Towards an Empirical Measure of Spacecraft Innovation: The Case of Communication Satellites

Zoe Szajnfarber* and Annalisa L. Weigel†
Massachusetts Institute of Technology, Cambridge, MA, 02139

This paper seeks to frame the discussion of innovation in the space sector and creates a platform for future analysis. To accomplish this, it addressed three aspects of the task of measurement. First, it surveys several distinct literatures to establish precedence for defining a spacecraft innovation metric. Second, the conceptual trade-offs associated with adopting this principle in the context of communication satellites are elucidated and treated. By defining product boundaries along the dimensions of product scope and market transactions, three paradigms for measurement are proposed; namely, 1) the communication satellite enterprise; 2) the physical satellite; and 3) communication service. Third, under the constraints of historical data collection realities, next-best estimators are put forward as proxies for the parameters required to implement the proposed metrics. Based on these proxies, the relative merits of each measurement paradigm are illustrated through an analysis of the innovation history of communication satellites.

Nomenclature

a_i	=	Relative weight of the i^{th} characteristic
β_i	=	i^{th} resource constraint
c	=	Cost
C	=	Capacity
FPC	=	Function per cost
FPP	=	Functional performance perspective
i	=	Innovation
(In, r, Is, Av)	=	Capability Parameters: Integrity, Rate, Isolation, Availability
I(t)	=	Innovation input function
MPP	=	Market performance perspective
MoS	=	Minute of service
O(t)	=	Innovation output function
P	=	Price
PPP	=	Price per performance
$Q_{P/F}$	=	Quality (subscript P = performance, F = functional)
t	=	time
T	=	Design life
TFP	=	Technology functional perspective
T_{useful}	=	Useful life
TP	=	Technological progress
W	=	Power
X_i	=	Quantitative level of the i^{th} functional characteristic
Y_i	=	Quantitative level of the i^{th} performance characteristic

* Graduate Research Assistant, Department of Aeronautics and Astronautics and Engineering Systems Division, 77 Massachusetts Ave. Building 17-110, zszajnfa@mit.edu. Student Member AIAA.
† Assistant Professor of Aeronautics and Astronautics and Engineering Systems. Associate Fellow AIAA.

1 Introduction

SPACE systems are typically sophisticated, technologically complex, and expensive, with long development times and small production runs. They are designed to the specifications of a particular customer, whose needs often exceed the current technological state-of-the-art. Despite this implicit requirement to innovate, it is debatable to what degree traditional space agencies and companies are achieving this goal. The industry has come to accept exorbitant price tags as a necessity in the quest for rapid advances in space system functionality, but do these advances necessarily constitute innovation?

Part of the problem is a lack of consensus on what innovation actually is. While the term is broadly used across multiple disciplines to represent a critical element of success, "innovation remains a frustratingly fuzzy notion.[1]" Until the concept of innovation has been formalized as a concrete implementable metric, any discussion of the subject will remain abstract. This can lead to a downplaying of known problems. Unless there is an agreed to metric that can be meaningfully measured across multiple programs in history, there is no way to evaluate the innovativeness of space systems.

The overall goal of this research is thus to begin an important discussion on innovation in the space sector. To accomplish this, the paper addresses three aspects of the task of innovation measurement. First, it surveys several distinct literatures to establish precedence for defining a spacecraft innovation metric. Second, it elucidates and treats the trade-offs associated with defining such an innovation metric in the context of communication satellites; proposing both idealized metrics and next-best estimators given the reality of incomplete historical data. Third, based on these proxies, it implements and compares the proposed metrics. Finally, this paper examines how these results can be used to form the basis for an exploration of the fundamental dynamics of innovation in the space sector.

2 Definitions, Trends and Metrics

Innovation in the context of spacecraft has not been the subject of much scholarly work, though the concept of innovation is widely studied in other domains. This section summarizes the key insights from the broader innovation literature so that they may be incorporated into the present work on spacecraft.

2.1 Defining Spacecraft Innovation

The term innovation means many things to many people, and the definition of spacecraft innovation is less clear still. This section begins by surveying existing definitions of technological innovation and posits a new one in the context of spacecraft (the focus of this paper). The goal of this discussion is not merely to arrive at a synthesized definition of spacecraft innovation but to define an operational framework through which multiple, diverse satellite programs can be compared across history.

While both the process of innovation and the act of innovating are generally considered positive, the consistency in conception ends there. Explicit definitions of innovation tend to be either:

- so broad as to be all encompassing (*e.g.*, the Oslo Manual[2] and Community Innovation Survey[3] define technological innovations as comprising "*implemented technologically new products and processes and significant technological improvements in products and processes*")
- negatively constructed in such a way that while it may be clear what innovation is not, there remains considerable ambiguity as to what innovation actually is (*e.g.,* the Oxford Innovation Handbook[4] presents the synthesized definition that innovation is not invention; nor is it improvement, creativity or diffusion, although the concepts are closely related. Where invention is the first occurrence of a new product, process or idea, innovation requires that some novelty be carried out in practice.)
- or emphasize a differentiation between types or phases of innovation (*e.g.,* radical vs incremental[5, 6] vs modular and architectural[7], process vs product[8], fluid vs transitional vs specific phases[9], lead user innovation[10], etc…)

One common notion among these three classes of definitions is that innovation is a process and thus can neither be observed nor measured through a static lens.[11] In fact, most important innovations are in reality the sum of multiple interrelated inventions and improvements that have been integrated into a commercialized product over time.[12] Another common theme is that a new idea or capability becomes an innovation once someone is willing to pay for it; "new" has no value unless people want it.

These two core concepts can be combined broadly to define spacecraft innovation as: a measure of how performance outcome (as defined by the user), normalized by resource constraints (as experienced by the producer), changes over time. This can equivalently involve: a) generating a wholly new capability; or b) reducing the resources required to achieve an existing capability (e.g., making the system cheaper or lighter). Formally:

$$i = \frac{d}{dt}\left[\frac{O(t)}{I(t)}\right] \qquad (1)$$

While the definition captured in Eq. (1) is still quite general, it can be tailored to specific technology contexts and provides an operational framework for innovation analysis. In addition, by treating the innovation process as a black box, it allows the indefinable details of incremental change to be circumvented. In this way, multiple, historically and architecturally diverse satellite programs can be compared directly, by carefully defining system level inputs and outputs that can defensibly be measured over time[13]. The selection of these inputs and outputs is relatively straightforward once the system boundary has been clearly defined; yet, defining that boundary is non-trivial and depends on two questions:

1) Where is the line between *buyers* and *sellers* of "the product" drawn?
2) What constitutes "the product?"

While a single answer to these questions may seem intuitively obvious at first, multiple, equally legitimate and instructive boundaries can be drawn in both the dimensions of market and product scope. The remainder of this paper seeks to flesh-out the implementation of Eq. (1) for the specific case of communication satellites.

2.2 Alternative Innovation Metrics along the Market Dimension

Although no precedence was found for explicitly measuring satellite innovation, quantitative techniques for measuring and forecasting technological progress have been the subject of significant previous investigation (see Ref. [14] for a recent review paper). The range of technological studies that have been conducted can be categorized in terms of where they fall along the market dimension; specifically, those taking a technology functional perspective, market performance perspective, or the hybrid functional performance perspective. This section summarizes the key insights from each of the three categories. In the below discussion, measures of quality (Q) map directly to the innovation output defined in Eq. (1)

2.2.1 Technology Functional Perspective (TFP)

The functional perspective is the most traditional of the approaches to measuring technology change. It involves determining a metric which characterizes the technological artifact under study, so that the evolution of said metric can be studied empirically. In the forecasting context, an equation is then fit so as to best describe, and predict, the technological progress.[15] It is commonly held that the technological state of the art (SOA), is best represented by a tradeoff surface describing the intersection among multiple functional capabilities per Eq. (2). [14]

$$Q_F = \sum_{i=1}^{n} \left(\frac{X_i}{a_i}\right)^n \tag{2}$$

The concept here is that innovation happens in the design space, as particular technologies are improved over time, but is experienced in the use space, as those technology improvements combine to produce system performance. The existence and evolution of trade-off surfaces has been demonstrated mathematically in several empirical technology studies.[16, 17] This approach has proven useful for predicting the direction of near-term technology change; however, because of the detailed technical knowledge required for each system under study and the mathematical complexity associated with fitting multi-dimensional expansion surfaces, the insights tend not to be generalizable.[15]

