What Drives Spacecraft Innovation?
A Quantitative Analysis of Communication Satellite History

by
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ABSTRACT

The overall goal of this research is to develop a better understanding of how innovation can, and should, happen in the space sector. Part A: Towards an Empirical Measure of Spacecraft Innovation, frames the discussion of innovation in the space sector and creates a platform for future analysis. To accomplish this, it addresses 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 surrogates for the parameters required in implementing the proposed metrics. Based on these surrogates, the relative merits of each measurement paradigm are illustrated through sample analyses.

Part B: Lessons from Communication Satellite History (1964-2006), captures the first detailed attempt to quantitatively analyze innovation in the space sector. Building on the communication satellite innovation metric (developed in Part A) and a spacecraft innovation framework (developed as part of ongoing work) Part B presents a preliminary model of communication satellite innovation. In addition to innovation being a function of the rate of performance normalized by price, spacecraft innovation is shown to be strongly influenced by characteristics of the customer-contractor contractual relationship. Specifically, DoD contracts tend to result in a lower level of innovation on average as compared to other customers and particular customer-contractor pairs perform differently and exhibit a second order relationship in time. No pair was observed to sustain better than average innovation in the long run.

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NOMENCLATURE

a_i = Relative *w*eight of the i[th] characteristic
β_i = i[th] resource constraint
c = Cost
C = Capacity
Ci = contractual parameter
CPF = Cost per function
g_i = generational parameter
i = Innovation
(In, r, Is, Av) = Capability Parameters: Integrity, Rate, Isolation, Availability
I(t) = Innovation input function
$Icu_{i}con_j$ = customer contractor interaction effect
IM = innovation metric
$Mcont_i$ = contractor main effect
$Mcust_i$ = customer main effect
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
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

1 INTRODUCTION

On October 4th, 1957, the faint beeps of Sputnik ushered in the dawn of the space age. A mere 83.6 Kg, with a diameter less than 58 cm,[2] the Soviet built satellite represented a challenge to the, until then presumed, American technical and military superiority.[3] The use of space, which began as a cold war race between super powers, has since blossomed into a platform for a global industry. Half a century later, more than 900 operational satellites orbit the earth, operated by 40 countries.[4] Compared to Sputnik's beach ball-sized stature, modern communications satellites are enormous, weighing in at 5000 Kg.[4] Functional performance has increased so extensively that it is hard even to compare the two levels. Applications today include communications, navigation, remote-sensing, scientific research and environmental monitoring. Satellites have become indispensable tools in our daily lives, enabling on-board GPS in personal vehicles, global communications, weather forecasts and early warning for natural disasters among others.

However, despite a rich legacy of delivering impressive technology, government space acquisitions – both military and civil – are increasingly characterized by schedule slips and cost overruns. According to the House of Representatives' Report of the Committee on Armed Services, "*simply put, the Department of Defense (DoD) acquisition process is broken. The ability of the Department to conduct the large scale acquisitions required to ensure our future national security is a concern of the committee."[5]* Similarly, a recent Government Accountability Office (GAO) report highlights the level of underperformance on a series of space projects, stating that

> *DoD's space system acquisitions have experienced problems over the past several decades that have driven up costs by hundreds of millions, even billions, of dollars; stretched schedules by years; and increased performance risks. In some cases, capabilities have not been delivered to the warfighter after decades of development.[1]*

The programs featured in Figure 2 include the Advanced Extremely High Frequency (AEHF) satellites, the Wideband Global SATCOM (WGS) and the Mobile User Objective System (MUOS), which are all communication satellites, and the Global Positioning System (GPS) II.[1]

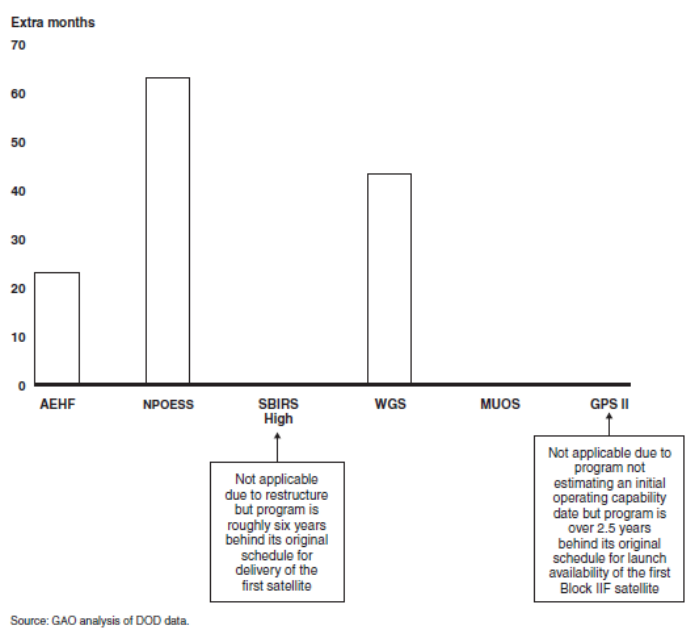

Figure 1 Additional Months Needed since Program Start[1]

On the civil side, the National Aeronautics and Space Administration's (NASA) record isn't better. For example, the Mars Science Laboratory (MSL), originally priced at $650-million will now cost an estimated $2-billion.[6] Similarly, cost estimates of the James Webb Space Telescope, set to replace Hubble, have grown from $1-billion to $4.5-billion.[6] These are not isolated instances. A former NASA Associate Administrator for Space Science reported to the New York Times that:

> *NASA's next two weather satellites, built for the National Oceanic and Atmospheric Administration, have now inflated to over $3.5 billion each! The list goes on: N.P.P., S.D.O., LISA Pathfinder, Constellation and more. You don't have to know what the abbreviations and acronyms mean to get it: Our space program is running inefficiently, and without sufficient regard to cost performance.[7]*

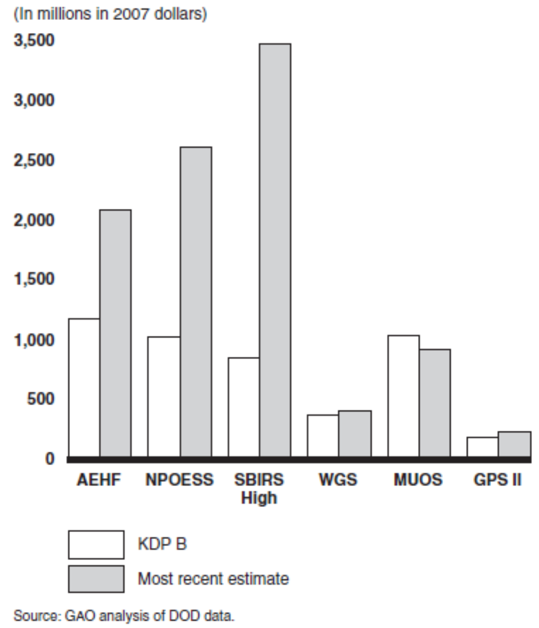

Figure 2 Differences in Unit Life Cycle Cost from Key Decision Point (KDP) B (Program Start) and 2007 Estimate.[1]

This record of poor performance has not gone without comment. Multiple *blue ribbon* panels have been convened and many Government Accountability Office (GAO) reports written (key recommendations summarized in Figure 3). The NASA reports abound as well (see for example Refs. [8-13]). Bringing to bear the members' vast experience working in the current acquisition paradigm of large monolithic spacecraft, their recommendations emphasize a "back-to-basics" philosophy (*i.e.*, maturing payload technologies outside of acquisition programs, increasing the technical competence of the acquisition core and emphasizing the importance of front-end specification).[14] One key theme of the recommendations, that programs will be less likely to overrun if only mature (i.e., proven) technologies are acquired, seems intuitively true. It also raises an important questions, are billions of public funds being allocated to government space projects so that they can play it *safe*? Where is the boundary between pushing limits and controlling costs?

Government space acquisition systems exist in part, because some military needs are unique and/or sufficiently important to national security that their fulfillment cannot be left up to the free market. Other common justifications include that exploration is an important goal; or that there are economic benefits derived from government investment in space (estimates of the rate of return on NASA's spending reach as high as 23:1).[15] Whatever the actual numbers, the point remains that NASA and the DoD are in the business of pushing technological boundaries; an expensive pursuit.

		Rumsfeld (2001)	NDIA (2003)	Young (2003)	GAO (2006)	DAPA (2006)	NRC (2008)
technology	Restore funding for testing space technologies	X			X		
	Maintain U.S. technological lead in space	X					
	Keep R&D separate from systems acquisition				X		X
	Identify technology for rapid exploitation and control					X	
management	Establish Presidential and NSC space advisory groups	X					
	Integrate defense and intelligence space activities	X					
	Improve front-end systems engineering (req's=resources)		X	X	X	X	X
	Improve collaboration on requirements		X		X	X	X
	Budget space programs to most probable (80/20) cost			X			
	Evaluate contractor cost credibility in source selections			X			
	Conduct independent program assessments at MDA's			X			
	Do not allow requirements creep			X	X	X	X
	Match PM tenure with delivery of a product			X	X	X	X
	Pursue incremental increases in capability				X		
	Withold contractor award fees when goals not met				X		
	Establish a stable program funding account					X	
	Structure development to achieve IOC within 3-7 years						X
policy	Recognize space as top national security priority	X					
	Deter and defend against hostile acts in space	X					
	End practice of appointing only flight-rated CINCSPACE	X					
	Incentivize government career paths in acquisitions	X	X	X		X	X
	Improve workforce technical competence	X		X	X	X	X
	Research systems architecting design tools		X				
	Establish mission success as guiding principle			X			
	Compete acquisitions only when in best interest of gov't			X			
	Develop integrated strategy for R&D and acquisitions				X		X
	Encourage LSI to compete major subsystems					X	
	Evaluate gov't internal training programs for acquisition						X

Figure 3 Key Findings from Recent Studies of the DoD Acquisition System [1-6]

While a more conservative approach might yield better (i.e., more accurate) cost estimates, it wouldn't necessarily yield cheaper programs; explicitly pushing the boundaries of knowledge is an expensive pursuit. Consider the commercial sector of the communication satellite industry. Commercial satellite acquirers (e.g., Intelsat Inc.) have perfected the art of developing communications satellites from paper-to-orbit in 3 years; on time and on schedule.[16] They have achieved this by buying what they know. Consequently, many of the major communication satellite technological improvements have come from government research and development (R&D) programs rather than commercial players.[17, 18] For example, Early Bird – the first commercial satellite, launched in 1965 by INTELSAT Corp. – followed directly from NASA's Syncom series. Similarly, NASA introduced despun antennas, experimented with new frequency ranges (L-band, VHF, and C-band) with ATS 1-5 in the mid 60s; three-axis stabilization, large deployable antennas, and high power at S-band and L-band with ATS-6 in the late 60s; direct broadcasting using traveling wave tube amplifiers (TWTA) in the Ku-band in 1975. These and other NASA inspired firsts (see Figure 4) formed the basis for modern satellite communications.[17]

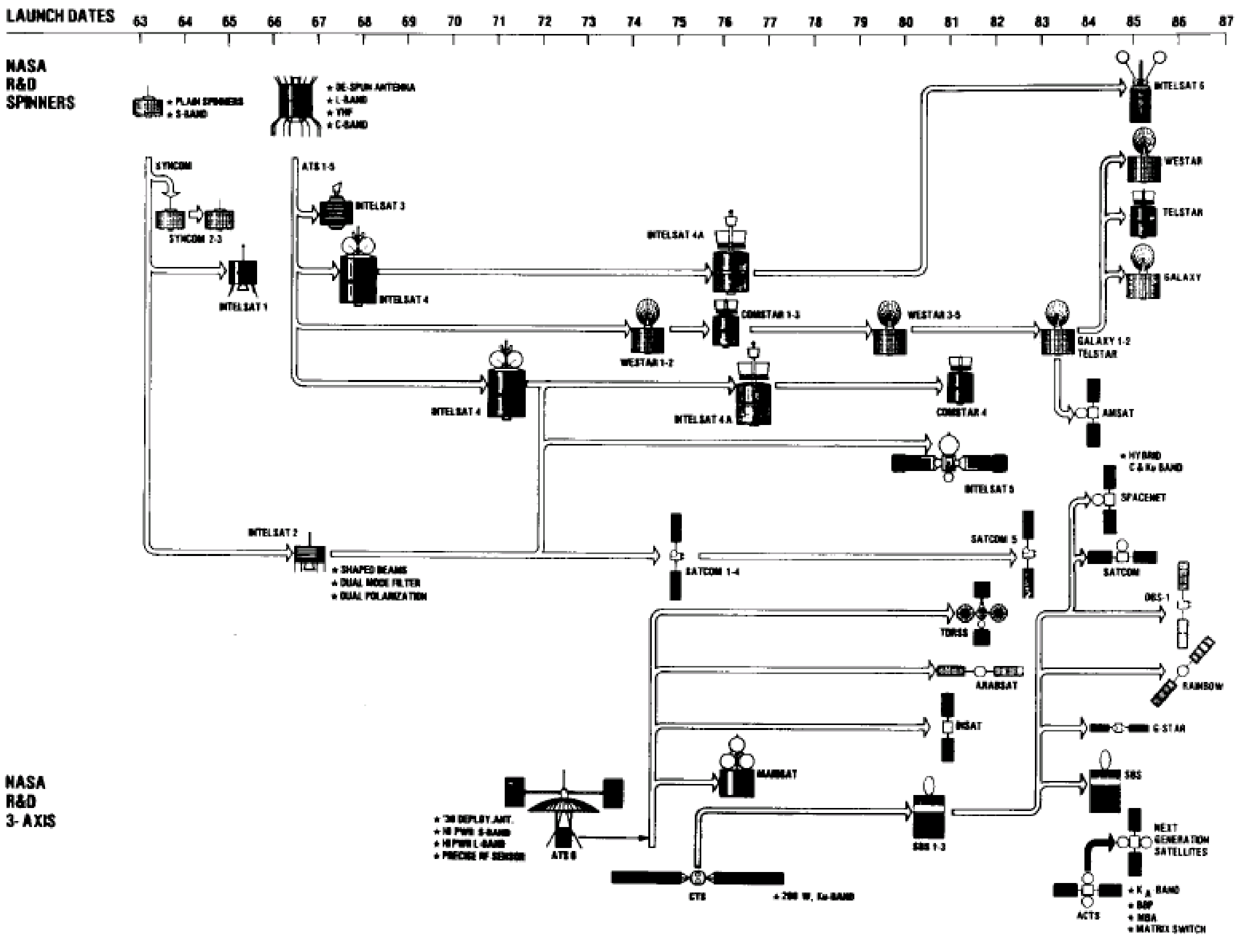

Figure 4 **Genesis of Communication Satellites through NASA R&D [17]**

Thus, where government space acquisition systems have produced major technological progress, they have failed to control costs and hit schedule targets. Conversely, where commercial satellite buyers have succeeded in meeting cost and schedule goals, they have failed to make major advances in the state of the art. Both present problems, acting on different sides of the innovation equation.

