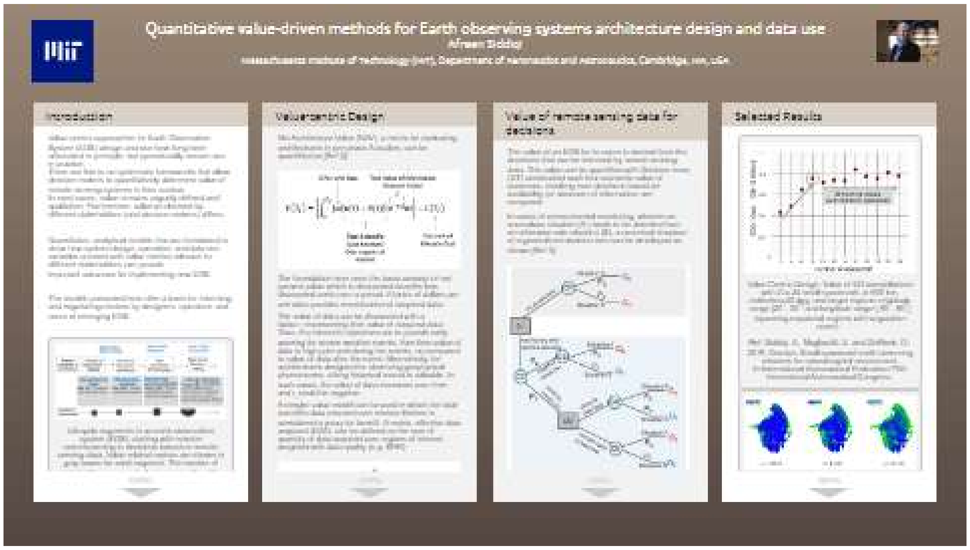
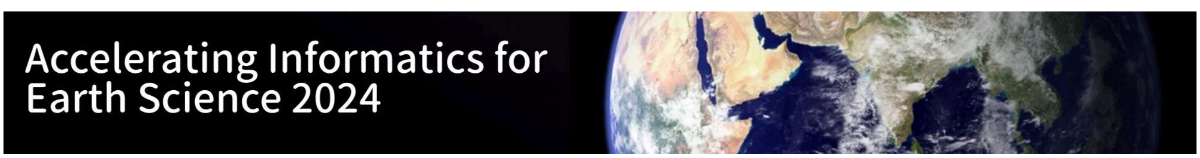
Quantitative value-driven methods for Earth observing systems architecture design and data use



Afreen Siddiqi

Massachusetts Institute of Technology (MIT), Department of Aeronautics and Astronautics, Cambridge, MA, USA

PRESENTED AT:

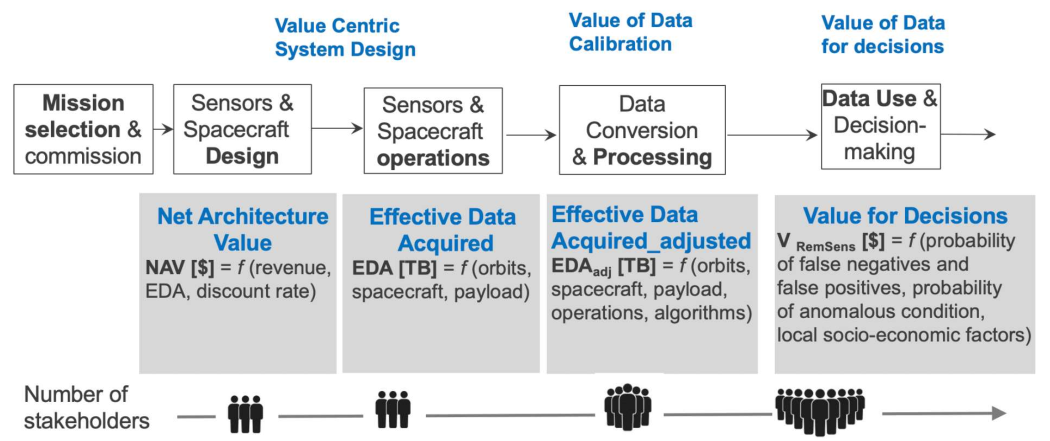


INTRODUCTION

Value-centric approaches for Earth Observation System (EOS) design and use have long been advocated in principle, but operationally remain rare in practice. There are few to no systematic frameworks that allow decision makers to quantitatively determine value of remote sensing systems in their context. In most cases, value remains vaguely defined and qualitative. Furthermore, value as deemed by different stakeholders (and decision makers) differs.

Quantitative, analytical models that are formulated to show how system design, operation, and data use variables connect with value metrics relevant for different stakeholders can provide important advances for implementing new EOS.

The models presented here offer a basis for informing and negotiating choices by designers, operators, and users of emerging EOS.



Lifecycle segments in an earth observation system (EOS), starting with mission commissioning to decisions based on remote sensing data. Value-related metrics are shown in gray boxes for each segment. The number of stakeholders progressively increases along the segments [Ref 1].

Ref [1]: Value Analytics for Earth Observing Systems, IEEE Geosciences and Remote Sensing Symposium (IGARSS) 2024.

VALUE-CENTRIC DESIGN

Net Architecture Value (NAV), a metric for evaluating architectures in pre-phase A studies, can be quantified as [Ref 2]:

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

$ Per Unit Data (ω); Time Value of Information Discount Factor ($e^{-r_i t}$); Total Scientific Data Received Over regions of interest ($u(t) - \theta(t)$); Discounted Lifecycle Cost ($C(T_f)$)

The formulation here uses the basic concept of net-present value which is discounted benefits less discounted costs over a period. A factor of dollars per unit data provides monetization of acquired data.

The value of data can be discounted with a factor r_i representing time value of acquired data. Thus, if a mission's objectives are to provide early warning for severe weather events, then time value of data is high prior and during the events, as compared to value of data after the event. Alternatively, for architectures designed for observing geophysical phenomenon, a long historical record is valuable. In such cases, the value of data increases over time, and r_i could be negative.

A simpler value model can be used in which the total scientific data returned over mission lifetime is considered a proxy for benefit. A metric, effective data acquired (EDA), can be defined as the sum of quantity of data acquired over regions of interest weighted with data quality (e.g. SNR):

$$EDA_k = \sum_{j=1}^{S} \sum_{i=1}^{I_j} Q_{ij}{}^k \frac{1}{CV_{ij}^k}$$

$$CV_{ij}^k = CV_{ij}^k(SNR) = \frac{\sigma_{ij}^k}{\mu_{ij}^k}$$

The Signal-to-Noise Ratio (SNR) embodies sensor and orbit related variables, thus providing a basis for computing how technical design choices will affect mission value.

Table 1: Sensor and orbit design variables in SNR calculation for passive optical sensors

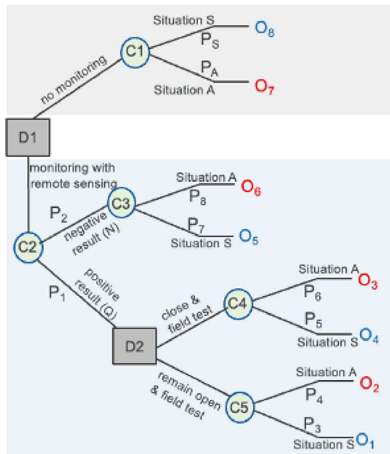
Sensor design variables	**Orbit / environment variables**
Detector Quantum Efficiency (Q_E)	Spacecraft ground track velocity (V_g)
Dynamic range (DR)	Position of Satellite
Operating wavelengths (λ)	Cross track and along track resolutions (X, Y)
Aperture diameter (D)	upwelling reflected solar radiance, L_{upi}
Cross track pixels (Z_c)	Atmosphere transmissivity ($\tau(\lambda)$)

Ref [2]: Siddiqi, A., Magliarditi, E. and de Week, O., 2019, July. Valuing new Earth observation missions for system architecture trade-studies. In IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium(pp. 5297-5300). IEEE.