2.2.2 Market Performance Perspective (MPP)

The market performance perspective takes an economic view of innovation. The idea is that the complexity of design interactions can be circumvented if attention is limited to changes that impact the market value of the product.[13, 18] In fact, in competitive markets for commodity products, hedonic regression can be used to infer efficiency improvements from observed price fluctuations.[19] Specifically, it is assumed that changes in quality will be reflected by changes in price. Therefore, the relative importance of each characteristic ai can be estimated by the regression shown in Eq. (3).

$$\begin{aligned} P &= a_0 + \sum_{i=1}^{n} a_i Y_i + U_i \\ Q_P &= \sum a_i Y_i \end{aligned} \tag{3}$$

Hedonic prices have also been equivalently used to measure coefficients in the functional domain (Xis replace Yis and costs become the response variable instead of price).[19] This concept was applied to measure communication satellite innovation in a previous study,[20] the results of which will be discussed in more detail later in the paper. The main advantage of this market-level approach is that it is more robust to architectural changes since users are blind to the particular technical instantiation of a system as long as it fulfills their needs.[20] Though, because of this level of abstraction from the technological solution, this approach is less able to provide insights into the nature of the change.

2.2.3 Functional Performance Perspective (FPP)

The functional performance perspective strikes a balance between the two extremes, seeking to measure progress in terms of the system's "essential function". It is a functional metric in that the measure is tied to the system's technical capabilities, not its market value; while at the same time a performance metric in that it focuses on what the system does, rather than how it does it. For example, Ref. [15] uses the broad functional categories of storage, transformation and transportation to study the time dependence of information technologies. The empirical example of how the quantity of data stored (O(t)) per cubic centimeter (I(t)) has increased along a single exponential trajectory, despite transitions from hand-writing on paper, through magnetic discs to optical drives, is used to illustrate the point. The functional performance perspective purports to yield insights into the structure of technology change, without being tied to particular technological artifacts.

2.3 Quantifying Spacecraft Inputs and Outputs at Different Product Levels

In the context of space systems, approaches to quantitatively comparing the values of alternative spacecraft architectures have been of central interest in the domain of tradespace exploration (see Ref. [21] for a review of the major activities). While this literature does not address the question of how to measure spacecraft innovation directly, it does tackle a similar task of quantifying constraints (i.e., inputs) and benefits (i.e., outputs) for various types of space systems. However, because of the system-of-systems nature of most space systems, not all inputs and outputs are measured at the same product level (i.e., the output of a satellite is different from the output of the constellation of satellites), something that is particularly important to consider when combining inputs and outputs to measure innovation. This section begins by summarizes the precedence for quantifying spacecraft systems inputs and outputs separately. Then it addresses the implications of the different product levels for combining inputs and outputs to measure spacecraft innovation.

2.3.1 Measures of Innovation Output

Taking a simplified functional perspective, spacecraft mass is often used as a crude measure of capability since larger satellites tend to be more complex and more functional. A more sophisticated measure of innovation output is embodied by the Generalized Information Network Analysis (GINA)[22] methodology. It is conceptually closest to the market performance perspective, though it incorporates aspects of all three approaches. The methodology's core contribution was the observation that multiple classes of earth orbiting satellites are in essence information transfer networks. Specifically, Shaw proposed that enterprise level "quality-of-service" (QP) can be characterized in terms of four quality parameters: 1) isolation; 2) rate; 3) integrity; and 4) availability. Specifically:

$$Q_P = f\,(Is, r, In, Av) \tag{4}$$

Abstracting system functionality in this way has been shown to allow the conceptual designs for thousands of competing communication satellite constellation architectures to be compared directly.[23] Although the definition is clearly linked to technical functionality, the abstraction is in terms of value delivered to the user. For example, in the case of communication satellites, Shaw argues that a suitable metric might be the number of billable voice-circuit minutes, which clearly takes an economic impact perspective.

However, focusing solely on the information transfer aspect of Eq. (4), the concept is quite similar to that proposed in ref [15]. The performance of the information transfer network is based on the link's usability over some fixed duration, in this case, capacity over useful life. A simplified version of Eq. (5) can be expressed as:

$$Q_P = C \times T_{userful} \tag{5}$$

As with other functional performance metrics, Eq. (5) is sufficiently abstract to compare architecturally diverse communication satellites, but is still tied to technological progress.

More recently, Multi-Attribute Tradespace Exploration (MATE)[24] has extended the concept of abstracting design differences along the dimension of user-centric performance, to compare a wider range of satellite architectures (see for example application to space-based radar[25, 26]). Where the GINA abstraction contends that increases in functionality only improve satellite performance in so far as they improve information transfer (focusing at the enterprise level), MATE leverages insights from multi-attribute utility theory (MAUT)[27] to integrate multiple "essential" performance attributes, similar to the technology function perspective (typically focusing at the spacecraft level). It uses a quality function deployment (QFD) matrix to relate design parameters to performance attributes, simplifying the numerical analysis required to find SOA trade-off surfaces by relying on the experience of the designer. Technical parameters (specified in the functional domain) enumerate the rows, and user attributes (specified in the performance domain) head the columns. The impact of each parameter on each attribute is then specified. In this way, the performance gain associated with changes in functionality can be examined directly.[28]

2.3.2 Measures of Innovation Input

In engineering design, cost is the traditional measure of input constraints. While monetary constraints are certainly critical, and it can be argued that all other constraints could be converted to cost impacts anyway, there may be times when the consideration of other constraints is appropriate and necessary. This depends on how the system boundary is drawn along the product dimension. For example, measurements of lifetime costs, which include ground systems, the complete on-orbit constellation, operating and launch costs, capture a complete monetary constraint. Yet, when examining historical trends as will be done in this paper, it may not be possible to consider the entire system. In that case, care will need to be taken to include non-monetary constraints as appropriate. For example, launch services, in addition to representing a significant upfront cost, play an important role in the topological definition of on orbit assets in the satellite system network. The choice of launcher will constrain available mass and volume, impacting system design, leading to important implications for cost baselines (see ref [29] for an evaluation of cost impacts on launch choices). If the cost of launch choices is included as an input to the innovation metric, then constraint parameters like mass and volume are internalized as intermediary details. But, if product scope does not include the choice of launch vehicle these constraints must be accounted for in some other way. This could be accomplished as suggested in Eq. (6):

$$I(t) = c_{Lifetime} = f(c_{Satellite}, Launch_{constraints}, Ops_{constraints}) \tag{6}$$

In Eq. (6), the constraint imposed by the launcher could be captured by the launch mass; the implicit assumption being that some launch trade-off decision has already been made and the result constrains the design primarily through mass restrictions. Similarly, decisions about ground stations and operations can be internalized through appropriate definition of the input and output. For example, a satellite designed to communicate via a maritime receiver would require more power and beam precision, for the same quality of data link, as a lesser satellite communicating with a land-based receiver. In this case, only including the satellite side of the communication link in the performance will give a crude accounting for ground trades.

2.3.3 The Challenge of Integration Input and Output Measures as a Consistent Metric (I/O)

Measures of input and output have been commonly integrated through metrics like cost per function (e.g., Ref. [22]). Cost per function is nominally a measure of the level of innovation per Eq. (1), since cost is a suitable I(t) and number of satisfied users is a user-domain measure of O(t). However, it cuts across the performance-function split defined in section 2.0. Following ref [30], while related, cost and price are measured from different points of view. Cost is a measure used in the design space and is calculated as a role-up of constituent subsystem costs. Price, on the other hand, is observed in the user space and is a measure of the customer's willingness to pay for a set of performance attributes. Thus, if a performance metric, like "number of satisfied users," sits in the user space, then it should be normalized by price (the monetary user space constraint) rather than cost. In addition to matching the performance and functional perspectives, the level of product must also align. In the above example, since "number of satisfied users" is a satellite service output, the relevant price should also be a price for service (and not, for example, the price paid to launch a single satellite). Section 3 examines the dimensions of market and product, in combination, to define useful input-output measurement paradigms.