SPACECRAFT INNOVATION: A measure of how performance outcomes (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). (p. 18 of this thesis)

1.1 PROBLEM STATEMENT

While many recommendations have been made, and many actions have been taken to address documented limitations of current space acquisition systems, a satisfactory solution remains beyond reach. As framed above, innovation is an important goal of, and justification for, space activities; be they military (new capabilities), civil (new capabilities and economic benefits) and commercial (economic growth and profit). Further, it integrates a core tradeoff in the mission of space agencies – push limits while controlling costs. Yet, despite an extensive and growing literature on technology innovation, little work has been done to apply insights from innovation theory to space acquisition reform.

Part of the problem is a poor understanding of how characteristics of the space sector (i.e., monopsony-oligopoly market structure and extremely complex robust products) impact the way in which innovation can and should be encouraged. This can lead to inappropriate choices of innovation strategies and, ultimately, to an environment that does not foster innovation successfully. Since effective change is necessarily preceded by an increased understanding of what is currently wrong, this research work aims to fill that gap by identifying and explaining patterns of spacecraft innovation through an analysis of the sector's history.

An innovation lens seems particularly relevant because where previous studies have taken an experiential perspective – which necessarily leads to a focus on known problems within the current system – the use of an innovation metric allows for a broad spectrum statistical analysis of an entire sector. It is hoped that this holistic view will yield new insights that will complement the body of thinking derived from the various blue ribbon reports. Before any analysis can be done however, an approach to quantifying spacecraft innovation must be developed and tested.

Although many of the ideas are applicable to spacecraft in general, this thesis focuses on communication satellites in particular. This is because the market incorporates military, civil and commercial players and it is one of the only classes of spacecraft that include a statistically significant sample sized.

1.2 RESEARCH QUESTIONS

With the governing objective of gaining a better understanding of how innovation can, and should, happen in the space sector, this thesis will seek to answer the following questions:

1. *How can spacecraft innovation be meaningfully quantified and measured?*

   While a broad literature on measuring and forecasting technological change exists, it is spread across multiple disciplines (including economics, technometrics, cost estimation etc.) and little work has been done in the context of spacecraft. Application to the space domain is non-trivial with constraints along the dimensions of market structure, product complexity and data restrictions unique to space assets. However, without such a metric, any discussion of the subject will remain abstract.

2. *Using the aforementioned metric, what lessons can be learned from an analysis of the history of the communication satellite sector?*

    Lessons of the past often provide a good baseline for what might happen in the future. In a sense, the 50 year history of space endeavors creates a natural experiment in satellite contracting. Leveraging the quantitative abstraction developed in response to Q1, hypotheses for how innovation should be generated can be tested.

1.3 STRUCTURE OF THE THESIS

The body of this thesis is structured as two distinct parts, each serving to answer one of the two research questions.

Part A: Towards an Empirical Measure of Spacecraft Innovation, frames the discussion of innovation in the space sector and creates a platform for future analysis. To accomplish this, it addresses 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 surrogates for the parameters required in implementing the proposed metrics. Based on these surrogates, the relative merits of each measurement paradigm are illustrated through sample analyses and comparison to previous work.

Part B: Lessons from Communication Satellite History (1964-2006), captures the first detailed attempt to quantitatively analyze innovation in the space sector. Building on the communication satellite innovation metric (developed in Part A) and a spacecraft innovation framework (developed as part of ongoing work[14]) Part B presents a preliminary model of communication satellite innovation. In addition to innovation being a function of the rate of performance normalized by price, spacecraft innovation is shown to be strongly influenced by characteristics of the customer-contractor contractual relationship. Specifically, DoD contracts tend to result in a lower level of innovation on average as compared to other customers and particular customer-contractor pairs perform differently and exhibit a second order relationship in time.

Although the two parts of the thesis draw from similar literatures, their objectives and methodologies are sufficiently different to merit splitting up the literature survey. As a result relevant parts of the literature are introduced at the beginning of each of Parts A and B.

PART A: TOWARDS AN EMPIRICAL MEASURE OF SPACECRAFT INNOVATION

With the overall goal of better understanding how innovation happens in the space sector, Part A of this thesis develops a quantitative basis for future discussion. Specifically seeking to answer the question: How can spacecraft innovation be meaningfully quantified and measured? To accomplish this, Part A addresses three aspects of the task of 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. Third, based on these surrogates, it implements and compares the proposed metrics. Finally, this part 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[19] and Community Innovation Survey[20] 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[21] 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[22, 23] vs modular and architectural[24], process vs product[25], fluid vs transitional vs specific phases,[26] lead user innovation,[27] 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.[28] 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.[29] 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 supplier), 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:

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

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[30]. The selection of these inputs and outputs is relatively straightforward once the system boundary has been clearly defined; however, 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. [31] for a recent review paper). The range of technological studies that have been conducted can be categorized as technology function focused, market performance focused, or functional performance focused. This section summarizes the key insights from each of the three categories. In the below discussion, measures of quality 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 technology forecasting approaches. A metric is determined, 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. [32] It is commonly held that the technological state of the art (SOA), or essential quality, is often best represented by a tradeoff surface describing the intersection among functional capabilities per Eq. (2).[31]

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

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.[33, 34] 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.

2.2.2 Market Performance Perspective (MPP)

The market 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.[30, 35] In fact, in competitive markets for commodity products, hedonic regression can be used to infer efficiency improvements from observed price fluctuations. [36] Specifically, it is assumed that changes in quality will be reflected by changes in price. Therefore, the relative importance of each characteristic a_i can be estimated by the regression shown in Eq. (3).

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

Hedonic prices have also been equivalently used to measure coefficients in the functional domain (X_is replace Y_is and costs become the response variable instead of price).[36] This concept was applied to measure communication satellite innovation in a previous study,[37] 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 how the particular technical instantiation of a system is as long as it fulfills their needs.[35] However, 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. [32] 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 PRECEDENCE FOR QUANTITATIVE ABSTRACTIONS FOR SPACECRAFT

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. [38] 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 the Generalized Information Network Analysis (GINA)[39] methodology. It is conceptually closest to the market performance perspective; however 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 system "quality-of-service" (Q_P) 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.[40] 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 minute, 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 [32]. 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:

$$Q_P = C \times T_{userful} \quad (5)$$

As with other functional performance metrics (FPMs), 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)[41] 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[42, 43]). Where the GINA abstraction contends that increases in functionality only improve satellite performance in so far as they improve information transfer, MATE leverages insights from multi-attribute utility theory (MAUT)[44] to integrate multiple "essential" performance attributes, similar to the technology-function perspective. 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.[45]

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 can be converted to cost-impacts anyway, there may be times when the consideration of other constraints is appropriate and necessary. For example, measurements of lifetime costs, which include ground systems, the complete on-orbit constellation, operating and launch costs, capture a complete monetary constraint. However, 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 [46] 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. However, 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):

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

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-side trades.

2.3.3 The Challenge of Integrating 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. [39]). CPF 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 2.2. Following ref [47], 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 ComSat 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. However, 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 input-output 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 Figure 5abc. 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.

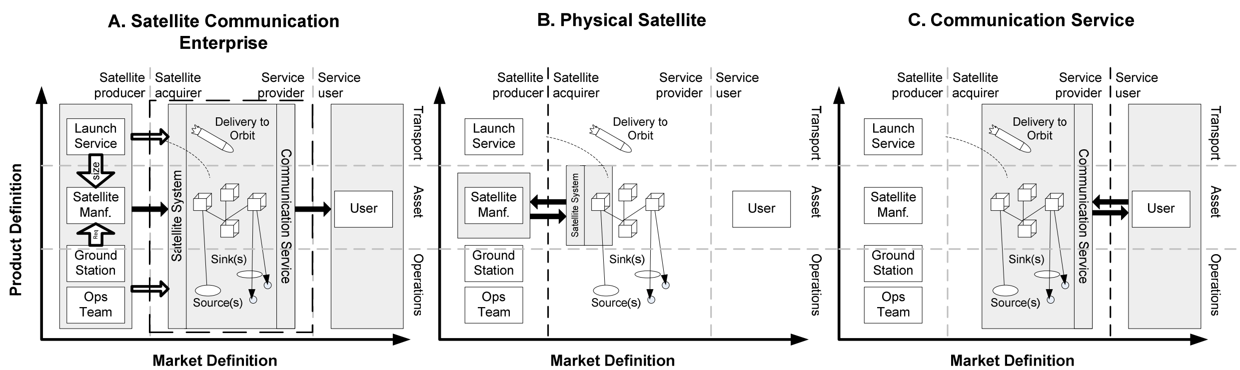

Figure 5 **Range of Communication Satellite System Boundary Definitions**

3.1.1 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 Figure 5a. 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:

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

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:

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

3.1.2 *PHYSICAL SATELLITE*

The second definition of system boundary – the physical satellite – considers the transaction between the satellite manufacturer and acquiring enterprise as shown in Figure 5b. 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:

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

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

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

3.1.3 *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 Figure 5. 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:

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

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

3.2 PRACTICAL SURROGATES 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., surrogates) are proposed. Since all three boundary paradigms identified above split the metrics between monetary, quality-of-service and time measures, the discussion is split that way here too.

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 Fig.s are reported in millions of 2005 USD, adjusted using the NASA deflator as published on the "NASA Cost Estimating Website[1]". 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 surrogates: 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 surrogate for empirical 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 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. However, the results of 40 year's worth of collection effort are housed in the Communication Satellite Database (CSD), published yearly by TelAstra Inc[48]. 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 several thousand satellites launched since 1965. While this data set is sufficiently large to provide insight into industry trends, the question remains whether price is an appropriate surrogate 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:

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

[1] http://cost.jsc.nasa.gov/models.htm the downloadable Excel file is based on OMB data collected in 2003

In a "normal" competitive market, the relationship between these two quantities can be extremely non-linear; however, the market for satellites is not competitive on the buy-side. In fact, there is typically only one buyer with a pre-specified willingness to pay. Combined with strict acquisition regulations, a nominally proportionate relationship between satellite cost and price emerges as shown in Eq. (10). Thus, in this context, price is an appropriate surrogate 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: Surrogates 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 need 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) as well as 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); however, since trade-off surfaces are extremely difficult to derive, and none currently exists for communication satellites, following Ref.[36], 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 data base 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[49], for which capacity data was available. In effect, a parameter is sought that closely mirrors the capacity trend over time.

Figure 6 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, however, be explained and justified in engineering terms when viewed in the context of historical satellite development. In Figure 6, 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,[2] 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.

