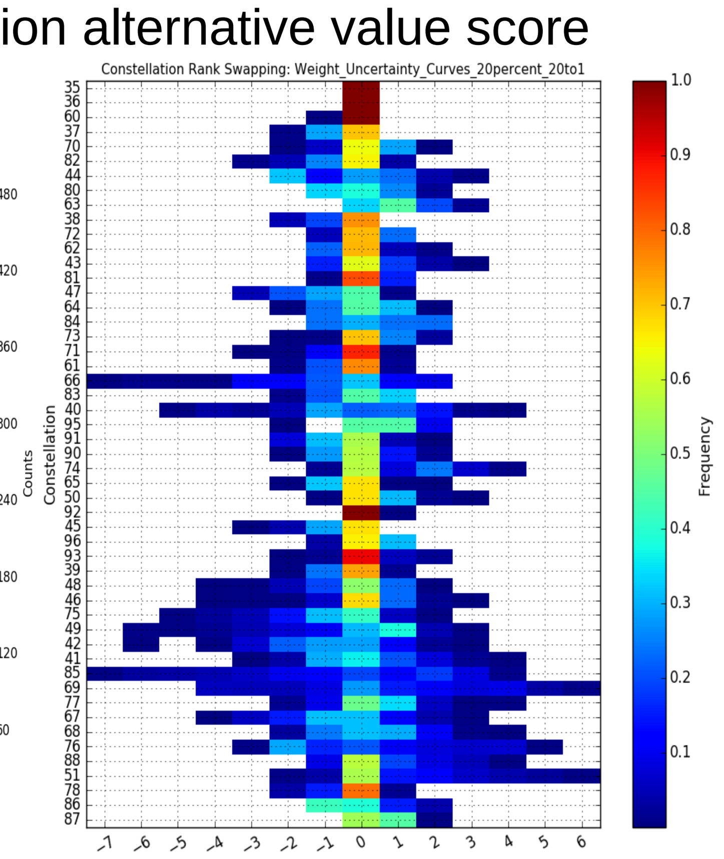

Figure 3: Alternative preference order swapping under 20% weight variation.

Swing-Weight Uncertainty: Interchange

- Alternative to random variation when desired rank swapping inadequate
  - Useful for nonlinear swing-weight structure
- Baseline weights swapped down/up in rank based on draws from uniform distribution (30% swap probability)

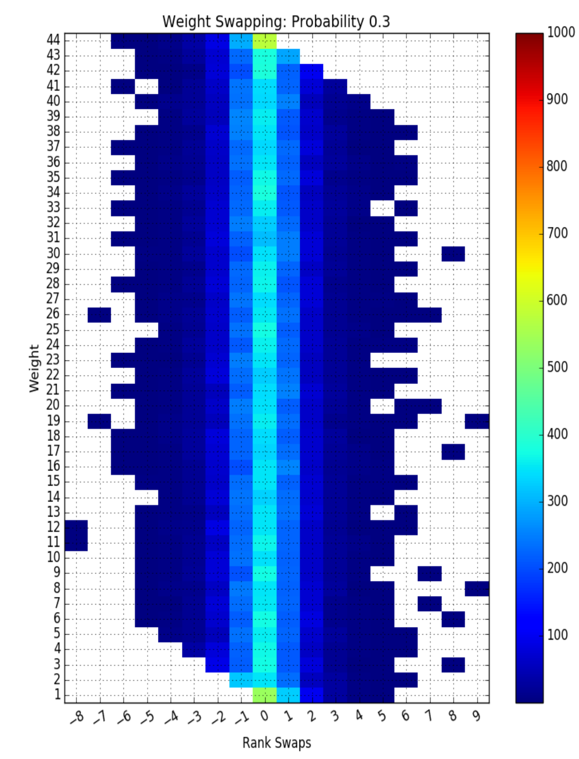

Figure 4: Swing-weight swapping under 30% interchange model.