3 Developing a Communication Satellite Innovation Metric

As described above, there are multiple ways to define the innovation inputs and outputs required to implement Eq. (1). Metrics that split along the market dimension, from those focusing on the structure of the technological knowledge, to those considering only the impact of changes in the market, were described. Yet, when the precedence for spacecraft metrics was explored, it became apparent that a second dimension, to capture the levels of product scope, was needed as well. This section defines three boundary paradigms, within the market-product space, that make sense for communication satellites. Initially it defines an idealized innovation metric for each without regard for data availability issues. Then it revisits the metrics with consideration of implementation realities.

3.1 Idealized Metric Development

Setting aside the constraints associated with collecting historical satellite data for a moment, the spectrum of potential communication satellite input-output boundary definitions are illustrated in Fig. 1abc. While the enterprise level goal of communication satellite development is to deliver service to the user, multiple transactions occur along the path to delivering that service, each with a definable and potentially boundable input and output. Thus, if innovation measures change in input and output over time, as long as one is careful about the boundary definition (and completeness of the cut), innovation can be "tracked" at any level. The sections that follow define three potential communication satellite boundary definitions and their corresponding inputs and outputs.

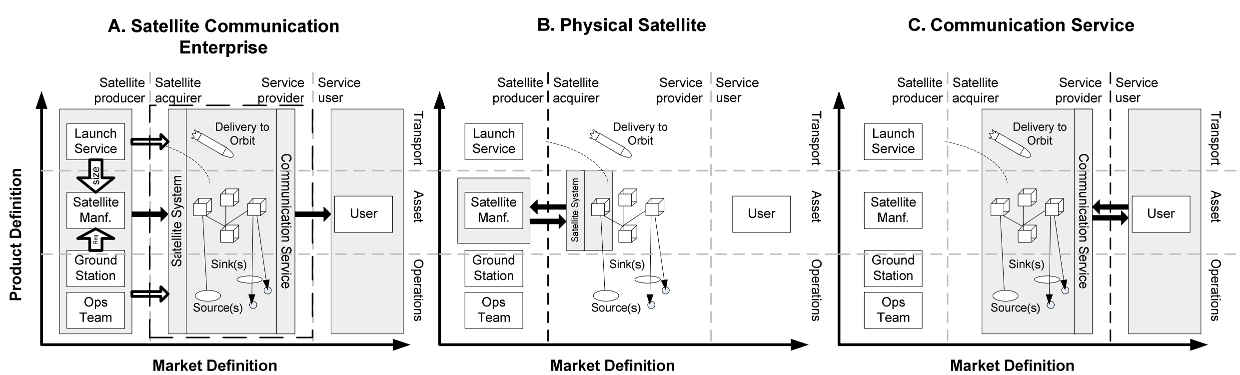

Fig. 1 Range of Communication Satellite System Boundary Definitions

1. Satellite Communication Enterprise

The first definition of system boundary – the satellite communication enterprise – considers the satellite acquirer to be both buyer (of the physical system) and seller (of the communication service) simultaneously, as shown in Fig. 1a. Following the GINA abstraction described above, the key insight here is that the physical satellite has value to its buyer only in so far as it provides the information transfer service desired by the end user. The relevant measure of output is then captured by Eq. (5) specified above:

$$O(t) = Q_P = C \times T_{userful} \quad (7a)$$

where capacity should be a measure of billable voice circuits (or equivalent) and life is a measure of the satellite's useful life. As a buyer of the physical system, the corresponding input measure is the price paid for the physical system. However, since the physical satellite is being acquired as part of a larger enterprise, other constraints imposed by the overall architecture should be incorporated as inputs as well:

$$I(t) = f(P_{Sat}, \beta_1, \ldots, \beta_N) \quad (7b)$$

3.1.1 Physical Satellite

The second definition of system boundary – the physical satellite – considers the transaction between the satellite manufacturer and acquiring enterprise as shown in Fig. 1b. Taking the perspective of the satellite manufacturer, it is appropriate to measure inputs and outputs in the design space. Then, innovation can be observed as changes in the cost to produce a normalized level of functionality. The relevant measure of output is then captured as a trade-off surface in subsystem functions:

$$O(t) = Q_F = f(a_1, \ldots, a_n, X_1, \ldots, X_n) \quad (8a)$$

And the input is simply a measure of the cost to produce that functionality:

$$I(t) = c_{sat} \quad (8b)$$

3.1.2 Communication Service

The third definition of system boundary – the communication service – considers the transaction between the system user and satellite service providers, as shown in Fig. 1c. The user, in this case an individual or group requiring the ability to communicate information from one point to another, inputs money (in the form of a fee for service) in return for the output of service (some quantity of communication minutes at an acceptable quality level). In this case, the nature of the system that makes this communication possible is irrelevant to the user, except in so far as it detracts from the communication. Framed this way, the GINA abstraction is directly applicable and innovation can be observed as changes in the price to receive some nominal level of service. Specifically, the input and output to Eq. (1) are thus:

$$O(t) = Q_P = f\,(Is, r, In, Av) \quad (9a)$$

$$I(t) = P_{service} \quad (9b)$$

3.2 Practical Proxies Given Empirical Constraints

For innovation trends to have value for analysts and decision makers, they must be based on empirical measures of historical programs. In the preceding section, data issues were alluded to, but the emphasis was on conceptual challenges to measuring innovation. Now, consideration must be given to the realities of working with historical data. In this section, data collection issues for historical satellite programs are discussed, and next best parameter equivalents (i.e., proxies) are proposed. The discussion is split into input and output data constraints, and closes by addressing time measurement.

3.2.1 Input Data Issues: Historical Costs and Prices

Conceptually, the cost element of trending innovation is straightforward: discount all costs to some baseline time and compare them directly. In this paper, all monetary figures are reported in millions of 2005 USD, adjusted using the NASA deflator as published on the "NASA Cost Estimating Website‡". It is the practical aspect of collecting historical cost data that is difficult. Cost data, the money spent to produce the spacecraft, is typically restricted due to its proprietary nature. Although certain government contracts require the disclosure of cost data, the sample size is quite small and does not provide a sufficiently large cross-section to abstract industry trends.

In the absence of true cost data, there are two candidate proxies: cost models and historical price data. While there are a number of relatively mature cost estimating tools currently available (see for example, the NASA Advanced Missions Cost Model (AMCM)), they are not suitable as a proxy for empirical past costs. The models are designed to aid engineering managers in predicting future program costs, based on key design parameters and assumptions regarding typical rates of progress in the industry. Thus, their outputs effectively "beg the question" with respect to empirically measuring innovation. Nonetheless, analysis of AMCM predictions can provide valuable insight into NASA's assumptions concerning the rate of technological progress in the space sector.

Historical price data, the money spent to purchase a finished spacecraft, like cost data, is quite difficult to collect. While some price data, at least for government contracts, are in principle publicly available, there is no formal centralized record system, making complete data sets difficult to come by. Fortunately, the results of 40 years worth of collection effort are housed in the Communication Satellite Database (CSD), published yearly by TelAstra Inc[31]. The CSD's primary sources of data are publications in the open literature, supplemented by informal interviews and engineering common knowledge. It is the most comprehensive collection of satellite price data that the authors could find, containing data on hundreds of satellites launched since 1965. While this data set is

‡The downloadable Excel file is based on OMB data collected in 2003

sufficiently large to provide insight into industry trends, the question remains whether price is an appropriate proxy for cost.

There is a fundamental difference between the meanings of cost and price. Cost is a measure of the aggregate costs of developing and manufacturing the constituent parts, where price is a reflection of the market's willingness to pay for the functional capabilities of the product. Specifically:

$$\begin{aligned} c &= \sum cpf_i \\ P &= f(a_1,...,a_n,Y_1,...,Y_n) \\ P &\propto c \end{aligned} \tag{10}$$

In a "normal" competitive market, the relationship between these two quantities can be extremely non-linear; however, the market for satellites is not perfectly competitive on the buy side. In fact, there is typically only one buyer with a pre-specified willingness to pay for any given satellite. Combined with strict acquisition regulations for government purchaes, a nominally proportionate relationship between satellite cost and price emerges as shown in Eq. (10). Thus, in this context, price could be an appropriate proxy for cost.

$$c \cong P \approx P_{contract} \tag{11}$$

It is worth clarifying that the above discussion is concerned only with satellite costs and prices. The distinction has little relevance for service prices. For the communication service paradigm, price paid by the user for a minute of service (MoS) is the relevant monetary metric and could be collected as a historical record of prices charged by service providers at different points in history. This data is not contained in the CSD referenced above.

