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Title: Spacecraft Evaluation Tool Verification and Validation

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Spacecraft Evaluation Tool Verification and Validation

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Nomenclature

NRE	=	nonrecurring (costs), FY2008$M
RE	=	recurring (costs), FY2008$M

I. Introduction

This document details the verification and validation of the Spacecraft Evaluation Tool (SET). The SET is used to quantify the value propositions for monolithic and fractionated spacecraft. The two most volatile metrics in the value proposition are the mass of a spacecraft and its respective lifecycle cost. Therefore, the SET verification and validation focuses on these two metrics in the value proposition. Previous applications of the SET lead to the establishment of numerous valuable insights regarding monolithic and fractionated spacecraft value propositions; for more information about this see *Assessing the Impacts of Fractionation on Pointing-Intensive Spacecraft* (O'Neill, 2009).

II. Methodology: The Spacecraft Evaluation Tool

The research methodology is embodied in the Spacecraft Evaluation Tool (SET), which was developed over the course of two years, and quantitatively assesses monolithic and fractionated spacecraft value propositions. The SET is a software program that uses a Microsoft Excel® and Matlab® integrated programming language and visualization platform. The SET is a bottom-up (to the fidelity of subsystem components) spacecraft modeling tool and was programmed without a reliance on any models developed by others, the only exception being some elements of the SET cost model. The three functional divisions of the SET are inputs, model algorithms (simulation), and outputs; conceptual groupings of these three SET constituents are shown in Figure 1. For a given spacecraft, the SET employs a Monte Carlo Analysis (MCA) to simulate potential lifecycle's for that spacecraft based on the SET input values specified, and subsequently generates the SET outputs, which are used to form the value proposition for the spacecraft.

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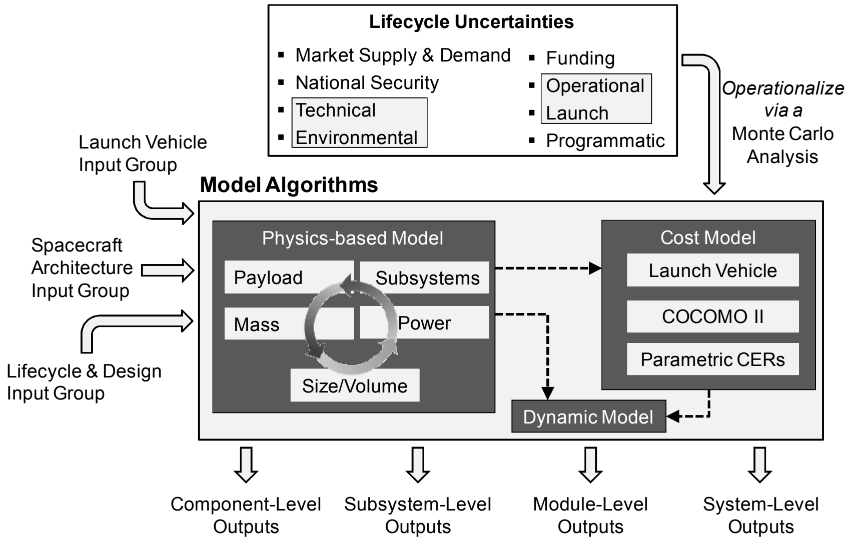

Figure 1. SET Functional Overview.

III. Methodology: Verification & Validation

The Spacecraft Evaluation Tool verification entails a demonstration of the SETs mass and cost estimation accuracy, whereas the SET validation entails a discussion pertaining to the attainment of the aforementioned contributions of this research effort. Given that the SET does not rely on historical analogies to past/existing spacecraft (*i.e.,* it is not a design-by-analogy model), the results from the SET verification & validation (V&V) are entirely a function of the SET's inherent accuracy, and therefore ability quantify spacecraft value propositions.

A. Verification

The SET verification focuses on corroborating the accuracy of the spacecraft value proposition metrics that have the strongest dependency on a given spacecraft assessment tool (model); hence, for a given spacecraft, these metrics are the most likely to be different depending spacecraft assessment tool used to quantify them. Given that there are no historical or existing fractionated spacecraft, the SET verification for modeling fractionated spacecraft makes the necessary assumption that the SET verification for modeling monolithic spacecraft demonstrated hereafter is extensible, in terms of fostering confidence in the estimation accuracy of the SET, to fractionated spacecraft.

1. System Mass

The verification process begins through demonstrating the accuracy in the SET-produced mass estimates for monolithic spacecraft performing RSMs. For this aspect of the SET verification, nine existing RSM monolithic spacecraft were selected as reference points on the basis of their similar architectural (*i.e.,* subsystem and payload) composition to that in which spacecraft architectures are modeled in the SET. These nine spacecraft were subsequently assessed by the SET based on their respective payload performance (*i.e.,* Earth-image resolution), mission lifetime, and launch and orbital characteristics. The second step of the mass verification involved correlating the SET estimation of mass of, to the actual mass for each of the nine spacecraft considered (see Figure 2). The dry and wet masses for the spacecraft were obtained from synthesizing numerous open-source spacecraft databases, the only sources of such information available in academia, and cross referenced, if possible, with the respective manufacturers of these spacecraft (Krebs, 2009; Wade, 2009; TBS Internet, 2009; Satellite Imaging Corporation, 2009; Rapid Intelligence, 2009; GeoEye, 2009; eoPortal, 2009; DigitalGlobe, 2009; McDowell, 2008, 1999; Sandau, Roser, & Valenzuela, 2008; Kramer, 2002). The reporting of these mass values in the databases were highly inconsistent and hence whichever mass (dry or wet) could be ascertained was the one used for the correlation.