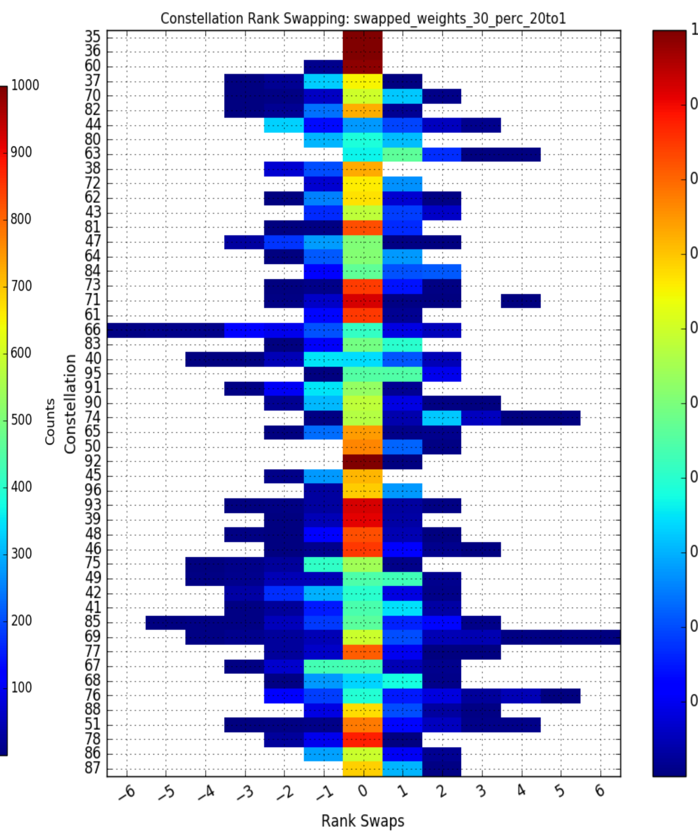

Figure 5: Alternative preference order swapping under 30% interchange model.

Swing-Weight Uncertainty Confidence Intervals

- Non-overlapping CIs → sig. performance differences
- Overlapping CIs → interchangeable alternatives
- Interchanges occur less freely than overlap suggests due to correlations
- Overlapping CIs + alternative swapping (Figs. 3,5) yield correlation insight

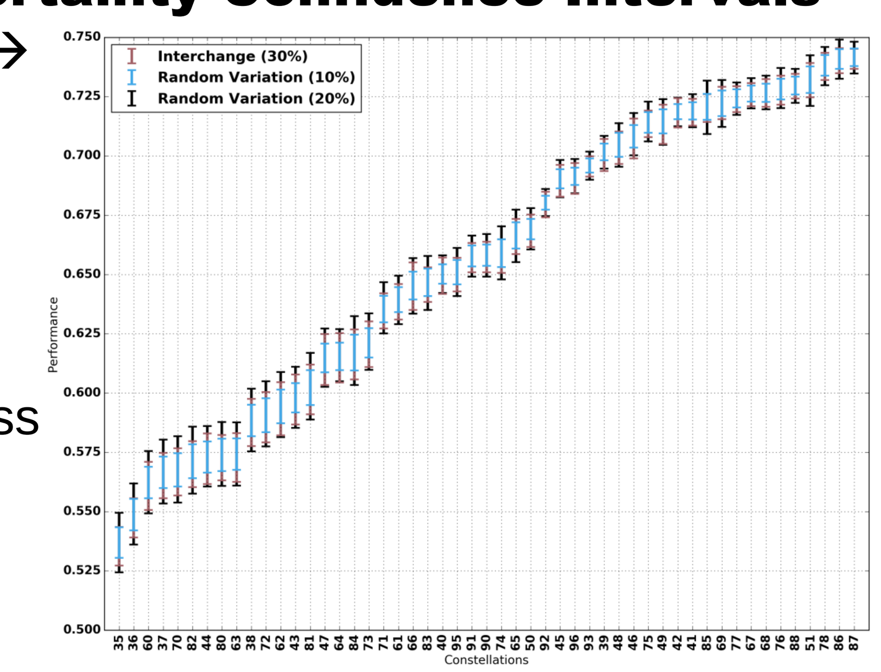

Figure 6: 95% confidence intervals for 10%/20% random swing-weight variation and 30% interchange approach.

Alternative Scoring Uncertainty

- Uncertainty in scoring alternative against EVM
- Limited engineering data, coarse performance measures performance, scoring judgements
- Alternative performance inputs altered to give best and worst case objective scores
- Value calculated from Monte Carlo score draws within score ranges; 95% CIs established (Coakley et al. 2018)
- Swing-weight and scoring uncertainty combined
- **Efficient Frontier (EF)**→alternative cost-benefit
- Emphasizes **min cost** & **max value** (Crawley et al. 2015)
- EF + uncertainty reveals most cost-effective & potentially interchangeable alternatives