VALUE OF REMOTE SENSING DATA FOR DECISIONS

The value of an EOS for its users is derived from the decisions that can be informed by remote sensing data. This value can be quantified with Decision trees (DT) constructed such that economic value of outcomes, resulting from decisions based on availability (or absence) of information, are compared.

In cases of environmental monitoring, wherein an anomalous situation (A) needs to be detected from an otherwise safe situation (S), a canonical structure of a generalized decision tree can be developed as shown [Ref 3]:



Value of sample information and Bayesian probabilities can then be used to derive non-linear analytic expressions (Table 2) that quantify value of remote sensing data ($V_{RemSens}$). The analytic expressions allow for exploring key factors related to the application that may drive value and can inform investment and use decisions.

Table 2: probabilities for monitoring decisions

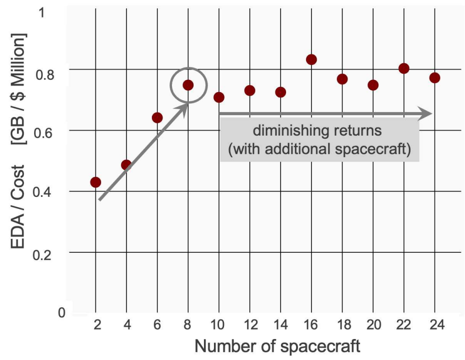
$P_1 = P(Q) = [1 - P(N\|A)]P_A + P(Q\|S)(1 - P_A)$
$P_2 = P(N) = 1 - P(Q)$
$P_3 = P(S\|Q) = \frac{P(Q\|S)P(S)}{P(Q)} = \frac{P(Q\|S)(1-P_A)}{P(Q)}$
$P_4 = 1 - P_3; P_5 = P_3; P_6 = P_4; P_8 = 1 - P_7$
$P_7 = P(S\|N) = \frac{P(N\|S)P(S)}{P(N)} = \frac{[1 - P(Q\|S)(1-P_A)]}{1-P_1}$

For the DT shown, the value of remote sensing for informing decisions is calculated as:

$$V_{RemSen} = C_2 - C_1 = (P_2C_3 + P_1D_2) - (P_AO_7 + P_SO_8)$$

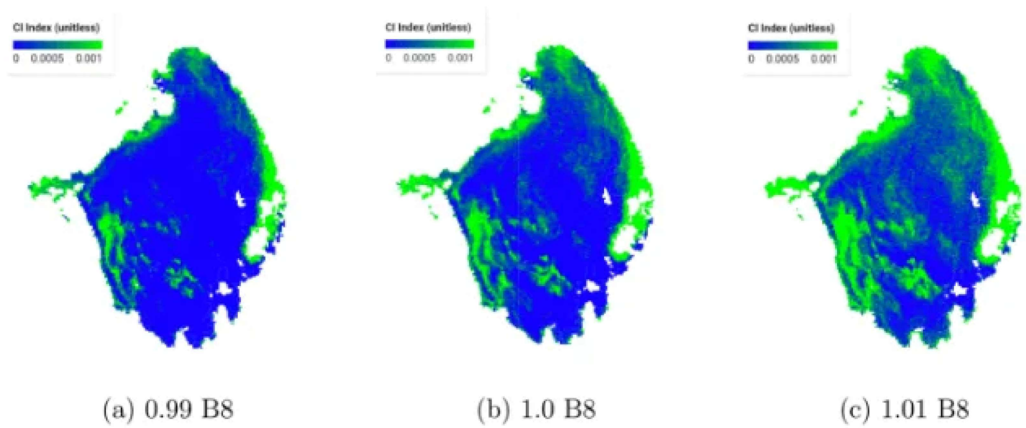
Ref [3]: Siddiqi, A., Baber, S. and De Weck, O., 2021, July. Valuing radiometric quality of remote sensing data for decisions. In 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS (pp. 5724-5727).