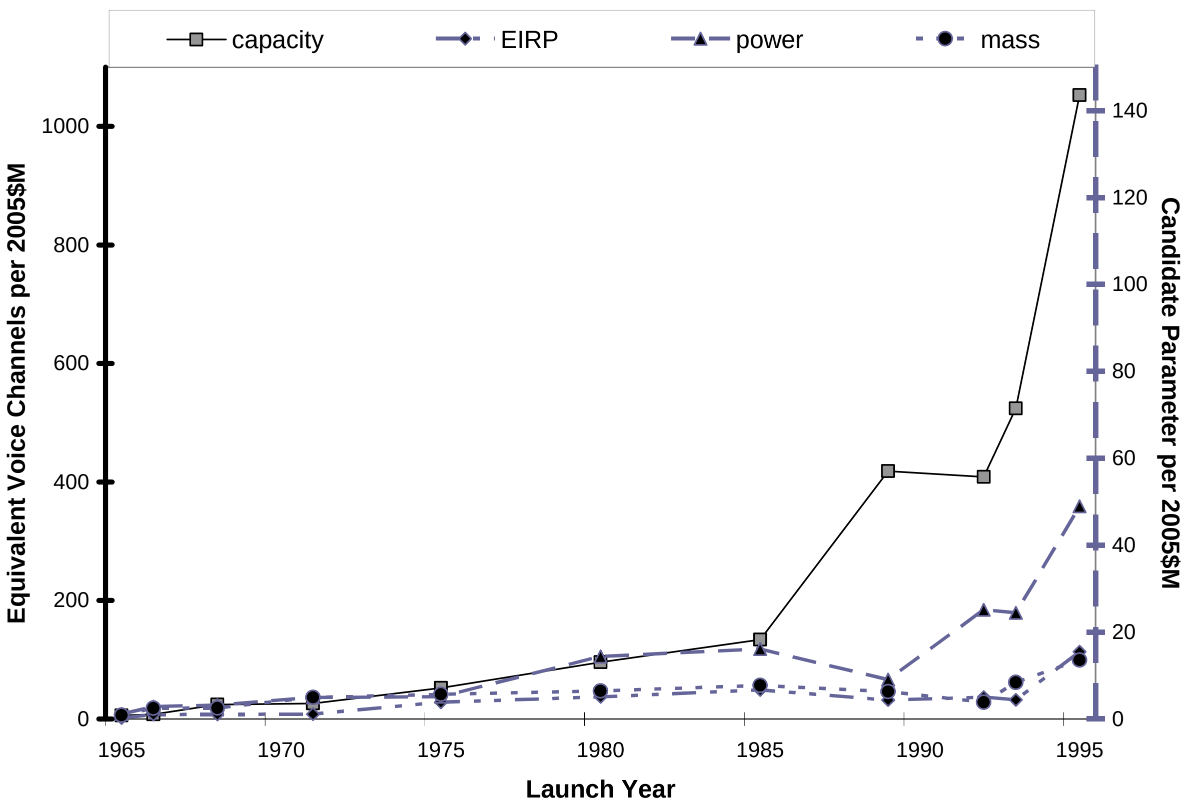

Figure 6 **Comparison of Functional Parameters to Capacity Time Trend**

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

In general terms, the functional capability of a communication satellite can be improved, either by increasing 1) 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 significantly increasing the attainable transmit power for a satellite of a given mass. In the Intelsat series (shown in Figure 6) the switch from spin to 3-axis stabilization occurred between Intelsat IV-A (1975) and Intelsat V (1980);[49] 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.[49]

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. However, in the absence of a large set of satellite capacity data, the surrogate:

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

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. However, 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 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.

$$T_{Userful} \sim T \tag{14}$$

3.3 SUMMARY OF PRACTICAL SURROGATES TO THE CONCEPTUAL MEASUREMENT APPROACHES

In section 3.1, three boundary paradigms were identified; they are 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 3.2, the practical constraints to measurement, imposed primarily by data availability, were discussed and surrogate 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 2.2 and 2.3. 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	Surrogate
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 3.1) and practical (section 3.2) challenges associated with measuring innovation having been addressed, this section illustrates how calculations can be performed 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*[3] (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,

[3] For a list of the subset of database programs used, please contact the authors directly.

particularly with respect to the upfront development cost associated with a new design, it is sufficient for our purposes[4].

4.1 COMMUNICATION SATELLITE ENTERPRISE

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

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

Figure 7 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 power represents a surrogate for the basic capability of a communication satellite, and that efficiency of power usage has increased over time, the positive trend in Figure 7 suggests that innovation is occurring in the communication satellites sector.

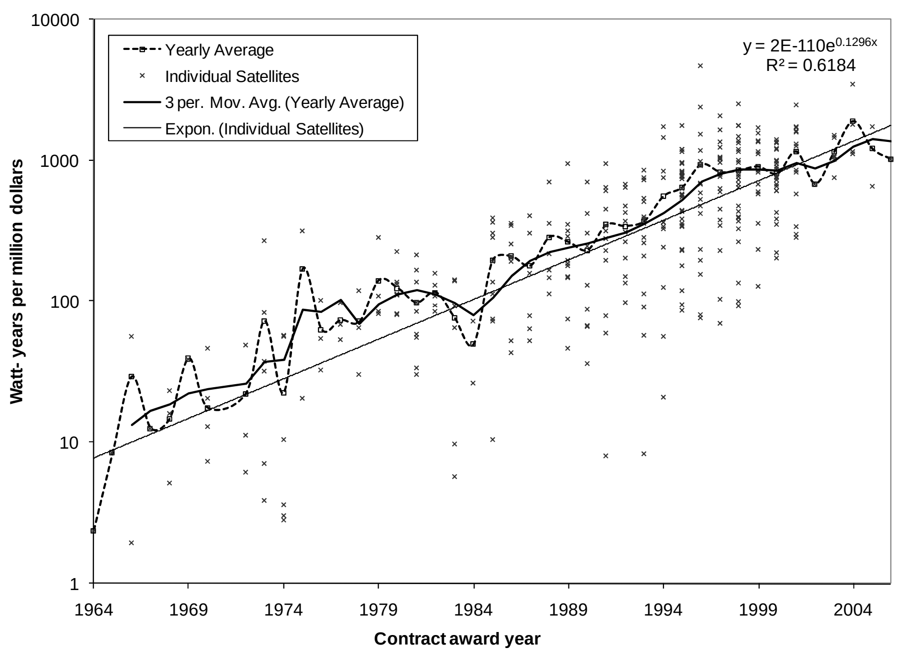

Figure 7 Evolution of the Communication Satellite Enterprise Metric over Time

[4] The analysis in ref. [47] 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. suggests that returns to scale are insignificant in this industry

It is worth noting the extent of variation in the individual satellites' level of innovation 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 Figure 7 create a basis for such an exploration.

4.2 PHYSICAL SATELLITE

Substituting the surrogate 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 a_i in the numerator must be estimated. To do this, section 2 offers two approaches. First, following ref [36], 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. [37] 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 [37] 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 [37] 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 Figure 7.

A linear multiple regression of the form:

$$P = a_0 + \sum a_i X_i \quad (18)$$

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 R^2 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). Figure 8 plots the evolution of the ratio specified by Eq. (16), using the regression output in Table 2, over time. The overall trend is marginally positive. However, since the variation about the mean is obviously non-uniform, a better weighting function is likely needed to improve this metric. The MATE[45] approach (described in section II) could provide an alternative to the hedonic price quality surrogate 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.

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 surrogate 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 Figure 8. results. Figure 8 is more similar to Figure 7 than Figure 8 in that the increasing trend is quite clear; however, like Figure 8, the strength of the trend is quite weak. This difference may be a function of the particular surrogates being used, or it may be related to the difference in paradigm; exploring this further may be a fruitful area for future analysis.

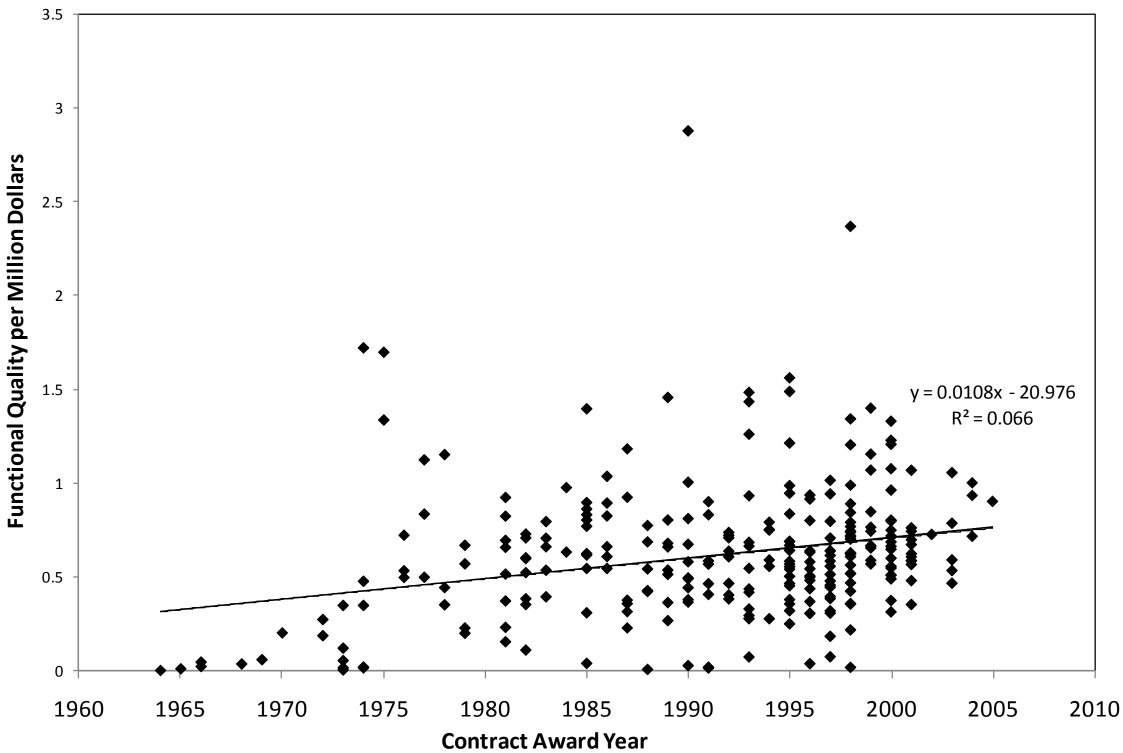

Figure 8 **Evolution of the Regression-based Physical Satellite Paradigm Metric over Time**

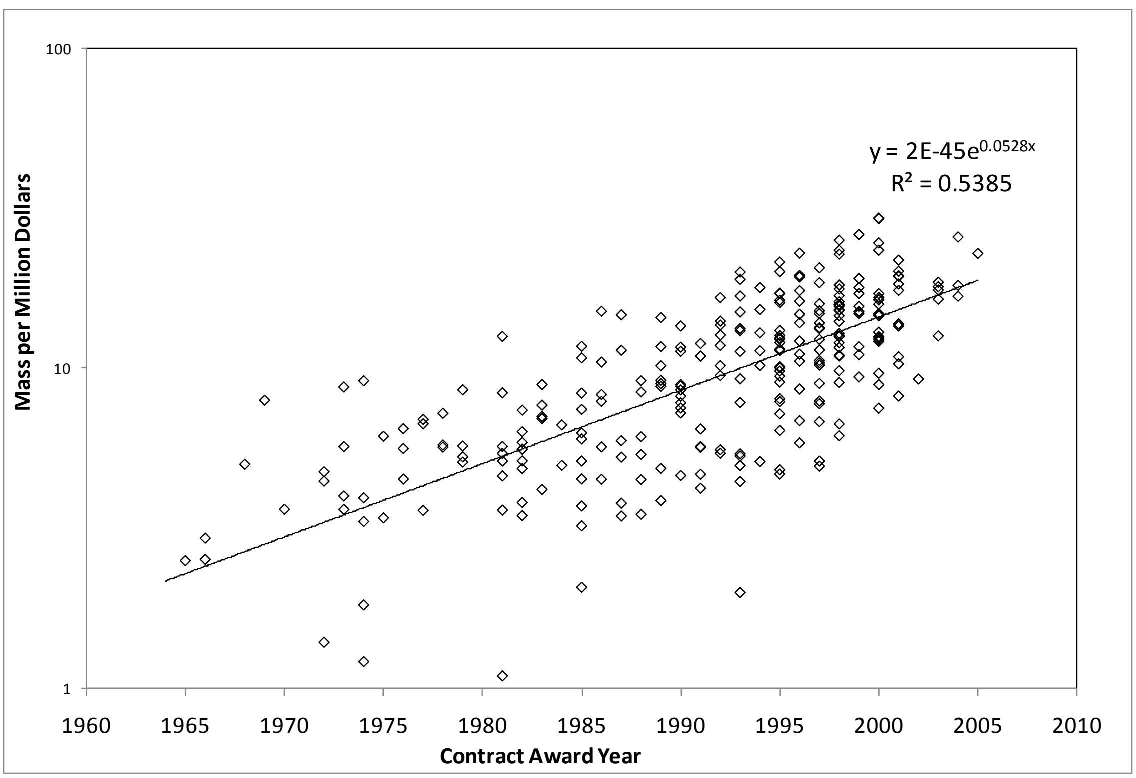

Figure 9 **Evolution of the Heuristic-based Physical Satellite Metric over Time**

4.3 Communication Service

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

$$i = \frac{d}{dt}\left[\frac{O(t)}{I(t)}\right] = \frac{d}{dt}\left[\frac{MoS}{P_{service}}\right] \tag{19}$$

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, led 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 systems, 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. As such, this section is structured in four parts; the first three sections address the validity of the representation for each method and the last part compares their relative utility.

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 metric. 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 Figure 7 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. However, 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; the question becomes: which architecture best fulfills the customer-defined objective(s)? making abstractions like GINA [39] and MATE [45] 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 paradigm, 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 [39] was shown to be suitable. However, 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[50] (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 constituent technology. Since the early days of satellite communications, the general architecture has remained the same – large, bent-pipe, GEO, solar-powered, many transponders etc… - 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).[51] These types of changes are not 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 communication context. First, the hedonic assumption that communication satellites behave as commodity products, is clearly wrong. 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 R^2s 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, have 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 surrogate 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; however, 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 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 collected for the communication satellite market; however it is believed to be available 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.

5.4 Picking a Metric Going Forward

The three boundary paradigms presented herein each strive to represent the level of innovation of a diverse set of communication satellite programs developed over the last 50 years. Given limitations in data availability and our ability to conceptualize capability for various types of systems, the Communication Satellite Service paradigm appears to be the most promising moving forward. While both of the Communication Satellite Service and Physical Satellite paradigms, for which the metric was implemented, yield similar results, the Physical Satellite paradigm required several potentially suspect assumptions to be made. Further, the Communication Satellite Service paradigm transforms the population of satellites into a more conducive form for analysis – it nearly eliminates heteroscedacity of the data, while maintaining a wide spread of variation. However, if a data set, suitable for implementing with the Communication Service paradigm becomes available, this conclusion that the communication Satellite Service paradigm yields the best basis for further analysis should be revisited.