3.2.2 Output Data Issues: Proxies for Functionality and Performance

Where historical costs are difficult to collect at all, some level of technical data is generally available. The trouble is getting enough of the right data to estimate each of the metrics defined in section 3. This is particularly challenging in the performance domain because published specifications tend to list technical parameters relevant to designers, rather than service attributes relevant to end users. While the technical parameter data are suitable for the calculation of function as needed for the Physical Satellite analysis, data from which performance attributes can be derived are needed for both the Communication Service and Communication Satellite Enterprise analyses.

The CSD contains technical data, including satellite mass, power, design life for most programs, and number of transponders, transmission frequency (e.g., C, Ku, Ka), and Effective Isotropic Radiated Power (EIRP) for some.

Thus a functional trade-off surface could be calculated as proposed in Eq. (2) to implement Eq. (9a); but, since trade-off surfaces are extremely difficult to derive, and none currently exists for communication satellites, following Ref.[14], a weighted, linear combination of sub functions will be assumed. Specifically:

$$Q_F = \sum_{i=1}^{n} a_i X_i \tag{12}$$

The CSD does not contain any parameters from which capacity can be derived directly. Since capacity is critical to the measure of both the performance metrics specified in Eqs (8a, 10a), for the richness of the price information in the database data to be harnessed, an understanding of the relationship between the subsystem functional parameters contained in the database and the key system level performance attribute of capacity must be established. This task is accomplished using a small subset of Intelsat technical details, for the period 1965-1995[32], for which capacity data was available. In effect, a parameter is sought that closely mirrors the capacity trend over time.

Fig. 2 shows how each candidate parameter compares to capacity. It can be seen that while none of these functional parameters alone captures the capacity trend in more recent years, power tracks capacity most closely and for the longest time. Although this statement is not rigorous in a statistical sense, given the limited data, such an analysis would be inappropriate. The candidate parameter trends and their appropriateness as estimators of capacity can, nevertheless, be explained and justified in engineering terms when viewed in the context of historical satellite development. In Fig. 2, it can be seen that both mass and power track the capacity trend initially. However, where the mass trend has remained relatively constant over time,§ both the power and capacity increase significantly after 1975. Power continues to track capacity until 1985 when capacity shows a second steep increase. These two points of divergence correspond to important architectural changes.

In general terms, the functional capability of a communication satellite can be improved either by 1) increasing the transmit power, or 2) by using the available power more efficiently. With regard to the first point of divergence, early communication satellites were spin stabilized and as a result possessed a limited de-spun area upon which to mount directionally sensitive equipment (e.g., solar panels, antennas). This meant that communication power (and by implication capacity) was effectively limited in proportion to satellite mass. With the advent of 3-axis stabilization, this relationship was fundamentally changed; large solar panels could now be deployed thereby

§ This is not surprising since the engineering cost estimating community views mass as a rule-of-thumb estimator of cost.

significantly increasing the attainable transmit power for a satellite of a given mass. In the Intelsat series (shown in Fig. 2) the switch from spin to 3-axis stabilization occurred between Intelsat IV-A (1975) and Intelsat V (1980);[32] the point of divergence between the mass and power trends. Second, the divergence of capacity from power after 1985 can be understood in terms of more efficient use of bandwidth; Intelsat VII was the first of the series to employ frequency re-use techniques.[32]

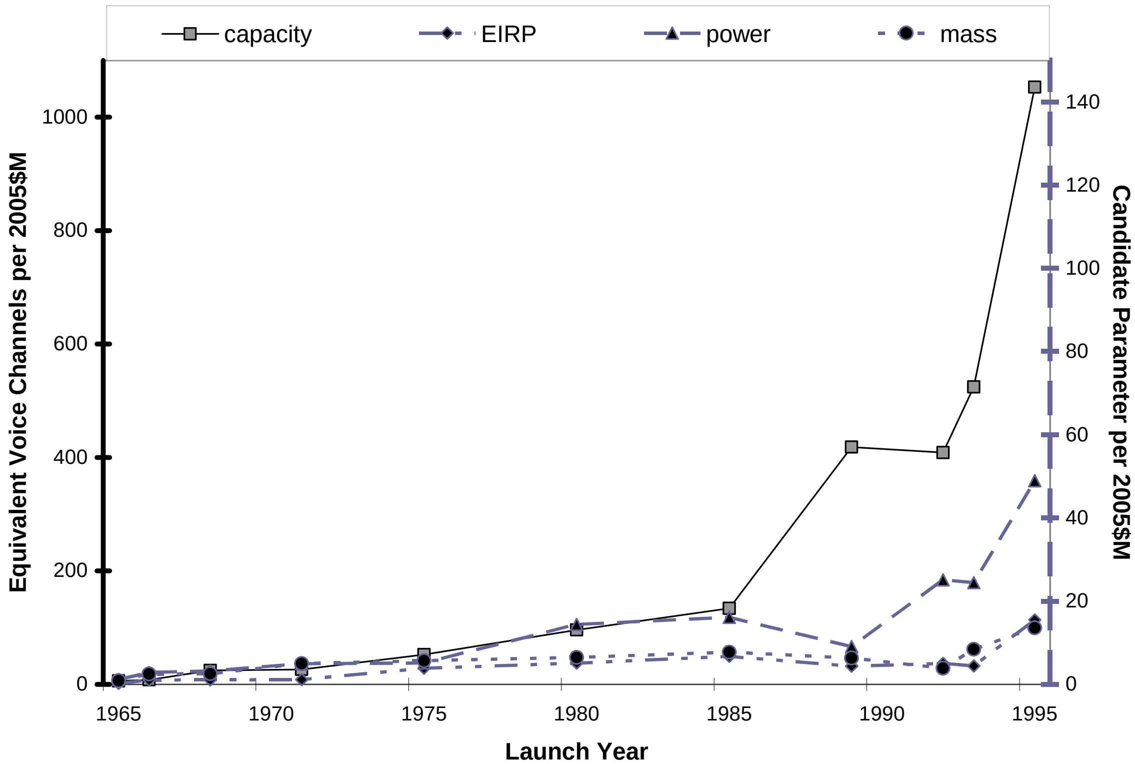

Fig. 2 Comparison of Functional Parameters to Capacity Time Trend

Thus, it is to be expected that as onboard processing becomes increasingly sophisticated and the relative importance of available power decreases, the gap between satellite power and capacity will increase. Nonetheless, available power remains a highest-lower-bound estimator of satellite capacity and the best of the available CSD parameters. There is certainly room for improvement with more compete technical data. But, in the absence of a large set of satellite capacity data, the proxy:

$$C \sim W_{Sat} \tag{13}$$

is proposed as a highest-lower-bound estimator. While the power metric cannot capture advances in the domain of beam re-use and power efficiency, it does provide a useful basis upon which to compare the capability level of architecturally different communication satellites.

3.2.3 The Dimension of Time

In the above discussion, the dimension of time has only been treated implicitly. Time is the dimension along which innovation is observable; in order to measure a difference, the normalized level of capability must be attached to a specific time in history. Is it therefore more appropriate to consider the contract award date, the launch date or the projected end of life? If the intervals between these project milestones were relatively constant, the choice wouldn't matter. But they are not, and the relative planned differences have design and cost implications. In order to standardize measurements, contract award date was chosen as the fixture for capability in history since the technology state-of-the-art is effectively frozen at that point in the design life. Design life will be used as the measure of longevity since actual operational life is an infeasible measure when many of the satellites under study have not yet been decommissioned.

$$T_{Userful} \sim T \quad (14)$$

3.3 Summary of Practical Proxies to the Conceptual Measurement Approaches

In section 3.3.1, three boundary paradigms were identified: the communication satellite enterprise, the physical satellite and the communication service. The conceptual trade-offs involved in their measurement were discussed and the measurement approaches they imply developed conceptually. In section 3.3.2, the practical constraints to measurement, imposed primarily by data availability, were discussed and proxy estimators were proposed; final details of the implementation will be worked out in the sections that follow. As shown in

Table 1, each of the product boundary paradigms is amenable to a different type of metric as defined in section 2. The communication satellite enterprise paradigm takes a functional performance perspective (FPP) to specify a performance per price (PPP) metric. The physical satellite paradigm takes a technology functional perspective (TFP) to specify a function per cost (FPC) metric. Finally, the communication service paradigm takes a market performance perspective (MPP) to specify a performance per price (PPP) metric.