Efficient Frontier

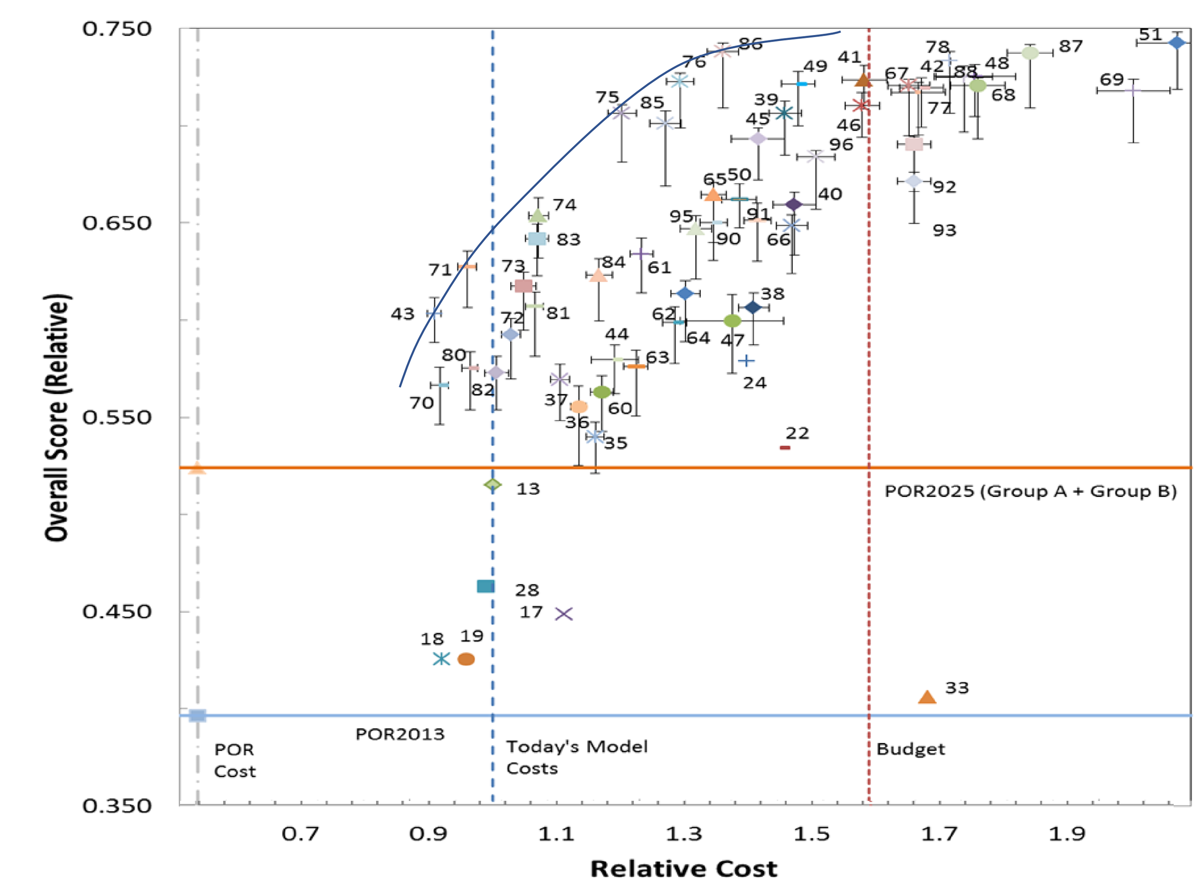

Figure 7: Efficient frontier with combined swing-weight (10%) and scoring uncertainty 95% confidence intervals. Blue line indicates min cost & max value front. Cost CIs given by Yeakel and Maier (2018).

Stakeholder Preference Uncertainty Note

- Swing-weight curve altered to 3:1 (orange line Fig. 1)
- Flattened curve increases (decreases) contribution of lower-ranking (higher-ranking)
- Final alternative preference ranks slightly altered
- 3:1 curve tightens grouping of alternative clusters but does not promote or denote clusters

Summary

- Quantifying uncertainty for preferred alternatives allows for the identification alternatives significantly more valuable than others under consideration
- Assumptions leading to overly frequent rank-order swapping only lead to a small number of preference swaps; variation does not alter the relative positioning of alternatives in the context of the EF
- Combining scoring/weight uncertainty differentiates architectural differences from process noise
- Altering swing-weights as stakeholder preference shift does not promote/demote alternative clusters
- NSOSA results relatively robust to uncertainty sources examined here

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