PART B: INNOVATION LESSONS FROM COMMUNICATION SATELLITE HISTORY (1964-2006)

In order to gain insights from historical data effectively, one needs two pieces: first, a suitable parameter to "track" and second, an analysis approach around which to structure the investigation. Part A of this thesis addressed the first piece, developing the following "best" innovation metric for communication satellites:

$$i = \frac{d}{dt}\left[IM\right] = \frac{d}{dt}\left[\frac{O(t)}{I(t)}\right] = \frac{d}{dt}\left[\frac{W_{sat} \times T}{P_{contract}}\right] \tag{20}$$

Note that the abbreviation IM (innovation metric) will be used hereafter to refer to the ratio inside the square brackets.

When the above equation was applied to the Communication Satellite Database, the data revealed a strong indication (R^2=0.7) of exponential growth in the sector's "capability baseline" overtime. 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, is the extreme variations of individual program performance around the industry mean, suggesting that other important factors are at play.

Since the overall 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. Part B reports on the next step in this research effort, seeking to explain this variation. There are two main phases to this work. First, the complementary strategies of data mining and theory guided exploration are employed to find statistically significant trends in the data. Second, the historical contexts of the "patterns" are probed in an effort to match theory to practice.

6 IDENTIFYING KEY EXPLANATORY PARAMETERS

Broadly speaking, there are two approaches to identifying trends in historical data: straight data mining and theory-based exploration. *Data mining* is the umbrella term for the process of extracting hidden trends from data. It requires no concept of what the trends should look like *a priori,* to be effective [52]; however, when theory does exist, it can reduce the search space and may improve the quality of the results.[53] The latter approach is sometimes called theory-based data exploration. This section describes how data mining techniques were used initially, and later refined with theory-based exploration to refine the baseline model of spacecraft innovation presented in Part A.

6.1 METHOD 1: DATA MINING

Data mining typically proceeds in three phases.[54, 55] First the data is pre-processed, which involves identifying a suitable dataset, removing observations that are noisy or absent and organized into feature vectors (i.e., a vector of parameters corresponding to each observation). This process was described, vis-à-vis the Communication Satellite Database, in section 4. Second, the data is mined. This typically involves some combination of *classification,*[5] *clustering*[6], *regression*[7] and *association rule learning.*[8] Finally, the results are interpreted for practical validity.

6.1.1 ANALYZING THE DATA

A linear regression model of the form:

$$\ln(IM) = \alpha_0 + \alpha_1 X_i + \ldots + \alpha_2 X_n \qquad (21)$$

was selected for the analysis because it allows for a continuum of *responses and* makes the least assumptions about the structure of the data (i.e., level of spacecraft innovation).[9] Backwards step-wise selection [53] was used to reduce the model. The regression output is summarized in Table 3. The results indicate that multiple parameters are statistically significant; nonetheless, including the significant factors in the regression generates only a relatively minor improvement in the overall fit (from $R^2 = 0.7$ to 0.72).

[5] Classification seeks to predict the membership of a particular observation in some predefined group
[6] Groups similar observations without prior assumptions regarding structure
[7] Regression analysis attempts to fit a function which models the response variable while minimizing "least-squared" error.
[8] Searches for hidden relationships between variables
[9] Both *Clustering* and *Classification* assume that the response variables fall into discrete categories (e.g., an e-mail is either legitimate or spam). This doesn't make sense when the response is "level of spacecraft innovation" which falls on a continuum from low to high. *Association Rule Learning* could potentially yield interesting insights, but is extraneous to the objective of identifying key explanatory parameters (it is more relevant to the follow-on task of exploring their interactions).

Table 3 Results of Multiple Linear Regression on the Innovation Metric

Parameter	Description	X_i	p-value
Constant	Intercept term	-105.32	0.000
Awdate	Date of contract award (time)	0.054	0.000
Arch	Dummy variable denoting stabilization method (spin vs 3-axis stabilized; 0/1)	Not statistically significant, p-value > 0.05	
Location	Dummy variable used to differentiate between customers located in the "west" (i.e., N. America and Europe) and the rest of the world (0/1)	0.1147	0.006
Org	Dummy variable used to differentiate between government and non-government customers	-0.1390	0.005
Type	Dummy variable for "firm fixed" versus "cost-plus" contracts	0.0632	0.019

6.1.2 Interpreting the Results

The metric defined in Part A frames innovation in its technical and economic context, measuring how the cost of achieving a particular level of functionality changes over time. However, even if the innovation metric could perfectly express the capability level of a particular satellite, one would not expect all the data points to fall exactly on the trend line. Two factors that might contribute to this deviation are generational shifts and contract structure. While in the aggregate, innovation may appear as a steady, incremental, exponential growth, there is strong evidence that technological change proceeds as a combination of incremental steps and radical leaps (see for example ref. [22, 56]). This generational discontinuity is why the familiar patterns of sequential s-curves exist. In the regression analysis, *Arch*, is the primary indicator of generational discontinuity. The other factor – contract structure - is relevant because real markets do not operate at perfect economic equilibrium. As a result, characteristics of the particular product development and transaction can influence its level of innovation achieved, relative to the expected. In the regression analysis, *Location, Org and Type* are three examples of contract parameters. The results in Table 3 indicate that three of the contractual parameters are statistically significant, while none of the generational parameters were.

6.1.2.1 Significance of Contractual Parameters – Limitation of the Coding

On first pass, it might seem strange that three contractual parameters are significant but barely improve the regression model (compared to the baseline time regression performed in Part A). This result is likely a byproduct of the granularity of the coding; namely, categorizing customers as broadly as "all American or European non-government firms" is not much better than customers in general. This does not mean that no customer category would improve the metric. Thus finer categories will be examined in Method 2: Theory-based Exploration.

6.1.2.2 Insignificance of the Generational Parameters - Removing the Time Dependence

The insignificance of the generational parameter is surprising, since the phenomenon of sequential "s-curves" is well established (see for example ref [23]). However, the communication satellite industry has not experienced major waves of creative destruction[28] as in other industries, in part because of the significant government involvement in the early stages and stable oligopoly of system integrators. As a result, the dominant design[26] of 3-axis stabilized, large, geostationary satellites emerged quite quickly and wasn't replaced until the relatively recent emergence of low earth orbit (LEO) constellations. However, limitations of the innovation metric (described in more detail in ref Part A) result in a limited ability to value the utility of constellations. Thus, the generational investigation is limited to the change from spin-stabilized to 3-axis stabilized architectures.

Figure 10 illustrates the statistical result of no difference. Although there is clearly a difference between the trend line for spin- and 3-axis-stabilized satellites, satellites in the spin category do not fall outside the expected range of innovation level for the given year. Further, a single exponential fit (R^2 = 0.694) is slightly better than the combination of two separate fits for the different generations. While one could argue that this is a case where statistical significance is not a good practical measure, this result does justify exploring the advantages of examining the data as a single generation.

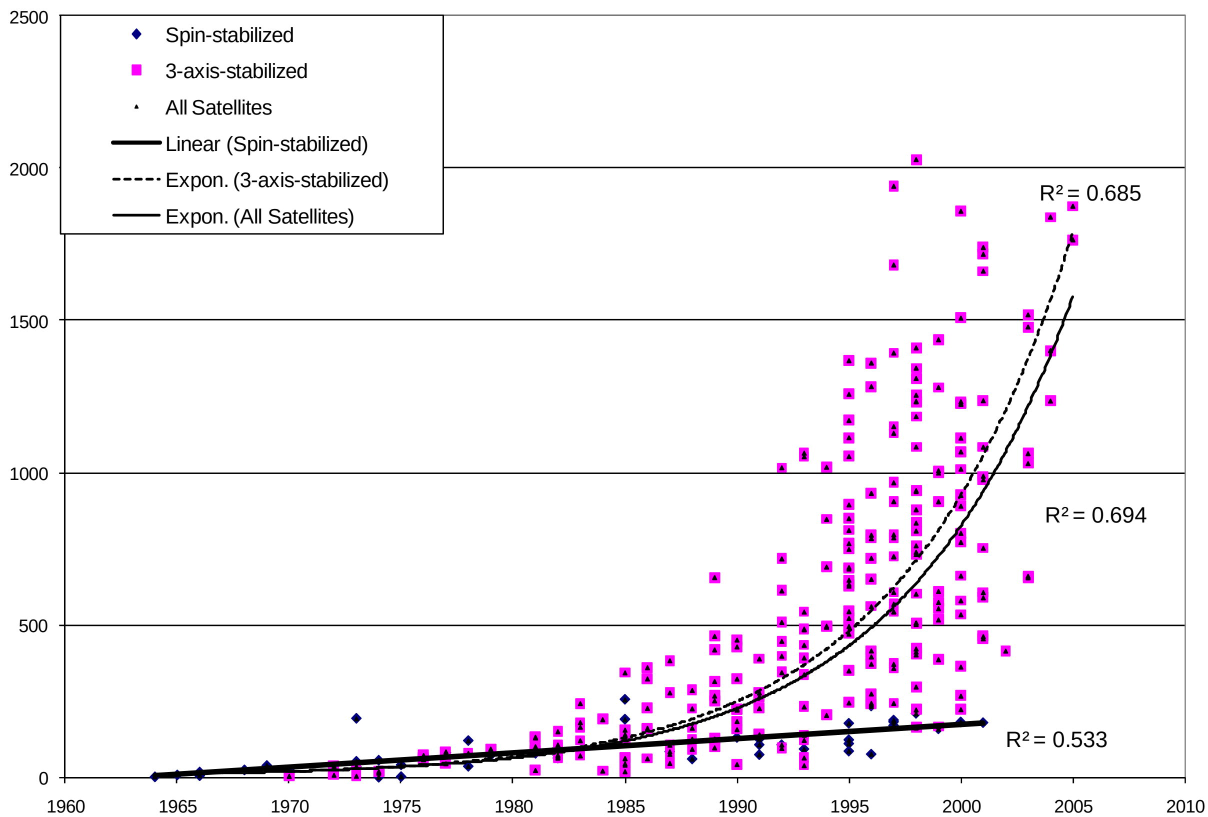

Figure 10 **Communication Satellite Generational Differences**

The data contained in the communication satellite database is both time-series (spanning 42 years of history) and cross-sectional (including many different types of programs in each year). Innovation occurs over time, but is driven by cross-sectional difference. Although 350 data points may seems like a large number, there are relatively few cross-sectional points in any one year. Thus, since it is relative innovative performance that is of interest from a strategic point of view, the cross-sectional richness of the data-set can be increased by removing the time trend (and thereby standardizing the data). Figure 11 plots innovation level as a difference from the industry mean; it is equivalent to Figure 7 with the time trend-line subtracted out.

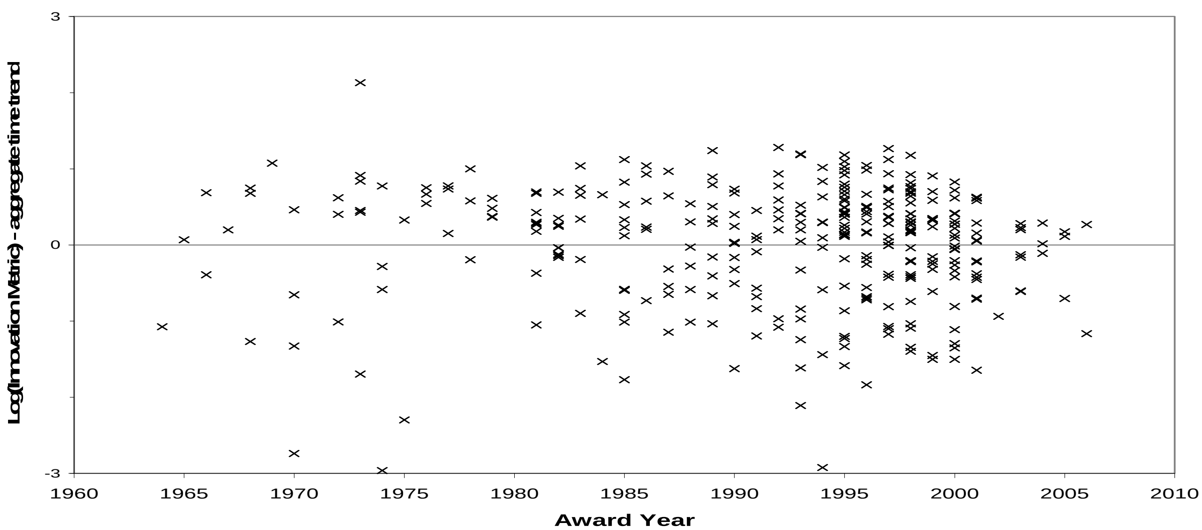

Figure 11 Deviations from the Industry Innovation Mean

The idea is that the capability baseline of the industry is improving in general (i.e., improvements in power electronics and processor capability should not be attributed directly to any communication satellite project), but some types of projects will consistently do better or worse than that mean. And, if the industry baseline is removed, characteristics of an above average project in, for example, 1970 can be compared directly to an equally above average project in 2000, thus increasing the number of projects that can be compared. The relatively equal spread from the 1960s to the 2010s seen in Figure 11 demonstrates that this assumption is valid in principle. However, this approach implicitly assumes that a single, consistent increase in the industry capability baseline has occurred over time. As discussed above, this assumption is likely invalid in general for most industries because of generational discontinuities. However, in the context of communication satellites, where the overall architecture has remained relatively constant for most of its history, and there is no statistical difference between the generations, the gains in cross-sectional richness appear to justify the trade.