Table 1 Summary of Communication Satellite O(t)/I(*t*) Metrics

Product Boundary	Ideal	Proxy
Communication Satellite Enterprise (FPP-PPP)	$C \times T_{Useful} / f(P_{Sat}, \beta_1, \ldots, \beta_N)$	$W_{Sat} \times T / P_{contract}$
Physical Satellite (TFP-FPC)	$f(a_1, \ldots, a_n, X_1, \ldots, X_n)/c_{sat}$	$\sum a_i X_i / P_{contract}$
Communication Service (MPP-PPP)	$f(Is, r, In, Av) / P_{service}$	$MoS / P_{service}$

4 Implementing the Metrics

The conceptual (section 3.3.1) and practical (section 3.3.2) challenges associated with measuring innovation having been addressed, this section illustrates how calculations can be performed and what insights can be gained under each of the three boundary paradigms summarized in Table 1; namely, the communication satellite enterprise, the physical satellite and the communication service. In all cases, the analysis is generated from data on 350 satellite programs spanning 42 years from 1964 to 2006 and compared to previous analysis where available. The 350 communication programs represent the maximum useable set of data in the Communications Satellite Database** (CSD). Programs were filtered based on completeness of data; specifically, data on contract award year, end of life power, operating life, dry mass and contract award price were required. In cases where multiple satellites were purchased under a single contract, the award price was simply divided by the number of satellites. Although this relatively crude approximation does not account for any economies of scale, particularly with respect to the upfront development cost associated with a new design, it is sufficient for our purposes††.

4.1 Communication Satellite Enterprise

Substituting the proxy metric proposed in Table 1 into Eq. (1), innovation in the communication satellite enterprise paradigm can be represented as:

$$i = \frac{d}{dt}\left[\frac{O(t)}{I(t)}\right] = \frac{d}{dt}\left[\frac{W_{sat} \times T}{P_{contract}}\right] \tag{15}$$

** For a list of the subset of CSD satellites used, please contact the authors directly.
†† The analysis in ref. [30] suggests that returns to scale are insignificant in this industry

Fig. 3 shows the trend that results, both as a moving average and a regression line, when the ratio in Eq. (15) is applied to the CSD data set and plotted over time. The y-axis has units of watt-years per million dollars. It should not be inferred that these are the units of innovation. Innovation, as it has been defined in this paper, is a heuristic that has meaning in a relative sense. Given that the trend of watt-years per million dollars has increased over time, the positive trend in Fig. 3 suggests that innovation is occurring in the communication satellites sector.

It is worth noting the extent of variation in the individual satellites' performance on the y axis for any given year. Also, that the spread of this variation is increasing in time. This suggests that while the average capability baseline appears to be increasing over time, other non-temporal factors impact innovation. This variation may in part be attributable to limitations of the proposed estimator, but is also likely indicative of real variations in the intended performance of various satellite programs. Further analysis is required to address this variation, but it should be apparent how the results presented in Fig. 3 create a basis for such an exploration.

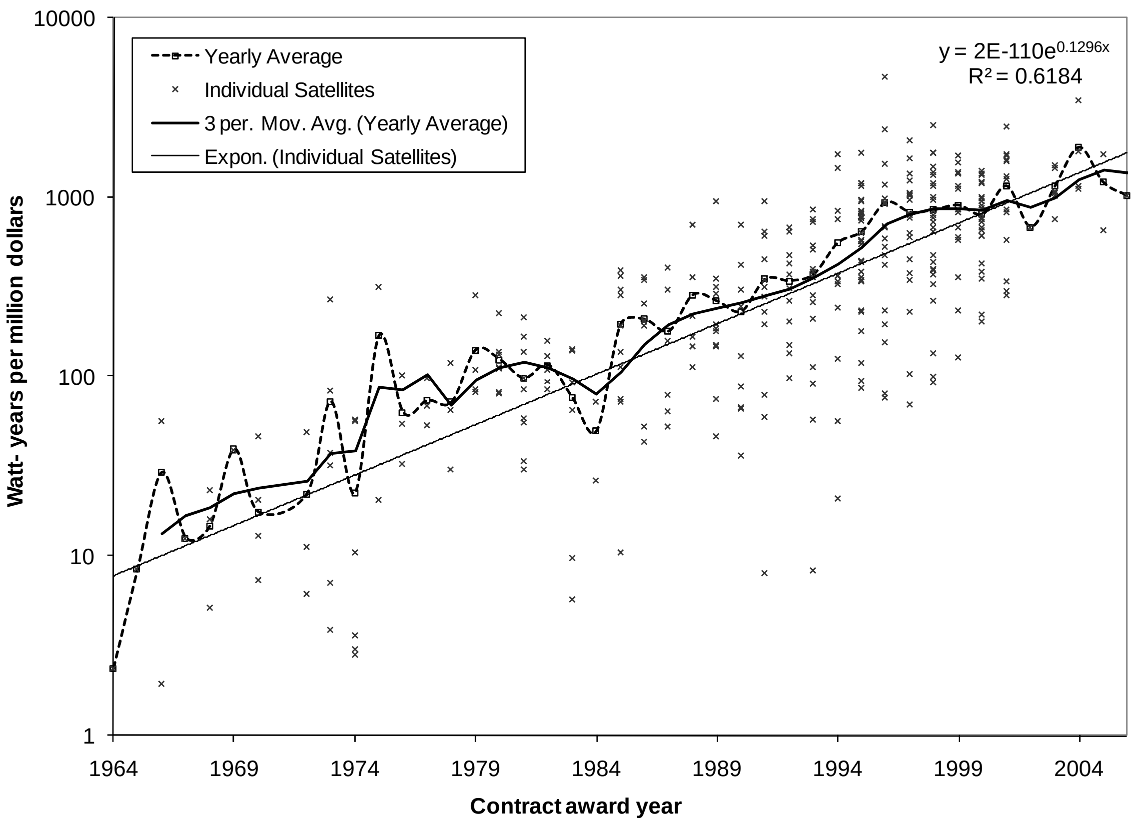

Fig. 3 Evolution of the Communication Satellite Enterprise Metric over Time

4.2 Physical Satellite

Substituting the proxy metric proposed in Table 1 into Eq. (1), innovation in the physical satellite enterprise paradigm can be represented as:

$$i = \frac{d}{dt}\left[\frac{O(t)}{I(t)}\right] = \frac{d}{dt}\left[\frac{\sum_{i}^{n} a_i X_i}{P_{contract}}\right] \tag{16}$$

In order to implement this metric with the data contained in the CSD, the weights ai in the numerator must be estimated. To do this, section 2 offers two approaches. First, following ref [19], the hedonic price method can be used as described by Eq. (3). This approach was previously employed to measure technology change in communication satellites in Ref. [20] using the 1992 version of the CSD. After fitting a communication satellite quality function per Eq. (3), the historical interval under review was segmented into equal periods so that a hedonic index of technological progress (TP) could be calculated:

$$TP_i = \frac{\Delta Q_i}{\Delta t_i} \tag{17}$$

Ref [20] found evidence of technological progress from one time period to the next. However, the hedonic price method requires the assumption of commodity product behavior. Specifically, the method assumes that changes in price are exclusively attributable to changes in useful functionality. Ref [20] argues that communication satellites can be treated as commodities because satellite acquirers specify their willingness to pay for a given functionality a priori. While this characterization ignores some important complexities associated with the manufacturer-buyer contracting relationship, without an alternative quality metric, price will be used to generate the quality function. In the current analysis, the quality function is normalized by price per Eq. (1) and the history examined continuously (as opposed to calculating a hedonic index) to facilitate comparison with Fig. 3.

A linear multiple regression of the form:

$$P = a_0 + \sum a_i X_i \tag{18}$$

was used to estimate the parameter weights. All potentially relevant parameters contained in the CSD were initially included in the regression. Table 2 shows a list of the explanatory variables found to be statistically significant. Despite high levels of statistical significance for many of the variables, the overall fit is quite poor, with an R2 of only 0.2409, indicating that other parameters not included in the regression are important in explaining satellite price (as would be expected of a non-commodity product). Fig 4 plots the evolution of the ratio specified by Eq. (16) over time, using the regression output in Table 2. The overall trend is marginally positive. But since the variation about the mean is obviously non-uniform, a better weighting function is likely needed to improve this metric. The MATE[28] approach (described in section II) could provide an alternative to the hedonic price quality proxy by weighting the importance of technical parameters according to their impact on user utility. However, this would require a representative user for all historical communication satellites to be defined.