SELECTED RESULTS

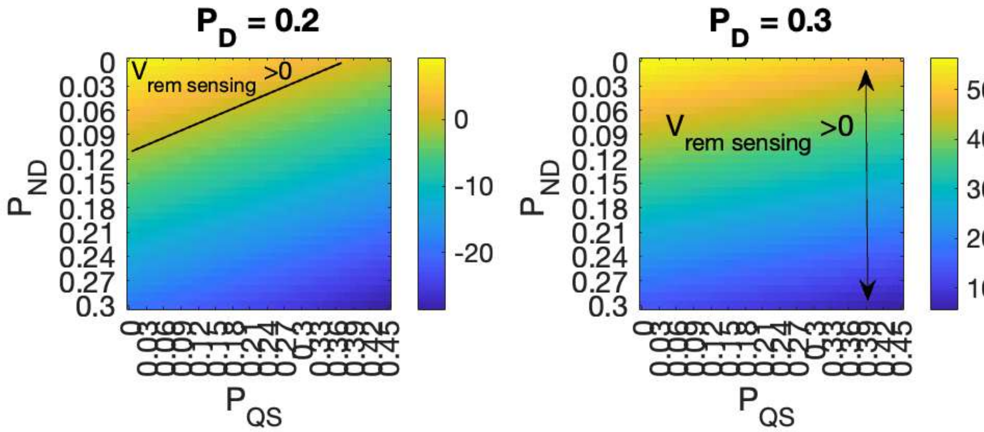


Value Centric Design: Value of EO constellations with 2 to 24 small spacecraft, at 600 km, inclination 40 deg, and target regions in latitude range [20°, 30°] and longitude range [-90°, 80°] (spanning equatorial regions with vegetation cover).

Ref: Siddiqi, A., Magliarditi, E. and DeWeck, O., 2019, October. Small spacecraft earth observing missions for natural capital assessment. In International Astronautical Federation-70th International Astronautical Congress.



Value of Data Calibration: Effects of +/- 1% (synthetic) error in band 8 of OLCI L1B data from Sentinel on results for Cyanobacteria Index (Ref: Sheila et al 2021)



Value of Data for Decisions: A case of value of remote sensing for Harmful Algal Bloom (HAB) monitoring was studied. P_{ND} (probability of false negative) and P_{QS} (probability of false positive) are varied to show when remote sensing data provides value for monitoring HABs in a region with different levels of P_D (probability of a HAB occuring). If P_D is equal to or greater than 30% in the case shown above, remote sensing data will provide value even when P_{ND} and P_{QS} are high [Ref 3].

The value models can be applied to a single mission case and can be used for informing and negotiating choices by stakeholders of emerging EOS. Such a systematic approach can improve sustained value delivery and overall utility to the EOS community.

AUTHOR INFORMATION

Afreen Siddiqi

Research Scientist,

Department of Aeronautics and Astronautics,

MIT

email: siddiqi@mit.edu

TRANSCRIPT

ABSTRACT

Value-centric approaches for Earth Observation System (EOS) design and use have long been advocated in principle, but operationally remain rare in practice. Here, an integrative framework for quantifying value is presented that connects architecture and design, data processing, and data use. Examples in constellation design, calibration for data quality, and decision applications from remote sensing data demonstrate how the approach can be applied. Additionally, closed form analytical models are formulated to show how system design, operation, and data use variables connect with value metrics relevant for different stakeholders. The models presented here offer a basis for informing and negotiating choices by designers, operators, and users of emerging EOS.