6.2 METHOD 2: THEORY-BASED EXPLORATION

In the previous section, an effort was made to associate different levels of innovation performance with top-level categories of program type (e.g., American, commercial programs). However, while the categories were found to be statistically significant, in practical terms, the differentiation was too coarse to be useful. In this section, a more detailed, bottom-up approach is taken. Expected patterns are hypothesized based on theory, to be proved or disproved by the data.

6.2.1 Expected Trends: Hypothesis Formulation

Characteristics of the space market (with its monopsony-oligopoly structure and complex robust products) constrain the ability for transaction dynamics (i.e., the continuous interaction of user needs and seller capabilities) to generate innovation naturally. As a result, where the strategic innovation management literature tends to prescribe ways in which firms and regulators can catalyze, and/or benefit from, dynamics that must exist (see for example [23, 26]), the goal in the space sector is fundamentally different. Institutional acquisition agencies (e.g., DoD acquisition core, NASA) exist in part to correct for market failures; and thus each of their goals is more to restore a broken dynamic than to strengthen a naturally occurring one. Ref. [14] examines how challenges imposed by the space market structure are corrected for, with varying degrees of success, by the DoD acquisition structure. Ref. [57] performs a similar analysis for the case of the European Space Agency (ESA). In this section, insights gained through that work are leveraged to develop historical "experiments" which can be conducted using the cross-section of program configurations captured in the data in Figure 11.

This paper will not dwell on the underlying theory (see ref. [14] for a more detailed treatment), but a brief background is required to motivate the competing research hypotheses. In the most basic sense, the continuous interaction of user -needs and seller -capabilities are thought to drive innovation.[58] In a competitive market, both are revealed completely through the mechanism of price.[59] However, in the monopsony-oligopoly market of space, this information transfer is limited in two ways. Firstly, a monopsony market is discrete and specific since the market only exists when the buyer wants to buy and, as a result, user needs must be specified explicitly since there is no aggregate behavior from which they can be inferred. Further, in the stable oligopoly that exists on the space sector sell-side, there is little incentive for contractors to invest in innovation on their own; they tend to innovate in response to government requests. Based on these constraints, one might expect that innovation in the space sector is dominated by a top-down specified innovation; namely, the customer defines a sufficiently advanced need and contractors are compelled to innovate just to fulfill the contract. In the historical data, this would manifest as a high correlation between level of relative innovation and particular customers (who are smart buyers).

HYPOTHESIS 1: Customer main effects will show a strong correlation with innovation performance.

However, this expectation of user-specified innovation presumes that customers are capable of defining the "right" level of advanced specification to drive innovation independently. The task of determining what the best next step vis-à-vis innovation is, for a complex product like a spacecraft, requires the integration of multiple knowledge areas. On the capability side, both a detailed knowledge of the components and their linkages (*i.e.,* architectural innovation[24]) is required. However, these areas of expertise are fragmented among system integrators, major subsystem contractors and component suppliers. On the need side, a trade-off must be made between operational desires and budgetary priorities. For example, in the DoD, these areas of expertise are divided between warfighters and congress respectively. As a result, in addition to expecting differences in the ability of customers to represent their needs, there is also a need for contractors to participate in defining the frontier of the possible. Although the nature of this relationship may vary under different circumstances, one would expect the existence of a relationship to facilitate the necessary transfer of information but at the same time limit the incentives to take risks. In the historical data, this would manifest as a high correlation between level of relative innovation and particular customer-contractor pairs.

HYPOTHESIS 2: Interaction effects will dominate the main effects in predicting innovation performance.

There is a third competing expectation. Given that contractors possess the detailed technical knowledge on which innovations are built, they are in the best position to initiate innovation. However, as discussed above they have limited incentives to do so because of their stable and powerful market position. That being said, there is still an advantage to favorably differentiating oneself from the competition, and prestige to be gained from being involved with successful, highly public projects. In addition, through repeated development efforts, contractors accumulate the complementary assets and tacit expertise which facilitate innovation.[60] Therefore it would not be unexpected to detect a difference among contractors vis-à-vis innovation. In the historical data, this would manifest as a high correlation between level of relative innovation and particular contractors.

HYPOTHESIS 3: Contractor main effects will show strong correlation with innovation performance.

6.2.2 Observed Trends: Analysis

Viewed together, the theory suggests that much of the variation in innovation level can be attributed to differences in customers, contractors and the relationship that emerges when they work together. Thus we expect a relationship of the form:

$$IM - a0 - a1t = \sum Mcusti(t) + \sum Mconti\,(t) + \sum\sum Icuiconj(t) \qquad (22)$$

where the terms on the right side of the equation denote the impact of each factor. Hypothetically, a full factorial experiment could be designed to measure each of these factors using an n-factor ANOVA. Particular customers and contractors would randomly be paired to develop satellites over time. You would want every customer to work with every contractor at different (and multiple) points in history. Clearly, such an experiment is not feasible to conduct in practice; however the data captured in Figure 11 show the results of a 42 year natural experiment, whereby particular customers and contractors have actually paired to develop satellites. Thus, similar analysis can be done on the results of this so-called quasi-experiment.

However, unlike in a designed experiment, the experiment cannot simply be re-run to fill in missing historical data points. Not surprisingly, the history of communication satellite development does not respect the full factorial design (i.e., not every contractor worked with every customer and definitely not multiple times over time). As a result, ANOVA analysis cannot be applied directly. Instead, the main effects (*i.e., the effect of each of the customers and contractors independently*) are analyzed separately and then the interaction effects (*i.e., the additional effect of each customer contractor pairs*) for a reduced sample are layered on top. In the analysis that follows, customers and contractors are defined as the buyer and seller as listed on the satellite contract. Where a particular firm has changed names, all instances were grouped as the same customer/contractor (e.g, HAC, HSC, BSC and BSS are all listed as Boeing), but where a company was purchased, broken up and "repackaged," the multiple instantiations are kept separate.

6.2.2.1 Customer Main Effects: Does the expected high correlation between levels of relative innovation and particular customers (who are smart buyers) exist?

In order to assess whether there is a statistically significant difference between customers, pair-wise t-tests were performed on the difference between each mean (at the 95% confidence level)[10]; the Tukey method was used to account for multiple comparisons. Figure 12 and Figure 13 show a summary of the data.[11] Figure 12 highlights the data points associated with three customers in particular, demonstrating that while each customer shows considerable variations in innovation levels over time, there is no consistent increasing or decreasing trend in time. Thus the mean innovation level of each customer can be compared without considering additional time effects. Figure 13 shows a box plot of all the comparisons, which yielded an overall $F_{(11,184)}$-statistic of 5.8 which corresponds to a p-value of 0.0000. This provides strong statistical evidence that the satellites contracted by at least one customer (in this case the US DoD as indicated in red in Figure 12) are systematically different from those contracted by other customers. The other customers are statistically equivalent. In other words, differences in buying ability can impact the project's innovation outcome; however, except for the DoD's poor performance as compared to other satellite customers, the differences are insignificant.

[10] Although the assumption of equal variance for the multiple pair-wise t-tests is likely violated, several pair-wise checks (allowing for unequal variances between samples) were run and yielded similar results. Thus it is believed that the equal variance assumption is acceptable in this case.

[11] Details on the statistical analysis used to generate the results in this paper are available from the authors upon request; key outputs are included in the appendix.

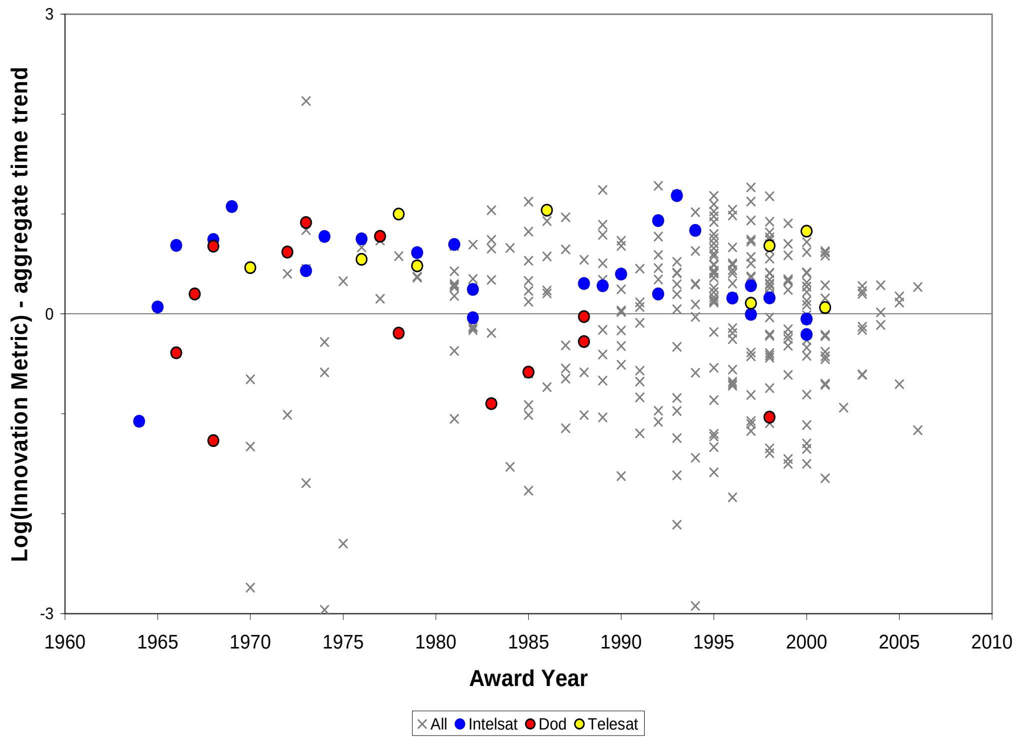

Figure 12 **Customer Differences in Time**

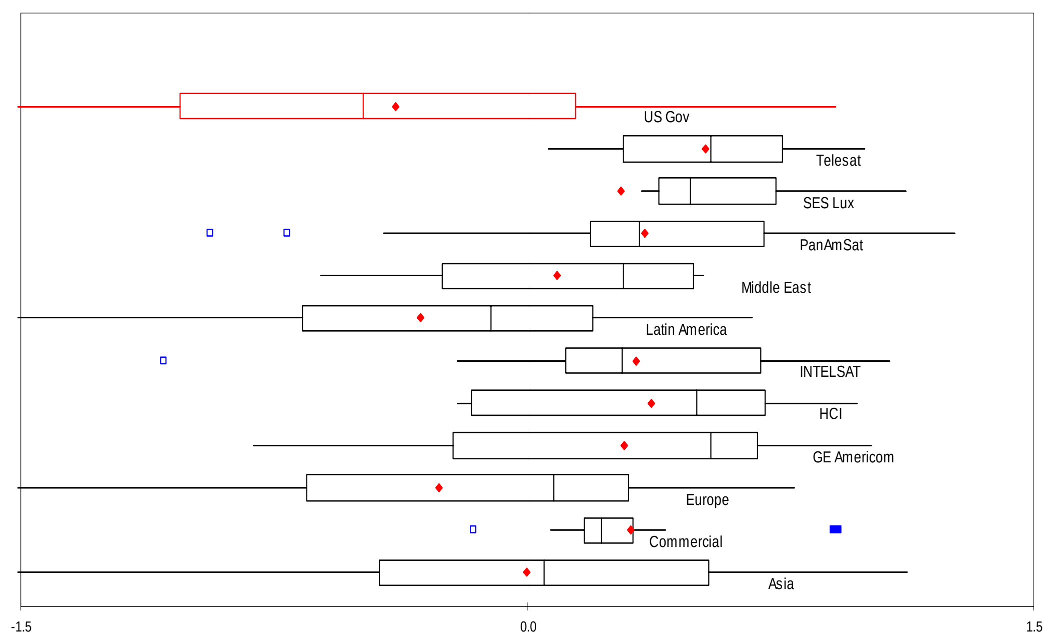

Figure 13 **Customer Comparison Box Plots**

6.2.2.2 Contractor Main Effect: Does the expected high correlation between level of relative innovation and particular contractors exist?

As above, pair-wise t-tests were performed on the difference between each mean (at the 95% confidence level). Again the Tukey method was used to adjust for multiple comparisons. Figure 14 and Figure 15 show a summary of the data. Figure 14 highlights the data points associated with three contractors in particular, showing that while each contractor shows considerable variations in innovation levels over time, there is no consistent increasing or decreasing trend in time. Thus the mean innovation level of each contractor can be compared without considering additional time effects. Figure 15 shows a box plot of all the comparisons, which yielded an overall $F_{(9,276)}$-statistic of 1 which corresponds to a p-value of 0.44. This means that there is no difference, from a statistical point of view, among the innovation outputs of the various contractors. In other words, there is no significant correlation between particular contractors and differences in innovation performance.