Table 2 Results of Multiple Regression on Satellite Price

Parameter	Description	a_i	p-value
Constant	Intercept term	4456.74	0.0210
AE/O	Dummy variable, 1 if customer is based in N America or EU	22.795	0.0393
G/N	Dummy variable, 1 if customer is a government agency	54.789	0.0000
Y	Year in which initial contract was signed	-2.219	0.0233
M	Mass of satellite without fuel	0.017	0.0414
Tr	Total number of primary transponders	-0.455	0.0395
%Ka	Percentage of transponders operating in Ka-band	120.02	0.0003
X	Dummy variable, 1 if 3-axis stabilized	42.386	0.0033

End of life power (EOLP), design life, %C-band and %Ku-band were also included but found not to be significant at the 5% level. There may be issues of multicolinearity (particularly in terms of EOLP and DRYMAS) but they should not affect the regression coefficient for AWDATE.

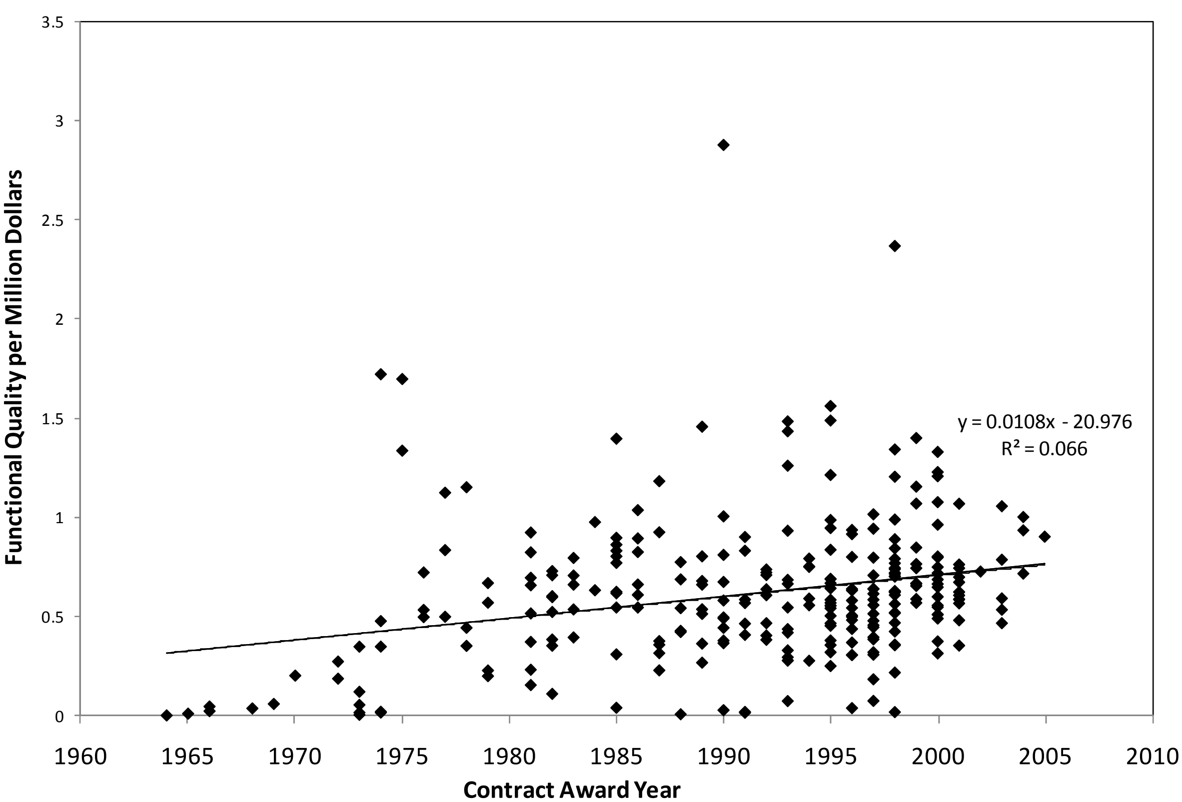

Fig 4. Evolution of the Regression-based Physical Satellite Paradigm Metric over Time

An alternative to using price to estimate the quality weights (as above) lies in the engineering rule of thumb that communication satellite mass is a proxy for functionality. This approximation can be used to simplify Eq. (16). Specifically, implementing Eq. (16) becomes an examination of how the mass per million dollars ratio has evolved over time. When this metric is applied to the CSD, the trend shown in Fig. 5 results. Fig. 5 is more similar to Fig. 3 than Fig 4, in that the increasing trend is quite clear; though, like Fig 4, the strength of the trend is quite weak. This difference may be a function of the particular proxies being used, or it may be related to the difference in paradigm. Exploring this further may be a fruitful area for future analysis.

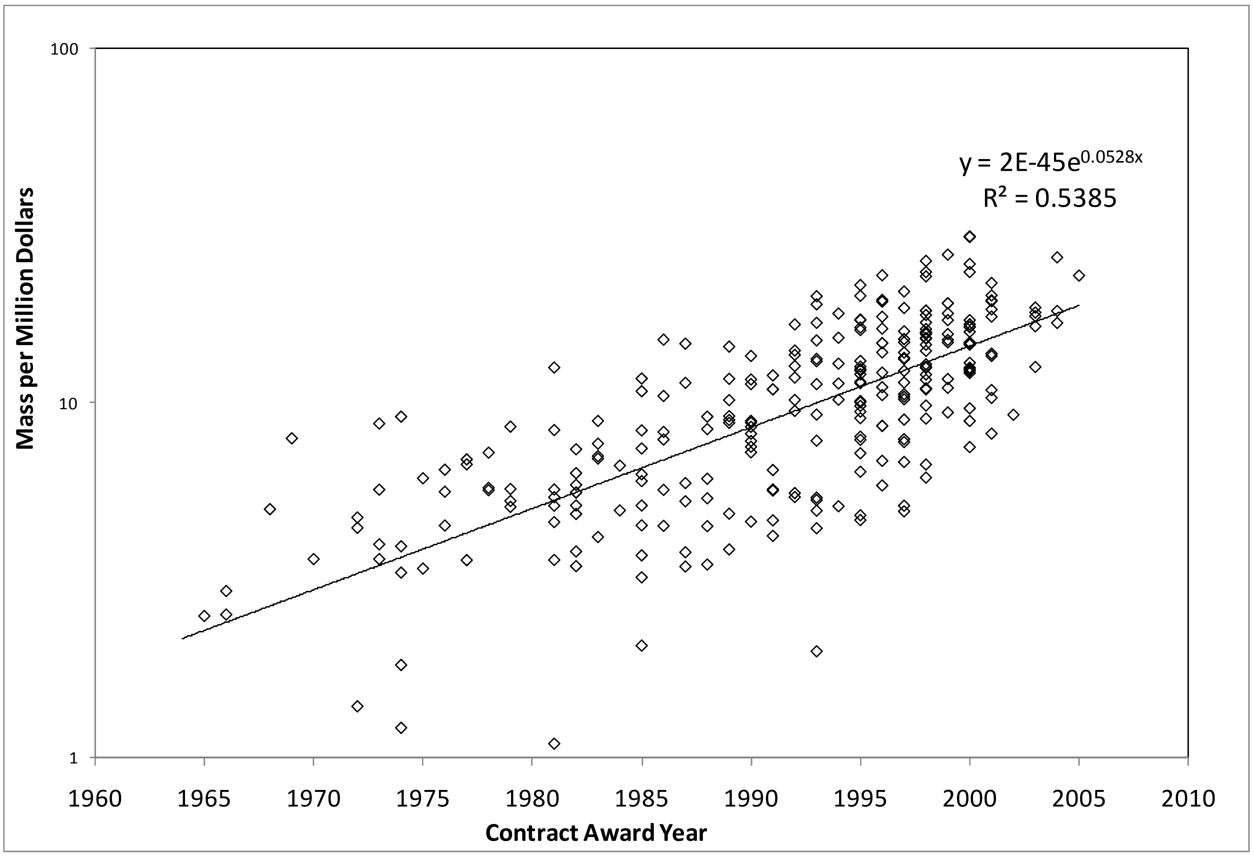

Fig. 5 Evolution of the Heuristic-based Physical Satellite Metric over Time

4.3 Communication Service

Substituting the proxy metric proposed in

Table 1 1 into Eq. (1), innovation in the communication service paradigm can be represented as:

$$i = \frac{d}{dt}\left[\frac{O(t)}{I(t)}\right] = \frac{d}{dt}\left[\frac{MoS}{P_{service}}\right] \tag{20}$$

This metric could be implemented by plotting the ratio of prices, charged by service providers, per minute of normalized service, at different points in history. The authors currently do not have a dataset suitable for such an analysis but believe it to be a worthwhile avenue for future work. In addition, since the hedonic pricing assumptions are respected in the communication service paradigm (communication service users are indifferent to where the signal comes from) a more representative quality metric could be derived using hedonic regression.