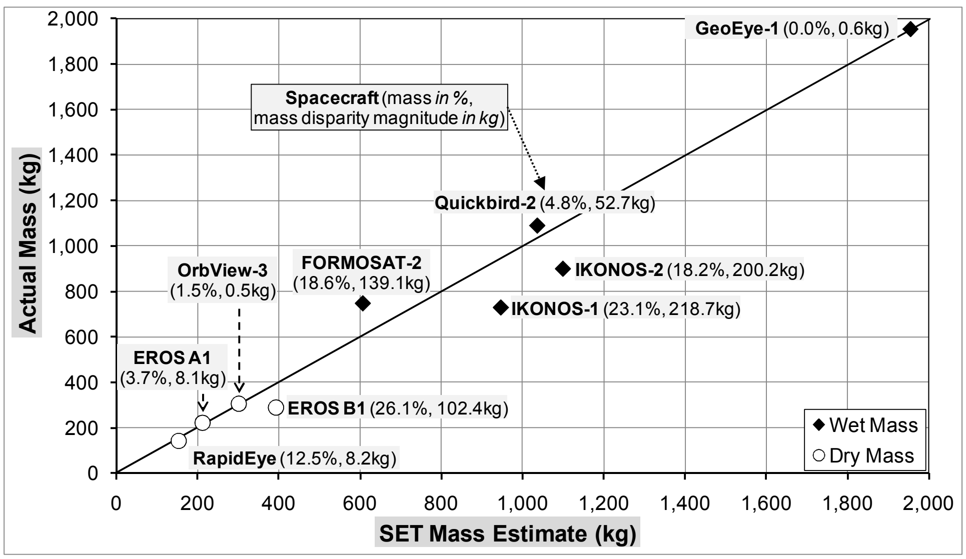

Figure 2. SET Mass Verification.

The root mean square error (RMS) value from the mass correlation shown in Figure 2 is 115.8 kg or 14.9 %, an appreciably low RMS value given the diversity of subsystem and payload compositions across the nine spacecraft considered. It is also worth noting that the SET estimated the wet mass of GeoEye-1 to an accuracy of 0.6 kg, a remarkable achievement given that the SET is bottom-up, but still conceptual spacecraft modeling tool.

2. System Static Lifecycle Cost

Given the proprietary nature of spacecraft cost information, the SET System Static LCC verification can only be substantiated through a citation of the source(s) used for the various LCC constituents in the SET cost model; these are summarized in Table 1. The wrapper and bus subsystem costs are predominantly quantified by Unmanned Space Vehicle Cost Model CERs, which are derived from spacecraft mass regression analyses; however, some

CERs were also taken from *Space Mission Analysis and Design* (Tecolote Research Inc., 2009; Tieu, Kropp, & Lozzi, 2000; Larson & Wertz, 1999). Manufacturer quotes are used for the computer system hardware cost estimates, and the software cost and development time is quantified using the well-vetted COCOMO II tool, which is embedded in the SET cost model (Boehm, 2000). Similarly, cost estimates for the propulsion system and propellant are based on quotes from the respective manufactures of these spacecraft constituents. In terms of the payload cost, this is based on a NASA Telecommunications and Data Acquisition (TDA) Study, which characterizes the cost-performance (resolution) relationship between numerous optical payload systems (Lesh & Robinson, 1986). The ground station costs are estimated from the suite of open-source costing tools available from the *NASA Cost Estimating Handbook* and *Website* (NASA, 2008, 2009). Lastly, the launch vehicle costs, for all twenty-two launch vehicles modeled in the SET, are quoted from the manufacturers of these launch vehicles if possible and, if not, taken from the *International Reference Guide to Space Launch Systems* and other open-source databases (Krebs, 2009; Wade, 2009; Isakowitz, Hopkins, & Hopkins Jr., 2004; NPO InterCos, 2009; Zak, 2009). All SET cost model constituents are adjusted for inflation such that the resulting spacecraft LCC estimates produced by the SET are quantified in terms of 2008 fiscal year, millions of dollars (FY2008$M).

LCC Constituent	NRE	RE	Cost Estimation Source
Bus Subsystems	Yes	Yes	Unmanned Space Vehicle Cost Model, 8th Edition
Computer System and Software	Yes	Yes	COCOMO II *and* Manufacturers
Propulsion & Propellant	Yes	Yes	Manufacturers
Payload	Yes	Yes	NASA Telecommunications and Data Acquisition Study
Wrapper (*e.g.,* personnel, labor)	No	Yes	Unmanned Space Vehicle Cost Model, 8th Edition *and* SMAD
Ground Station Leasing	No	Yes	NASA Cost Estimating Website
Launch Vehicle	Yes	No	Manufacturers, Steven Isakowitz's *Guide to Launch Systems*

Table 1. SET Lifecycle Cost Constituents.

B. Validation

The validation of the SET is substantiated through the SETs inherent functionality as well as any documentation pertaining to the SET, all of which demonstrate the fulfillment of the four research contributions aforementioned. Specifically, the first three research contributions, namely, the ability to explore value propositions in both breadth and depth using cardinal, "traditional" measures of effectiveness, are achieved through the SET construct, the breadth and depth of the SET inputs and outputs, and fidelity of the model algorithms. The fourth research contribution is specifically achieved through this and all other documentation pertaining to this research effort (O'Neill, 2009; O'Neill & Weigel, 2009). Attainment these research contributions is assumed sufficient validation of the SET.

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