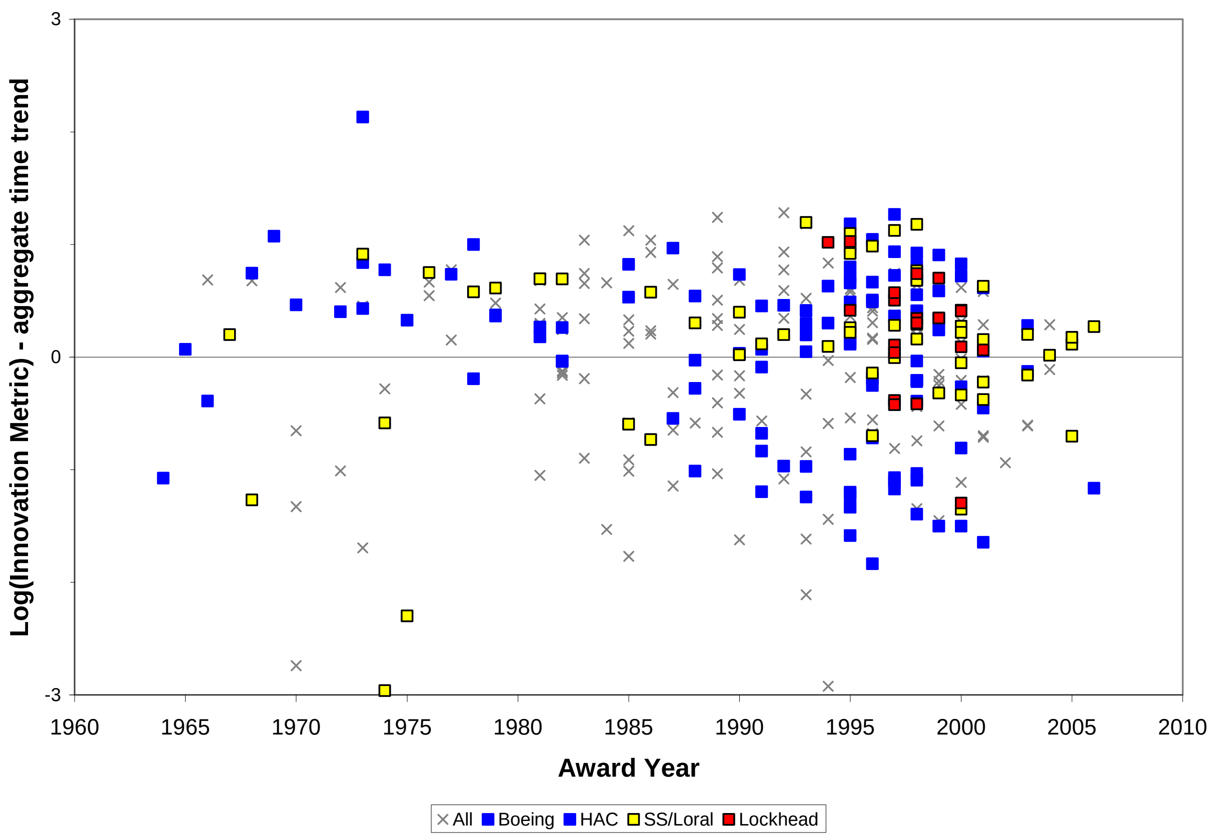

Figure 14 Contractor Differences in Time

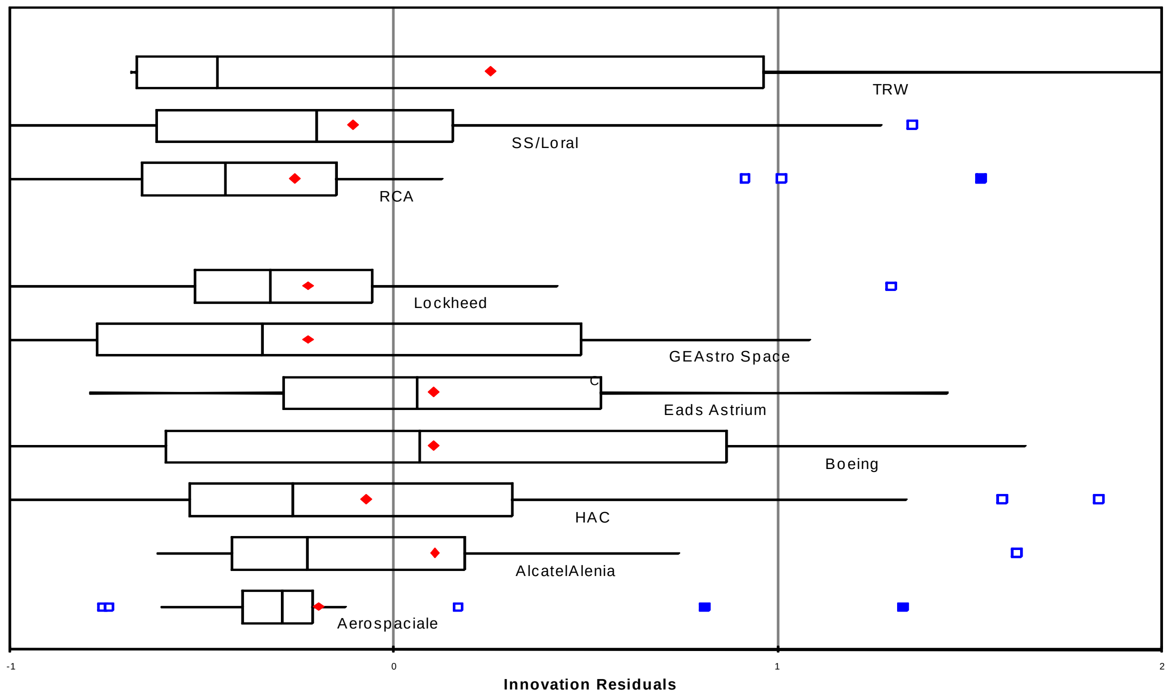

Figure 15 Box Plot of Contractor Differences

6.2.2.3 Customer-Contractor Interaction Effects: Does the expected high correlation between levels of relative innovation and particular customer-contractor pairs exist?

Since the previous sections revealed that the individual effects of particular customers and contractors are effectively insignificant, their interactions effects can be examined directly. However, there are practical limitations in a historical quasi-experiment which impact on measuring the interaction effects. There are a limited number of customers who have worked with multiple contractors and even fewer pairs of customers and contractors which have alternated working with each other. Thus, for the purposes of this analysis, the data set was reduced to programs involving one of Intelsat, Telesat and US DoD paired with one of Lockheed, Boeing and Space Systems Loral. These firms/agencies were selected purely because they were the only group with enough data points for any meaningful statistical analysis. The data is presented graphically in Figure 16.

As noted earlier, in the customer and contractor cases above, there were no apparent consistent trends in time, making aggregate tests for the difference between means appropriate; however, this is not the case here. In addition, the limited quantity of data in each group makes the prospect of achieving statistically significant differences slim (even if the differences are practically significant). Instead, a regression was performed on each customer set, with dummy variables for each contractor. The following form was assumed:

$$Icu_i con_j(t)|_j = m + \sum Mcont_i(t) \qquad (23)$$

Even with the limited data, for both the Telesat and Intelsat cases, p-values less than 0.01 were achieved for the overall regression. These differences can be observed qualitatively in Figure 16. Boeing is the contractor for each of the blue, green and purple data sets yet there was an observable difference in performance. Similarly, on the customer side, while both the green and yellow sets are Telesat acquisitions, there is an obvious difference between the two sets.

Perhaps the most interesting aspect of Figure 16 is the apparent higher order trend in time. The nature of this relationship was explored through regression. Least squares fits of the form

$$Mcont_i(t) = m + \gamma_1 t + \gamma_2 t_2 \tag{24}$$

were applied to each customer-contractor pair as shown in Figure 16. While not all significant (as a result of the sparsity of the data), the p-values (shown on the plot) are quite low, providing evidence that a second order relationship exists. In addition, a comparison of Figure 11 and Figure 16 illustrates dramatically, the extent to which customer-contractor interactions explain variations in innovation performance about the industry mean.

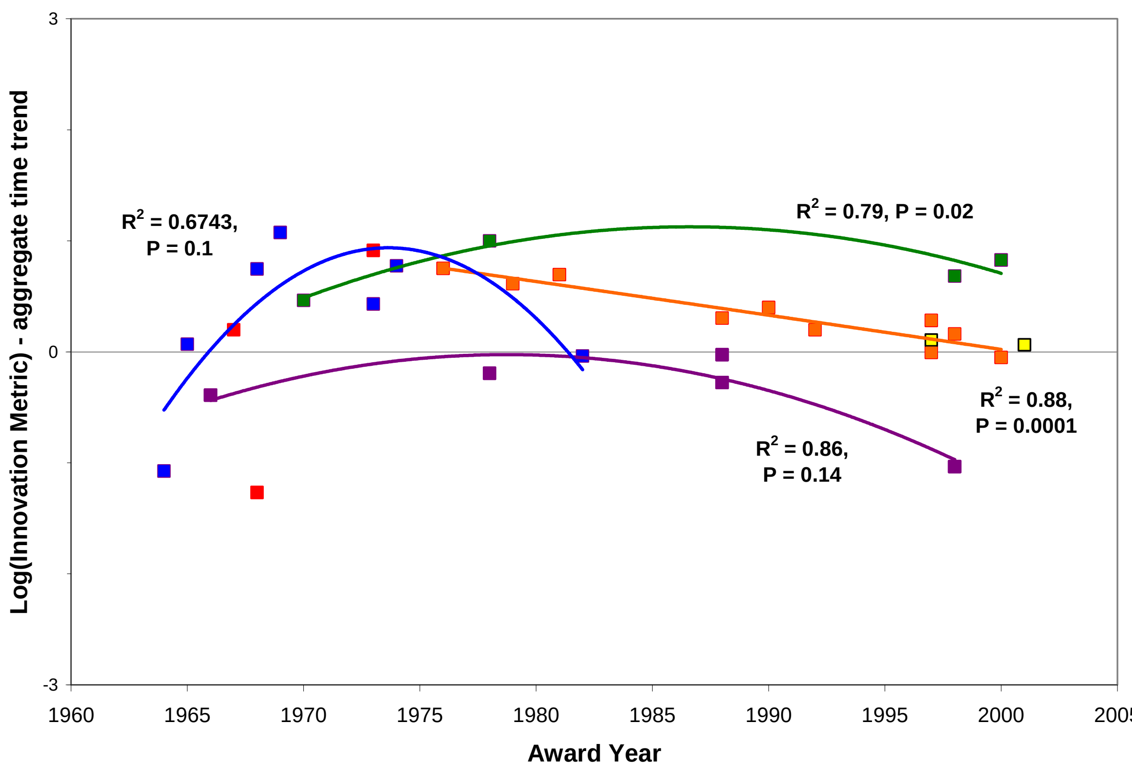

Figure 16: Customer Contractor Interactions

7 INTERPRETING THE RESULTS

In the preceding sections, a combination of data mining and statistical hypothesis tests were used to identify parameters key to explaining communication satellite innovation. Recalling that the goal of this work is to improve the innovation model developed in ref. 1 and by extension, work towards developing strategies that foster better innovation in the space sector, this section explains how the above analysis leads to an improved model. It also examines the extent to which these results can be generalized and can be used to inform strategy.

7.1 REVISING THE MODEL

Part A argued that innovation can be observed as the rate of change of performance normalized by cost over time. For the case of communication satellites, the following least upper bound estimator was proposed:

$$Innovation = \tfrac{d}{dt}\left[Power \times Life / P_{Satellite}\right] \tag{25}$$

Using the CSD dataset, the following regression model was estimated:

$$\mathrm{Ln(IM)} = 0.132t - 257.7 \tag{26}$$

However, as discussed above, despite an R^2 of 0.7, significant variation remained in the residuals. This is, in part, because the model only considers technical performance characteristics and cost factors while ignoring generational and contractual parameters. Believing that these later two categories would account for a significant portion of the unexplained variation, the above analysis combined data mining and hypothesis testing to identify and measure the importance of these factors.

The above analysis estimated both main and interaction effects for the differences between customers and contractors. Only one main effect was found to be significant; namely, that of the DoD as customer ($Mcust_{DoD}$). The interaction effects associated with several customer-contractor pairs were also found to be significant. Regression coefficients (Icu_icon_j and m_{ij}) were calculated for combinations of (Boeing, Lockheed, Loral), (Intelsat, Telesat, DoD) as discussed in section 6.2.2. When only significant effects are included, the following model results:

$$\mathrm{Ln(IM)} = 0.132t - 257.7 + Mcust_{DoD} + \sum\sum(m_{ij} + Icu_icon_jt_2) \tag{27}$$

Eq. 27 does not include any generational factors because the analysis revealed that generational differences have not historically been an important differentiator among the innovation performances of communication satellites. That is not to say that they can't be or won't be, especially since architectural parameters have been shown to be more important than business ones in other industries.[26] Rather, that there have not been many major architectural/generational changes and those few have not contributed statistically as explanatory variables in the regression. For this subset of the data, the improvement of the overall fit is substantial (compare Figure 11 and Eq. 26 with Figure 16 and Eq. 27) yielding an increased explanation of ~60%.

7.2 WHAT HAVE WE LEARNED?

While there is certainly value to understanding trends in the past, the overriding goal is to improve decision- making in the future. The question is thus, how can we use the insights captured in Eq. 27 to improve innovation in the space sector? To answer this question fully is beyond the scope of this paper, but as a beginning, this section takes a more detailed look at the implications of the results of the 3 statistical tests performed above. Namely, what does it mean that: 1) the DoD is the only customer that is different from any of the others; 2) no contractor is different from the others; and 3) some customer-contractor pairs are different and exhibit a second order relationship in time?