5 Comparison of the Three Approaches

The preceding sections have illustrated three approaches to conceptualizing and empirically measuring innovation for communication satellites. They are based on system boundary definitions which slice the measurement problem along the dimensions of market and product. As long as the implementations of the metrics are internally consistent, the three metrics should be equally capable of measuring communication satellite innovation. However, they yield insights into different aspects of the innovation process. Further, as a result of the significant constraint imposed by the lack of wide availability of historical data, simplifications needed to be made to the idealized conceptualizations. In section 4, these simplifications, and the nature of the available data, lead to a mapping of each paradigm to a particular implementation methodology. While the paradigms need not be linked to these methodologies in general, in the context of this paper, the integrity of each methodology is strongly connected to the strength of the results. As a result, since the goal of this paper is to lay the foundation for future analysis of the drivers of innovation in the space sector, an assessment of the methods is of central interest.

Where section 4 focused on the mechanics of implementing the metrics proposed in section 3, this section assess the utility of the results in facilitating future analysis of historical trends in communication satellite innovation. Specifically, this section asks the questions: Given limitations in data availability and our ability to conceptualize capability for various types of paradigms, which method provides the most useful basis upon which to compare historically diverse programs over time? This question has two main parts. The first queries the validity of each method's representation of point-innovation levels and the second queries the relative utility of the methods as a basis for future discussion and quantitative historical analysis.

5.1 Communication Satellite Enterprise

The communication satellite enterprise paradigm takes a functional performance perspective (FPP) to specify a performance per price (PPP) metric. As discussed above, this approach has the potential to combine the advantages of both market- and technology-based metrics. The functional performance is defined at a sufficiently abstract system level to be comparable across a wide range of architectural instantiations, while remaining sufficiently connected to the physical system to yield insights into the technological progress. Thus, further analysis of the data presented in Fig. 3 is expected to yield insights into both the structure of communication satellite technology change, but also variability in the effectiveness of non-technical (i.e., contract, market, business structure) factors.

In terms of implementation of the three approaches, the communication satellite enterprise metric is the most intuitive; it weighs outcomes versus inputs as a simple ratio. On the other hand, the method is highly contingent on the ability of a domain expert to abstract a suitable essential enterprise level function for which data is also available. This is complicated by the fact that the validity of the abstraction relates to the homogeneity of relevant user needs. As a result, what works well in the tradespace exploration paradigm may be less effective in historical innovation analysis. Tradespace explorations are typically performed to evaluate alternative architectures for a particular mission. This has the effect of reducing the decision space, as the question then becomes "Which architecture best fulfills the customer-defined objective(s)?" This make abstractions like GINA [22] and MATE [28] possible. When the goal is to compare historical missions, on the other hand, the question is quite different. While each design was presumably tailored to the objectives of its customer, those objectives may not be consistent across customers and time. Thus, instead of abstracting based on the stated objectives of the particular customer as in the tradespace exploration technique, when analyzing innovation histories, essential functions must be identified that normalizes across the objectives of multiple customers.

For the base case of communication satellites, a metric following the GINA abstraction [22] was shown to be suitable. But for more complicated spacecraft types it may not be possible to find a common essential function across a large enough sample size. For example, how do you compare an imaging satellite designed to take low-resolution, low refresh-rate images of the polar ice caps to one designed to take frequent, high-resolution images of troop movement to support military intelligence? With the different requirements for orbits, optics and pointing accuracy[33] (among other attributes) it seems like abstracting functionality to information transfer – one proposed essential function – is overly simplistic. The solution might be to reduce the set of comparison from "imaging satellites" to "high-resolution, intelligence imaging satellites" but this will result in smaller sample size and reduced generalizability. Besides the difficulty in defining a suitable performance metric, the constraint of data availability is no less significant for imaging satellites than for the case of communication satellites as discussed above.

Thus, when a suitable functional abstraction can be found and data is attainable, the satellite enterprise paradigm provides a strong basis for further analysis. However, if other, more complicated types of satellites are to be studied, this approach may not be appropriate, unless a method for abstracting user-centric performance can be developed in general.

5.2 Physical Satellite

The physical satellite paradigm takes a technical function perspective (TFP) to specify a function per cost (FPC) metric. As discussed above, this approach has the potential to generate a deep understanding of the structure of technology change in the physical system. However, in the context of communication satellites, many of the advances in system performance have been achieved through improved utilization of the system, not changes to the architecture. Since the early days of satellite communications, the general architecture has remained relatively constant: large, bent-pipe, GEO, solar-powered, multiple transponder satellites Recent exponential increases in capacity have been achieved through creative, more efficient use of the available spectrum (e.g., narrow spot beams and ground station placement).[34] These types of changes are not as observable in the physical satellite boundary paradigm.

Further, although the parametric regression employed in the physical satellite paradigm draws a strong footing in the statistics and cost estimation literature, and as a result seems familiar and intuitive, it requires strong assumptions that may not be appropriate in the communications context. First, the hedonic assumption that communication satellites behave as commodity products is arguably inappropriate. However, without another more suitable quality metric, prices were used to estimate the weights of the various technical parameters. Although this yielded potentially information rich clusters of programs, with R2s near zero, the validity of the results are suspect. Second, regression based analysis assumes a true trend and is extremely susceptible to outliers. In the case of spacecraft, many programs are outliers in that they deviate from any predictable norm, but cannot be characterized as bad data; they are simply special cases. Nonetheless, these legitimate outliers can have extremely high leverage on the overall trend.

In addition, the technological capability baseline of components used in multiple spacecraft subsystems has increased over time due to factors external to the space industry. As a result, there are problems of multicollinearity between technical parameters which are assumed to be independent. Finally, spacecraft are complex socio-technical systems whose costs and levels of innovation are determined by a multitude of parameters, some of which aren't measurable at all and many of which have not been recorded in historical datasets. This leads to low coefficients of determination and high errors. Interestingly, the simplified heuristic – that mass is a proxy for satellite functionality – yielded a much higher coefficient of determination and more homogenous trend, although not as high as in the communication satellite enterprise paradigm. The same problems of data availability (discussed in section 5.5.1) apply here; but, this method can naturally be extended to other spacecraft, assuming access to appropriate technical parameters. Therefore, the physical satellite paradigm, coupled with variations on the parametric estimation, may be the best option in cases where system level metrics per the communication satellite enterprise paradigm can't be defined and the structure of technology change is of primary interest.

5.3 Communication Service

Given the challenges of collecting cost and service quality data in the space sector, the prospect of inferring innovation from commodity price fluctuations is extremely exciting. Since communication services derived from satellites can be viewed as a commodity, many established analysis techniques become available. In addition, by defining the service as the product, the difficulties associated with defining a user centric performance metric are circumvented; in this case, the service contract makes clear what the user believes they are paying for. At this point, historical service price data has not been made widely available for the communication satellite market, though it is believed to exist and is an important area of future work. However, it is worth pointing out that as a market performance perspective (MPP) on a performance per price (PPP) metric, limited information about the structure of the technology change can be inferred. This approach will be most useful in comparing the satellite paradigm to other methods of delivering communication service and assessing the extent to which satellites can represent a disruptive platform for future information transfer in the commercial market.

