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Bayesian framework for assessing the value of scientific space systems: Value of information approach with application to earth science spacecraft

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ABSTRACT

Space systems play an important role in today's society by generating or transmitting information from source to sink(s). The acquisition of the space system is often justified by the type, quantity and quality of information provided or transmitted. This work posits that the value of a class of space systems derives from and can be assessed through the value of information these systems provide. To this effect, a Bayesian framework is developed to assess system value in which systems are viewed as information sources, and stakeholders as information recipients. Information has value to stakeholders as it helps to update their beliefs, enabling them to make decisions that can yield higher expected pay-offs than in the absence of information. This increase in expected pay-offs is ascribed to the value of the system. Based on this idea, a new metric, *Value-of-Design* (*VOD*), is introduced to quantify the value of a class of space systems with unpriced services. The Bayesian framework assesses the *Value-of-Design* for the space system by considering the impact of the information transmitted on the actions taken by stakeholders, and estimating the resulting pay-offs from these actions. The framework here developed is then applied to the case of an Earth Science satellite that provides hurricane information to oil rig operators in the Gulf of Mexico. Probability models of stakeholders' beliefs, and economic models of pay-offs are developed and integrated with a spacecraft design tool. Results from the application point to clusters of payload instruments that yielded higher information value, and minimum information thresholds below which it is difficult to justify the acquisition of the system. Additionally, the system is analyzed in *Cost-VOD* trade space to provide program managers with additional insights into the coupling of a system's predicted value generation and its associated lifecycle cost.

1. Introduction

In 1958, the National Aeronautics and Space Act established the National Aeronautics and Space Administration (NASA) with one of NASA's key mandates being to advance the civil space program. Under this Act, the newly established agency was directed to focus on the "expansion of human knowledge of the Earth and of phenomena in the atmosphere and in space" [1]. The agency was tasked with identifying and executing space missions based on scientific merit so as to increase the knowledge of the scientific community, and subsequently, of society at large. The Act thus established a knowledge and information driven agency. The 2011 annual report of

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the Aerospace Advisory Safety Board stated, "one overarching and fundamental purpose of NASA is to create knowledge…[and] ensuring that this knowledge is captured and available to future generations is more than an obligation, it is a sacred trust" [2]. The premise of this work, that NASA is a knowledge generation agency, is thus well established and acknowledged. However, limited considerations have been given to assessing and articulating the value of the knowledge created and the linkages between knowledge generation in the scientific community, and their trickle-down effect and applications to society at large. In the past (and present) space system selection and linkages to knowledge generation were conducted using multi-criteria decision making techniques. System engineers were tasked with identifying a set of optimal design vectors that satisfies multiple conflicting objectives simultaneously; one of these criteria being the knowledge generated. The practice of systematically pinpointing this optimal set is known as vectorial optimization, and a wide array of concepts and methodologies have been developed that enables engineers to solve these optimization problems. While these methodologies offer a structured approach for decision-making in space system design and analysis, these methodologies indirectly, and at times obscurely, link the attributes of the space system to the societal value of knowledge generated by the space system.

In recent years, political and economic conditions led to calls for providing a sharper definition to this linkage and a better articulation of the value of the knowledge generated and the value of the space missions proposed. Ascribing social benefits to the data collected by space-borne scientific instruments is receiving greater attention as program managers are asked to justify space missions based in part on the relevance of the missions' resulting information products and the potential applications enabled to the wider society. In fact, as early as 1992, the imperative to provide a definitive link between the generation of scientific knowledge and the societal applications is evident in reports on setting priorities in space-based research. In 1992, the National Academies Space Studies Board noted "the collection of data, the creation of information through its analysis, and the subsequent development of insight and understanding should be key governing objectives for scientific research in space" [3]. The Space Studies Board further noted in the report "it behooves scientists seeking public support to demonstrate to the public and its representatives that the fruits of scientific research do indeed enhance the quality of life and the welfare of the nation's citizens" [3]. From these two statements, one can infer that as early as 1992, there was a desire to articulate the value of space missions and explicitly link the information generated from space-based research to societal benefits. More recently in 2007, NASA, the National Oceanic and Atmospheric Administration (NOAA), and the US Geological Survey (USGS) commissioned a report, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, to identify flight missions that should be deemed high priority over the next decade [4]. Part of the impetus for this report is the desire to create a strategic plan for space missions that support national needs for research and monitoring of Earth's ecological, atmospheric and geological systems. Eight criteria were identified as being critical to executing a successful space based national strategy in earth science. Two of the criteria applicable to this research are the "contribution to applications and policy making" and "affordability (cost considerations, either total costs for missions or costs per year)". The first criterion explicitly calls for identifying the linkage between advancements in scientific knowledge and societal benefits, while the second criterion recognizes the need for fiscal responsibility. One important corollary of this discussion is that if NASA is fundamentally a knowledge generation agency, then analyzing the value of knowledge generated should be a key imperative in the planning and execution of space missions.

Effectively, reports on setting priorities for space based research, such as that by the Space Studies Board and the Earth Science and Applications decadal report, called for a stronger emphasis on the assessment of the value of spacecraft and how scientific knowledge generated by said systems may be leveraged by the greater society. In doing so, these reports implicitly conceptualized scientific spacecraft as value delivery artifacts, and proposed that their value ought to be articulated and assessed. When the services provided by a system are priced in a given market (e.g., transponders on-board communication satellites leased or rented), the value of the system as seen from its owner or principal can be assessed through traditional discounted cash flow techniques such as the calculation of its Net Present Value [5]. Such a value analysis however is not feasible for a class of systems whose services are unpriced (no cash inflow) such as scientific spacecraft. In short, there is on the one hand an increased emphasis on the need to assess and articulate the value of scientific spacecraft, and on the other hand, traditional valuation techniques are not applicable to this class of systems. To address this challenge, we propose in this work that the value of such spacecraft derives from the value of information they provide.[1] To this effect, we develop a Bayesian framework to assess system value in which spacecraft are viewed as information sources, and stakeholders as information recipients. Information has value to stakeholders as it helps to update their beliefs, enabling them to make decisions that can yield higher expected pay-offs than in the absence of information. This increase in expected pay-offs is ascribed to the value of the system. The remainder of this work further develops this idea, provides an analytic framework for capturing the value of information provided, and applies it to the case of an Earth science spacecraft. Section 2 discusses the various definitions of information in an engineering context and provides a definition of information for space system design and acquisition. Section 3 develops a theoretical framework using Bayesian updating for

[1] Although we acknowledge space systems provide several distinctive value flows to a variety of stakeholders (see Refs. [4,6]) with each flow being an important component in the value generation of space systems, we focus in this work on the value of information provided by the system.