7.2.1 CUSTOMER DIFFERENCES

The customer differences statistical test was premised on the hypothesis that in a monopsony-oligopoly market, an appropriately advanced requirements specification is critical to generating innovation. If this were true, it would follow that "smart buyers," who specified appropriately advanced needs, would generate systematically higher levels of innovation than their less "smart" counterparts. Since the hypothesis that there would be a difference was shown to be false in general, though the DoD innovation outcomes were found to be different than other customers, what might this imply about a) the importance of requirements specification in general, and b) the DoD acquisition practices in specific?

While the existence of a difference among customers would provide evidence that needs specification is a key determinant of innovation, the lack of difference does not prove that it doesn't. This is because customer differences are not perfect equivalents to differences in how needs are specified. It was hoped that clusters of similar specification strategies would emerge; however, it may be the case that these strategies are more closely linked to project teams than organizations and, therefore, the variations within organizations are too large to observe the differences between them. Since the level of detail required to analyze spacecraft innovation at the project level is not available at present, other avenues will have to be explored.

The fact that the DoD acquisitions yielded innovation levels that were systematically lower than the industry mean is, at least in part, a function of the limitations of the metric. As discussed in ref. 1, the metric is not sufficiently detailed to capture performance characteristics such as encryption and redundancy, upon which the military places much greater value than do commercial operators. In addition the DoD's "block buy" practices, whereby the price for follow-on satellites are locked into the initial contract, is heavily penalized by the metric.

Despite these caveats, the defense acquisition system has received significant criticism in recent years (see for example ref. [1]) raising the question of whether this hypothesis test revealed something more significant than a limitation of the metric. One potential explanation for the DoD's lower ranking on the innovation metric is that the DoD is paying disproportionately for the cost of industry-wide innovation. Specifically, since DoD acquisitions contracts include new technology development costs, from which the industry at large benefits, depending on the magnitude of this investment, they could conceivably register as below average innovators despite being key drivers of change. The nature of DoD innovation is explored further in ref. [14].

7.2.2 CONTRACTOR DIFFERENCES

The contractor differences test is premised on the hypothesis that since contractors are in a better position to initiate innovation than customers (because of the contractors' intimate component and architectural knowledge), capability differentials among customers will emerge over time despite having limited incentives to innovate. These capability differentials should then lead to observable differences in innovation performance, from which positive attributes could be generalized. Since the hypothesis that there would be a difference was shown to be false, what does this imply about the importance of contractor expertise in generating innovation?

While it may be tempting to conclude that a lack of correlation between contractors and innovation performance suggests there is no differentiation among contractors, such an interpretation fails to appreciate the nature of the metric used. Innovation output, as defined in Eq. 1 and implemented in Figure 6, measures *planned* performance normalized by *contract* price; it does not account for discrepancies between contract and delivery, which, as illustrated in recent history, can be significant (*e.g.,* AEHF, NPOESS, SBIRS-High, GPS II). [1]

When the innovation history is viewed as a whole, this inability of the metric to capture delivery price performance is not a major limitation because lessons learned will be captured through the definition of the next specification; however, when particular projects are associated with particular contractors, the metric's limitation is significant. This is because much of the innovation value added by contractors occurs during development and is therefore not reflected in the contract parameters being measured. Thus, while the negative result of the contractors' differences test reinforces the notion that top-down specification plays a critical role in driving spacecraft innovation, it does not prove that differences in contractor expertise are not important as well. For this question to be tested, a database which reports statistics related to actual delivered performance and cost will be required.

7.2.3 DIFFERENCES IN CUSTOMER CONTRACTOR INTERACTIONS

The idea behind the customer contractor interactions test is that since the critical task of specifying appropriately advanced needs is the customer's responsibility while the detailed knowledge required to do so is possessed by the contractors, then successful collaboration between customers and contractors will lead to higher levels of innovation. The test would identify successful and less successful pairings which can then be examined in more detail to extrapolate generalizable characteristics. Since the hypothesis that there would be a difference was shown to be true within the limits of data availability, what does this imply about how customer contractor relationships should be structured in order to foster successful innovation over time?

The fact that some customer-contractor relationships work better than others is not in itself surprising or a particularly useful categorization. The more interesting element of the above result is the evidence of a second order time trend that it revealed (see Figure 16), because it yields insight into the structure of the relationship. This structure can be understood in one of two ways. Either the second order relationship is 1) a general phenomenon which results from the underlying innovation dynamics in the sector, or 2) it is the result of the particular set of historical circumstances and would be unique to each development.

Considering first the innovation theory point of view, a second order trend is consistent with the tension between stability and invention that characterizes the innovator's dilemma.[23] While long term working relationships tend to breed trust and collaboration[26] which are conducive to incremental innovation and increased efficiency within the existing paradigm, they also limit new ideas which typically come from entrant firms.[23] It therefore makes sense that levels of innovation would increase initially, but level off and decrease as the relationship became too stable.

On the other hand, consider, for example, the Intelsat-Boeing relationship (captured by the blue trend line in Figure 16 which shows the most pronounced instance of higher-order behavior in time. In this case, the second order relationship can be explained equally well by an examination of the history. Initially (1965 – mid 70s), Intelsat was the only provider of commercial communication satellite services and drove innovation in the sector by specifying increasingly advanced satellites from its supplier Hughes Aircraft (which later became Hughes Spacecraft, Boeing Spacecraft and Boeing Space Systems, all referred to as Boeing). For the first five series of satellites (I-V), subsequent satellite requirements were substantially increased in one area at a time (either capacity or coverage requirements) and were achieved with innovation in one or two new technologies.[49, 61]

The inflection point in the Intelsat-Boeing curve (in the early to mid 1970s) corresponds to both an internal and external shift. Internal to the relationship, the level of ambition in the requirements specification changed; for the last Intelsat-Boeing satellite, series VI, Intelsat required radically new capabilities in three areas: Capacity, Coverage and Flexibility to be achieved with five new technology developments.[49] External to the relationship, national satellite service providers began to emerge to meet the growing network needs. [51] This had the effect of both increasing and diversifying the buy-side of the market, which could explain the regression towards the mean in and of itself. Thus, before general statements can be made about how to structure customer contractor relationships so as to foster successful innovation, a more detailed survey of more customer-contractor relationships is required. The next steps involve examining multiple regression results in their detailed historical contexts, so that underlying innovation strategies can be isolated from other incidental market and technology factors.

8 Conclusion

In light of the overall objective of better understanding how innovation can, and should, happen in the space sector, this thesis set out to answer two questions: 1) *how can spacecraft innovation be meaningfully quantified and measured? And 2) using the aforementioned metric, what lessons can be learned from an analysis of the history of the communication satellite sector?* In response to the first research question, this thesis set out to frame a discussion of innovation in the space and defense sector. Specifically, it addressed three aspects of the task of measurement. It began by surveying 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 lead 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 supplier), changes over time. Innovation 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 surrogates for the parameters required to implement the proposed metrics. Based on these surrogates, the relative merits of each measurement paradigm were illustrated using the Communication Satellite Database.

The second research question was addressed through a statistical analysis of the innovation history of the communication satellite sector. Building on a communication satellite innovation metric developed in Part A and the spacecraft innovation framework captured in ref. [14], Part B presents a preliminary model of communication satellite innovation. In addition to innovation being a function of the rate of performance normalized by price, innovation was found to be strongly influenced by characteristics of the customer-contractor contractual relationship. Specifically, DoD contracts tend to result in a lower level of innovation on average as compared to other customers and particular customer-contractor pairs perform differently and exhibit a second order relationship in time. In both cases, the observed phenomenon can be explained by a combination of innovation theory and historical details. Future work will expand the customer-contractor pair analysis, so that fundamental innovation dynamics can be isolated from particular historical circumstances. Already, this analysis captured in this thesis has demonstrated the ability of this preliminary model to explain significant portions of the variations in innovation performance of hundreds of historical communication satellite programs. In so doing, it creates a basis for categorizing differences, which is a first critical step in developing a prescriptive model for innovation strategy.

8.1 Contributions

This thesis has made several contributions to the state of the art in analyzing innovation in the space and defense sector, as well as the broader discussion of acquisition reform. Though the analysis was limited to communication satellites as a sub-class of spacecraft, the approach is more generally applicable and many of the insights herein extend to other classes of spacecraft. Following the chronology of the thesis, they are:

1. An approach to quantifying spacecraft innovation:
    a. An operationalizable definition of innovation in the space sector.
    b. A framework for selecting system boundary paradigms and the corresponding innovation input and output definitions they entail.
    c. A set of idealized and surrogate metrics for each paradigm and a comparison of alternative analysis techniques.
2. The first detailed attempt to quantitatively analyze innovation in the space sector.
    a. New insights into the impact of customer-contractor interactions on innovation.
    b. Demonstration of the utility of this approach to test policy-relevant questions.

8.2 Future Work

The research was explicitly developed as a basis for future work. It is hoped that this research will be developed along one of the following three thrusts: metric and analysis tools development; space sector innovation hypothesis generation; and building towards a theory of innovation in the space sector.

8.2.1 Metric & Analysis Tools Development

The final metric selected in this Part A was the best available least-upper-bound estimator, given the current data set. While the metric was shown to be a useful differentiator among the innovation levels of historically diverse programs, better data will undoubtedly yield more nuanced results. Throughout Part A, suggestions were made for how different types of data would make particular methods more or less suitable. That discussion should be used as a guideline going forward.

8.2.2 Space Sector Innovation Hypothesis Development

Part B investigated one particular aspect of the space sector innovation dynamic; there are many other facets. Future work should investigate other attributes of innovation in the space sector, through similar statistical hypothesis tests. One promising approach, begun in [14], is to identify key challenges at the intersection of innovation mechanisms (as proposed in the management and innovation literature) and intrinsic characteristics of the space sector. The challenges can then be abstracted as testable hypothesis to be tested in the manner presented in this thesis.

8.2.3 Building Theory from Hypothesis Tests

The refined model, captured in Eq. (27), illustrates how significant portions of the variations in innovation performance of hundreds of historical communication satellite programs can be explained through the identification of simple dynamics. However, the current model is fit on a per-project basis which has limited prescriptive value. The next step towards a prescriptive model requires a typology of customer-contractor relationship categories to be defined. More data analysis will help, but it is expected that the quantitative work will need to be complemented by several carefully selected empirical cases.

8.3 Closing Remarks

During the Apollo era, federal support for large-scale technological products seemed unbounded; no objective out of reach. More recently, without the perceived threat of Soviet conquest, funding has been scaled back significantly and new less-ambitious projects continue to underperform. Nonetheless, technological progress does continue to be made; science missions journey to the far reaches of our solar system; warfare has been revolutionized by ubiquitous, real-time, access to information in deployed locations around the globe. Clearly, national mobilization in support of “technical stunts” is not the only way to generate innovation. Rather than wait around for the next Apollo, improving the acquisition system today requires an increased understanding of how to efficiently utilize the resources available. Extracting trends from historical innovation data is a start, but so much more remains to be done, building on the framework developed in this research.

REFERENCES

[1] GAO, "Space Acquisitions: Actions Needed to Expand and Sustain Use of Best Practices," U.S. Government Accountability Office. Testimony before the Subcommittee on Strategic Forces, Senate Committee on Armed Services, GAO-07-730T2007.

[2] S. Garber, "Sputnik and the Dawn of the Space Age: http://history.nasa.gov/sputnik/." vol. 2009: NASA HIstory Office, 2007.

[3] W. A. McDougall, *... the Heavens and the Earth: A Political History of the Space Age*. USA: Basic Books Inc., 1985.

[4] U. o. C. Scientists, "UCS Database 2009," http://www.ucsusa.org, 2009.

[5] "Report of the Committee on Armed Services, House of Representatives H.R. 5122," 2006.

[6] G. Musser, "Space Exploration Sticker Shock -- Economics at NASA," in *Scientific American*, 2009.

[7] A. Stern, "NASA's Black Hole Budgets," in *The New York Times* Clifton, VA, 2008.

[8] GAO, "NASA: Lack of Disciplined Cost-Estimating Process Hinders Effective Program Management," GAO-04-6422004.

[9] GAO, "National Aeronautics and Space Administration Significant Actions Needed to Address long-standing Financial Management Problems," GAO-04-754T2004.

[10] GAO, "NASA: Compliance with Cost Limits," GAO-05-492R2005.

[11] GAO, "NASA: Agency Has Taken Steps Toward Making Sound Investment Decisions for Ares I but Still Faces Challenging Knowledge Gaps," GAO-08-512007.

[12] GAO, "Business Modernization: NASA Must Consider Agency-wide Needs to Reap the Full Benefits of Its Enterprise Management System Modernization Effort," GAO-07-6912007.

[13] H. W. J. Gehman, J. L. Barry, D. W. Deal, J. N. Hallock, K. W. Hess, G. S. Hubbard, J. M. Logson, D. D. Osherch, S. K. Ride, R. E. Tetrault, S. A. Turcotte, S. B. Wallace, and S. E. Widnall, "Columbia Accident Investigation Board Report," NASA, Washington DC2003.

[14] Z. Szajnfarber, M. G. Richards, and A. L. Weigel, "Implications of DoD Acquisition Policy for Innovation: The Case of Operationally Responsive Space," in *AIAA Space 2008* San Diego, CA: AIAA, 2008.

[15] C. E. Associates, "The Economic Impact of NASA R&D Spending," NASA, 1976.

[16] D. Brown and M. W. Moyles, "Re-Thinking the Relationship," Space News, 2008.

[17] J. W. Baqwell and C. E. Mahle, "The Role of Technology in Influencing Future Civil Communication Satellites," *Proceedings of the IEEE,* vol. 78, pp. 1190-1205, 1990.