6 Summary

This paper set out to frame a discussion of innovation in the space and defense sector. To accomplish this, it addressed three aspects of the task of measurement. First, it surveyed several distinct literatures to establish precedence for defining a spacecraft innovation metric. In this way, a guiding principle was established; that innovations must be a) both novel and useful and b) can only be observed as change over time. This led to the definition of spacecraft innovation as: a measure of how performance outcome (as defined by the user), normalized by resource constraints (as experienced by the producer), changes over time. This can equivalently involve: a) generating a wholly new capability; or b) reducing the resources required to achieve an existing capability (e.g., making the system cheaper or lighter).

Next, the conceptual trade-offs associated with adopting this principle in the context of communication satellites were elucidated and treated. By defining product boundaries along the dimensions of product scope and market transactions, three paradigms for measurement were proposed; namely, 1) the communication satellite enterprise; 2) the physical satellite; and 3) communication service. Finally, under the constraints of historical data collection realities, next-best estimators were put forward as proxies for the parameters required to implement the proposed metrics. Based on these proxies, the relative merits of each measurement paradigm were illustrated through sample analyses.

The three boundary paradigms presented herein each strove to represent the level of innovation of a diverse set of communication satellite programs developed over the last 50 years. The analysis suggests that innovation is occurring in communications satellites. That innovation is occurring, in and of itself, is not surprising; one would hope that some level of innovation is occurring in an industry whose very mandate is to push boundaries. What is more interesting (and particularly apparent in the communication satellite service paradigm), is the extreme variations of individual program performance around the industry mean, suggesting that other important factors are at play.

Since the overarching goal of this work is to improve the spacecraft innovation process, based on an increased understanding of what drives innovation in the industry, it is this variation that must be explained. It is in explaining this variation where future work should be focused. While some of the variation may be attributable to the limitations of the empirical metric, it is believed that important insight can be gained from patterns in the residuals. Even with the quality of data as it is, if analyzed through a contextual historical and political lens, and by building on hypotheses derived from the innovation process literature, we believe that this data will yield significant explanatory value. The core value of this work is thus to lay a foundation upon which an understanding of the dynamics of innovation in this sector can be developed. This can only be accomplished analytically once an agreed to metric has been established. It is hoped that whether or not one of the three metrics for measuring space sector innovation presented herein is adopted in its current form, some consensus will be reached and the necessary analysis performed.

References

[1] "Innovation: A Dark Art no More," in *Economist*, 2007.

[2] OECD, "Proposed Guidelines for Collection and Interpreting Technological Innovation Data: Oslo Manual," 1992.

[3] "CIS-2 Questionnaire," in *The Oxford Innovation Handbook*, J. Fagerberg, D. C. Mowery, and R. R. Nelson, Eds.: Oxford University Press, 2005.

[4] J. Fagerberg, D. C. Mowery, and R. R. Nelson, "The Oxford Innovation Handbook," Oxford University Press, 2005.

[5] C. Christensen, *The Innovator's Dilemma*. New York: Harper Collins, 2003.

[6] M. L. Tushman, "Special Boundary Roles in the Innovation Process," *Administrative Science Quarterly,* vol. 22, pp. 587-605, 1977.

[7] R. Henderson and K. Clark, "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms," *Administrative Science Quarterly,* vol. 35, pp. 9-30, 1990.

[8] J. M. Utterback, *Mastering the Dynamics of Innovation*. Cambridge, MA: Harvard Business Press, 1994.

[9] J. M. Utterback and W. J. Abernathy, "A Dynamic Model of Process and Product Innovation," *The International Journal of Management Science,* vol. 3, 1975.

[10] S. Thomke and E. v. Hippel, "Customers as Innovators," *Harvard Business Review,* 2004.

[11] J. A. Schumpeter, *The Theory of Economic Development*. New York: Harvard University Press, 1934.

[12] S. J. Kline and N. Rosenberg, "An Overview of Innovation," in *The Positive Sum Strategy: Harnessing Technology for Economic Growth*, R. Landau and N. Rosenberg, Eds. Washington D. C.: National Academy Press, 1986, pp. 275-304.

[13] K. Smith, "Measuring Innovation," in *The Oxford Innovation Handbook*, J. Fagerberg, D. C. Mowery, and R. R. Nelson, Eds.: Oxford University Press, 2005.

[14] M. Coccia, "Technometrics: Origins, Historical Evolution and New Directions," *Technological Forecasting and Social Change,* vol. 72, pp. 944-979, 2005.

[15] K. Heebyung and C. L. Magee, "A Functional Approach for Studying Technological Progress: Application to Information Technology," *Technological Forecasting and Social Change,* vol. 73, pp. 1061-1083, 2007.

[16] A. J. Alexander and R. R. Nelson, "Measuring Technological CHange:; Aircraft Turbine Engines," *Technological Forecasting and Social Change,* vol. 5, pp. 189-203, 1973.

[17] S. Manaqi, J. J. Opaluch, D. Jin, and T. A. Grigalunas, "Technological Change and Petroleum Exploration in the Gulf of Mexico," *Energy Policy,* vol. 33, pp. 619-632, 2005.

[18] R. U. Ayres, "Empirical Measures of Technological Change at Sectoral Level," *Technological Forecasting and Social Change,* vol. 27, pp. 229-247, 1985.

[19] P. Saviotti, "An Approach to the Measurement of Technology Based on the Hedonic Price Method and Related Methods," *Technological Forecasting and Social Change,* vol. 27, pp. 309-334, 1985.

[20] C. Beaudry, "Enterprise in Orbit: The Supply of Communication Satellites," *Economics of Innovation and New Technology,* vol. 15, pp. 679-700, 2006.

[21] H. L. McManus, "Space System Architecture: Final Report of SSPARC: The Space Systems, Policy and Architecture Research Consortium (Thurst I and II)," MIT, Cambridge, MA2004.

[22] G. B. Shaw, D. W. Miller, and D. E. Hastings, "Development of the Quantitative Generalized Information Network Analysis Methodology for Satellite Systems," *Journal of Spacecraft and Rockets,* vol. 38, pp. 257-269, 2001.

[23] C. D. Jilla, D. W. Miller, and R. J. Sedwick, "Applications of Multidisciplinary Design Optimization Techniques to Distributed Satellite Systems," *Journal of Spacecraft and Rockets,* vol. 37, pp. 481-490, 2000.

[24] H. L. McManus, D. E. Hastings, and J. M. Warmkessel, "New Methods for Rapid Architecture Selection and Conceptual Design," *Journal of Spacecraft and Rockets,* vol. 41, 2004.

[25] C. J. Roberts, "Architecting Strategies Using Spiral Development for Space Based Radar," in *Technology and Policy Program*. vol. Master's Thesis Cambridge, MA: Massachusetts Institute of Technology, 2003.

[26] T. J. Spaulding, "Tools for Evolutionary Acquisition: A Study of Multi-attribute Tradespace Exploration (MATE) Applied to the Space Based Radar (SBR)," in *Aeronautics and Astronautics*. vol. Master's Thesis Cambridge, MA: Massachusetts Institute of Technology, 2003.

[27] R. L. Keeney and H. Raiffa, *Decisions with Multiple Objectives - Preferences and Value Tradeoffs*. Cambrige, UK: Cambridge University Press, 1993.
[28] A. M. Ross, "Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration," in *Engineering Systems Division*. vol. Ph. D. Thesis Cambridge, MA: Massachusetts Institute of Technology, 2006.
[29] A. L. Weigel, "Evaluating the Cost and Risk Impacts of Launch Choices," *Journal of Spacecraft and Rockets,* vol. 41, pp. 103-110, 2004.
[30] J. H. Saleh, J. P. Torres-Padilla, D. E. Hastings, and D. J. Newman, "To Reduce or to Extend a Spacecraft Design Lifetime?," *Journal of Spacecraft and Rockets,* vol. 43, pp. 207-217, 2006.
[31] R. Rusch, "Communication Satellite Database," 2006 ed Palos Verdes, CA: TelAstra, 2006.
[32] D. H. Martin, *Communication Satellites 1958-1995*. El Segundo, CA: Aerospace Corporation, 1996.
[33] J. T. Richelson, "U.S. Satellite Imagery 1960-1999," in *National Security Archive Electronic Briefing Book*. vol. 13.
[34] A. J. Butricia, *Beyond the Ionosphere: Fifty Years of Satellite Communication*. Washington D.C.: NASA History Office, 1994.