[18] C. W. Sherwin and R. S. Isenson, "Project Hindsight," *Science,* vol. 156, pp. 1571-1577, 1967.

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

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

[21] J. Fagerberg, D. C. Mowery, and R. R. Nelson, "The Oxford Innovation Handbook," Oxford University Press, 2005.
[22] P. Anderson and M. L. Tushman, "Technological Discontinuities and Dominant Designs: a Cyclical Model of Technological Change," *Administrative Science Quarterly,* vol. 35, 1990.
[23] C. Christensen, *The Innovator's Dilemma*. New York: Harper Collins, 2003.
[24] 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.
[25] J. M. Utterback and W. J. Abernathy, "A Dynamic Model of Process and Product Innovation," *The International Journal of Management Science,* vol. 3, 1975.
[26] J. M. Utterback, *Mastering the Dynamics of Innovation*. Cambridge, MA: Harvard Business Press, 1994.
[27] S. Thomke and E. v. Hippel, "Customers as Innovators," *Harvard Business Review,* 2004.
[28] J. A. Schumpeter, *The Theory of Economic Development*. New York: Harvard University Press, 1934.
[29] 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.
[30] K. Smith, "Measuring Innovation," in *The Oxford Innovation Handbook*, J. Fagerberg, D. C. Mowery, and R. R. Nelson, Eds.: Oxford University Press, 2005.
[31] M. Coccia, "Technometrics: Origins, Historical Evolution and New Directions," *Technological Forecasting and Social Change,* vol. 72, pp. 944-979, 2005.
[32] 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.
[33] A. J. Alexander and R. R. Nelson, "Measuring Technological CHange:; Aircraft Turbine Engines," *Technological Forecasting and Social Change,* vol. 5, pp. 189-203, 1973.
[34] S. Managi, 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.
[35] R. U. Ayres, "Empirical Measures of Technological Change at Sectoral Level," *Technological Forecasting and Social Change,* vol. 27, pp. 229-247, 1985.
[36] 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.
[37] C. Beaudry, "Enterprise in Orbit: The Supply of Communication Satellites," *Economics of Innovation and New Technology,* vol. 15, pp. 679-700, 2006.
[38] 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.
[39] 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.

[40] 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.
[41] 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.
[42] 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.
[43] 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.
[44] R. L. Keeney and H. Raiffa, *Decisions with Multiple Objectives - Preferences and Value Tradeoffs*. Cambrige, UK: Cambridge University Press, 1993.
[45] 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.
[46] A. L. Weigel, "Evaluating the Cost and Risk Impacts of Launch Choices," *Journal of Spacecraft and Rockets,* vol. 41, pp. 103-110, 2004.
[47] 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.
[48] R. Rusch, "Communication Satellite Database," 2006 ed Palos Verdes, CA: TelAstra, 2006.
[49] D. H. Martin, *Communication Satellites 1958-1995*. El Segundo, CA: Aerospace Corporation, 1996.
[50] J. T. Richelson, "U.S. Satellite Imagery 1960-1999," in *National Security Archive Electronic Briefing Book*. vol. 13.
[51] A. J. Butricia, *Beyond the Ionosphere: Fifty Years of Satellite Communication*. Washington D.C.: NASA History Office, 1994.
[52] M. Kantardzic, *Data Mining: Concepts, Models, Methods, and Algorithms*: John Wiley & Sons, 2003.
[53] R. Welsch, "Lecture notes: Statistical Reasoning and Data Modeling," Cambridge: Massachusetts Institute of Technology, Fall 2007.
[54] Y. Peng, G. Kou, Y. Shi, and Z. Chen, "A Descriptive Framework for the Field of Data Mining and Knowledge Discovery," *International Journal of Information Technology and Decision Making,* vol. 7, pp. 639-682, 2008.
[55] F. Usama, G. Piatesky-Shapiro, and P. Smyth, "From Data Mining to Knowledge Discovery in Databases," *American Association for Artificial Intelligence,* 1996.
[56] W. J. Abernathy and K. B. Clark, "Innovation: Mapping the winds of creative destruction," *Research Policy,* vol. 22, 1993.
[57] Z. Szajnfarber and A. L. Weigel, "Innovation Dynamics of Large Complex Technological Products in a Monopsony Market Structure: The Case of ESA Science Missions," in *Atlanta Conference on Science Technology and Innovation Policy* Atlanta, Georgia: IEEE, 2007.

[58] R. Rothwell and W. Zegveld, "Reindustrialization and Technology," in *Towards the Fifth-generation Innovation Process*. vol. 11, R. Rothwell, Ed.: International Marketing Review, 1994, pp. 7-31.
[59] W. Adams and W. J. Adams, "The Military-Industrial Complex: A Market Structure Analysis," *The American Economic Review,* vol. 62, pp. 279-287, 1972.
[60] D. J. Teece, "Profiting from Technological Innovation: Implications for Integration, Collaboration, Licensing and Public Policy," *Research Policy,* 1986.
[61] D. J. Whalen, "Communication Satellites: Making the Global Village Possible," NASA History Office.

APPENDIX A: FULL SET OF CONTRACTOR PAIR-WISE T-TESTS

Summary stats for samples

	Residual_Aerospaciale	Residual_AlcatelAlenia	Residual_ATK	Residual_Boeing	Residual_Eads Astrium	Residual_GEAstro Space	Residual_Lockhead	Residual_RCA	Residual_SS/Loral	R
Sample sizes	18	15	72	40	25	15	20	18	55	
Sample means	-0.195	0.106	-0.072	0.104	0.104	-0.223	-0.223	-0.256	-0.106	
Sample standard deviations	0.515	0.807	0.749	0.821	0.502	0.709	0.547	0.726	0.785	
Sample variances	0.266	0.651	0.562	0.675	0.252	0.503	0.299	0.527	0.616	
Weights for pooled variance	0.062	0.051	0.257	0.141	0.087	0.051	0.069	0.062	0.196	

Number of samples	10
Total sample size	286
Grand mean	-0.058
Pooled variance	0.554
Pooled standard deviation	0.744

OneWay ANOVA table

Source	SS	df	MS	F	p-value
Between variation	5.015	9	0.557	1.006	0.4350
Within variation	152.830	276	0.554		
Total variation	157.846	285			

Confidence intervals for mean differences

Confidence level 95.0%

Tukey method

Difference	Mean diff	Lower	Upper	Signif?
Residual_Aerospaciale - Residual_AlcatelAlenia	-0.301	-1.134	0.531	No
Residual_Aerospaciale - Residual_ATK	-0.123	-0.750	0.504	No
Residual_Aerospaciale - Residual_Boeing	-0.299	-0.974	0.377	No
Residual_Aerospaciale - Residual_Eads Astrium	-0.299	-1.035	0.437	No
Residual_Aerospaciale - Residual_GEAstro Space	0.028	-0.804	0.860	No
Residual_Aerospaciale - Residual_Lockhead	0.028	-0.746	0.801	No
Residual_Aerospaciale - Residual_RCA	0.061	-0.732	0.855	No
Residual_Aerospaciale - Residual_SS/Loral	-0.089	-0.735	0.557	No
Residual_Aerospaciale - Residual_TRW	-0.447	-1.458	0.565	No
Residual_AlcatelAlenia - Residual_ATK	0.178	-0.497	0.854	No
Residual_AlcatelAlenia - Residual_Boeing	0.003	-0.718	0.723	No
Residual_AlcatelAlenia - Residual_Eads Astrium	0.002	-0.775	0.780	No
Residual_AlcatelAlenia - Residual_GEAstro Space	0.330	-0.539	1.199	No
Residual_AlcatelAlenia - Residual_Lockhead	0.329	-0.484	1.142	No
Residual_AlcatelAlenia - Residual_RCA	0.363	-0.469	1.195	No
Residual_AlcatelAlenia - Residual_SS/Loral	0.212	-0.481	0.906	No
Residual_AlcatelAlenia - Residual_TRW	-0.145	-1.187	0.897	No
Residual_ATK - Residual_Boeing	-0.176	-0.645	0.293	No
Residual_ATK - Residual_Eads Astrium	-0.176	-0.728	0.376	No
Residual_ATK - Residual_GEAstro Space	0.151	-0.524	0.827	No
Residual_ATK - Residual_Lockhead	0.151	-0.451	0.752	No
Residual_ATK - Residual_RCA	0.184	-0.443	0.812	No
Residual_ATK - Residual_SS/Loral	0.034	-0.392	0.460	No
Residual_ATK - Residual_TRW	-0.324	-1.211	0.563	No
Residual_Boeing - Residual_Eads Astrium	0.000	-0.607	0.607	No
Residual_Boeing - Residual_GEAstro Space	0.327	-0.393	1.048	No
Residual_Boeing - Residual_Lockhead	0.326	-0.325	0.978	No
Residual_Boeing - Residual_RCA	0.360	-0.315	1.036	No
Residual_Boeing - Residual_SS/Loral	0.210	-0.285	0.704	No
Residual_Boeing - Residual_TRW	-0.148	-1.070	0.774	No
Residual_Eads Astrium - Residual_GEAstro Space	0.327	-0.450	1.105	No
Residual_Eads Astrium - Residual_Lockhead	0.327	-0.387	1.041	No
Residual_Eads Astrium - Residual_RCA	0.360	-0.375	1.096	No
Residual_Eads Astrium - Residual_SS/Loral	0.210	-0.364	0.784	No
Residual_Eads Astrium - Residual_TRW	-0.148	-1.114	0.819	No
Residual_GEAstro Space - Residual_Lockhead	-0.001	-0.814	0.812	No
Residual_GEAstro Space - Residual_RCA	0.033	-0.799	0.865	No
Residual_GEAstro Space - Residual_SS/Loral	-0.117	-0.810	0.576	No
Residual_GEAstro Space - Residual_TRW	-0.475	-1.517	0.567	No
Residual_Lockhead - Residual_RCA	0.034	-0.739	0.807	No
Residual_Lockhead - Residual_SS/Loral	-0.117	-0.738	0.505	No
Residual_Lockhead - Residual_TRW	-0.474	-1.470	0.521	No
Residual_RCA - Residual_SS/Loral	-0.150	-0.797	0.496	No
Residual_RCA - Residual_TRW	-0.508	-1.519	0.503	No
Residual_SS/Loral - Residual_TRW	-0.358	-1.258	0.543	No

APPENDIX B: REGRESSION OUTPUT FOR CUSTOMER-CONTRACTOR PAIRS

Results of backward regression for Boeing and DoD (Purple)

Step 1 - All variables entered

Summary measures

Multiple R	0.9289
R-Square	0.8629
Adj R-Square	0.7259
StErr of Est	0.2023

ANOVA Table

Source	df	SS	MS	F	p-value
Explained	2	0.5155	0.2578	6.2958	0.1371
Unexplained	2	0.0819	0.0409		

Regression coefficients

	Coefficient	Std Err	t-value	p-value	Lower limit	Upper limit
Constant	-9983.6836	3208.1890	-3.1119	0.0896	-23787.4066	3820.0394
Pce	10.0910	3.2382	3.1162	0.0894	-3.8419	24.0239
Pctte	-0.0025	0.0008	-3.1206	0.0892	-0.0061	0.0010

Results of backward regression for Boeing and Telesat (Green)

Step 1 - All variables entered

Summary measures

Multiple R	0.8901
R-Square	0.7922
Adj R-Square	0.7403
StErr of Est	0.1952

ANOVA Table

Source	df	SS	MS	F	p-value
Explained	1	0.5812	0.5812	15.2521	0.0175
Unexplained	4	0.1524	0.0381		

Regression coefficients

	Coefficient	Std Err	t-value	p-value	Lower limit	Upper limit
Constant	0.0834	0.1380	0.6040	0.5784	-0.2998	0.4665
Pcttc	0.0000	0.0000	3.9054	0.0175	0.0000	0.0000

Results of backward regression for Loral and Intelsat (Orange)

Summary measures

		Change	% Change
Multiple R	0.9398	0.0000	0.0%
R-Square	0.8833	0.0000	0.0%
Adj R-Square	0.8687	0.0188	2.2%
StErr of Est	0.1013	-0.0070	-6.5%

ANOVA Table

Source	df	SS	MS	F	p-value
Explained	1	0.6206	0.6206	60.5282	0.0001
Unexplained	8	0.0820	0.0103		

Regression coefficients

	Coefficient	Std Err	t-value	p-value	Lower limit	Upper limit
Constant	30.6946	3.9025	7.8654	0.0000	21.6954	39.6937
Pcttb	-7.6680E-06	0.0000	-7.7800	0.0001	0.0000	0.0000

Results of backward regression for Boeing and Intelsat (Blue)

Summary measures

Multiple R	0.8212
R-Square	0.6743
Adj R-Square	0.5115
StErr of Est	0.5020

ANOVA Table

Source	df	SS	MS	F	p-value
Explained	2	2.0874	1.0437	4.1409	0.1061
Unexplained	4	1.0082	0.2521		

Regression coefficients

	Coefficient	Std Err	t-value	p-value	Lower limit	Upper limit
Constant	-61239.0430	22115.1934	-2.7691	0.0504	-122640.6633	162.5774
Pca	62.0578	22.4201	2.7680	0.0504	-0.1904	124.3061
Pctta	-0.0157	0.0057	-2.7668	0.0505	-0.0315	0.0001

Note: a much better fit (R^2=.9) can be achieved with a third order fit; however, no empirical justification for third order time dependence could be reasoned.