What Drives Spacecraft Innovation?

A Quantitative Analysis of Communication Satellite Innovation History

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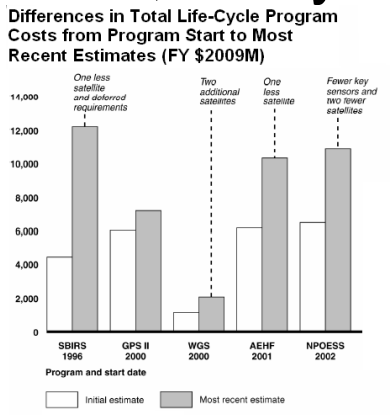
Motivation

- Recent acquisition performance

	Recommendations from Recent Review Boards	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

Source: Adapted from (Szajnfarber et al. 2008)

- Multiple "blue ribbon" panels, many recommendations



Source: Adapted from GAO-09-705T (2009)

- Opportunity for external insights and theory

Research Definition

- **Innovation** is a measure of how performance, normalized by resource constraints, changes over time. This can involve:
  - Generating a wholly new capability
  - Reducing the resources required to achieve an existing capability (e.g., making the system cheaper or lighter).

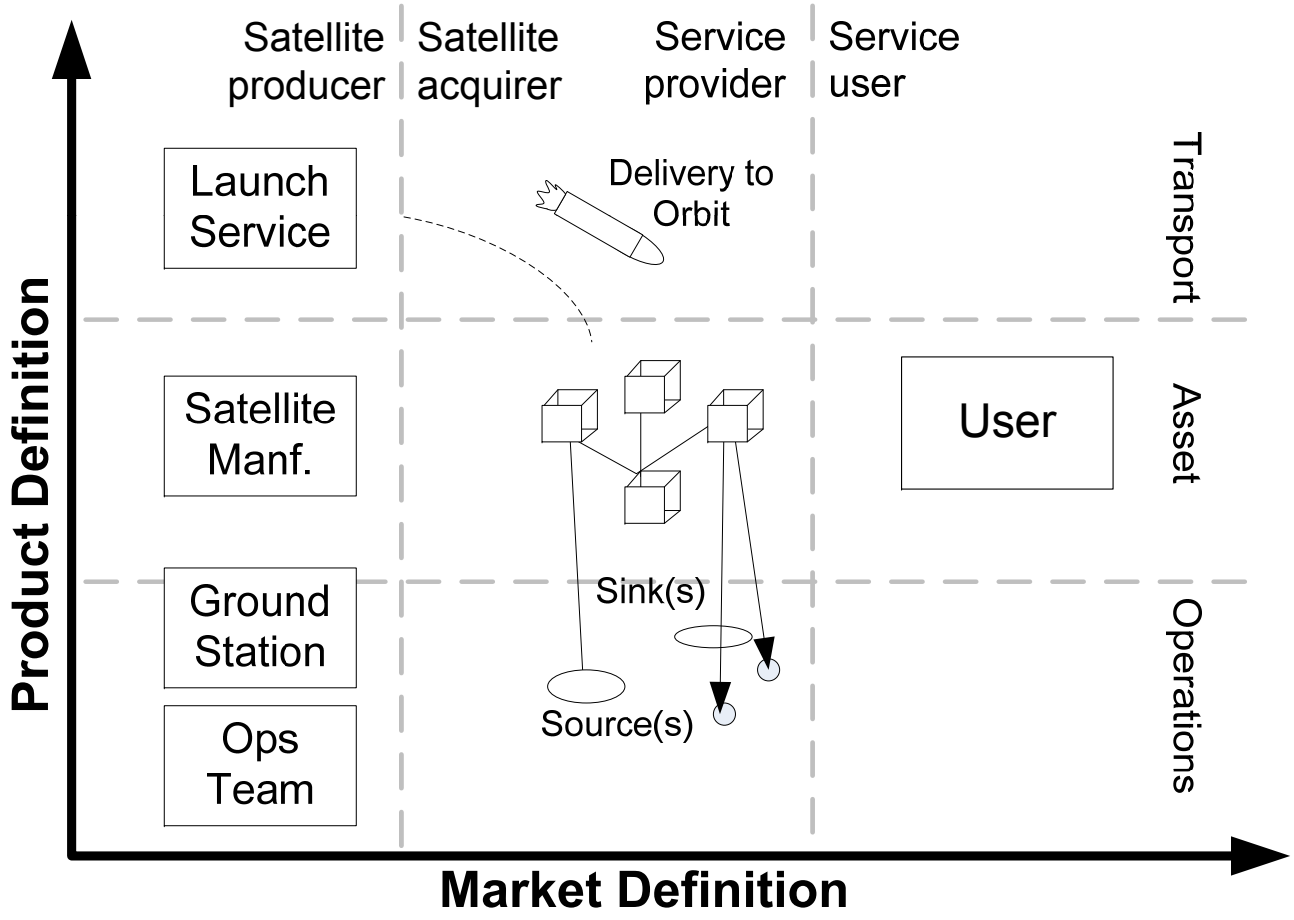
$$i = \frac{d}{dt}\left[\frac{Output(t)}{Input(t)}\right]$$

- **Objective**: Gain a better understanding of how innovation can, and should, be encouraged in the space sector through quantitative analysis

- **Key Questions**:
  1. How can spacecraft innovation be meaningfully quantified and measured?
  2. Using the metric from Q1, what lessons can be learned from an analysis of the history of the communication satellite sector?

Part A: Measuring Innovation

- **Innovation** is: $$i = \frac{d}{dt}\left[\frac{Output(t)}{Input(t)}\right]$$
- Input-output definition depends on system boundary



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Part A: Measuring Innovation

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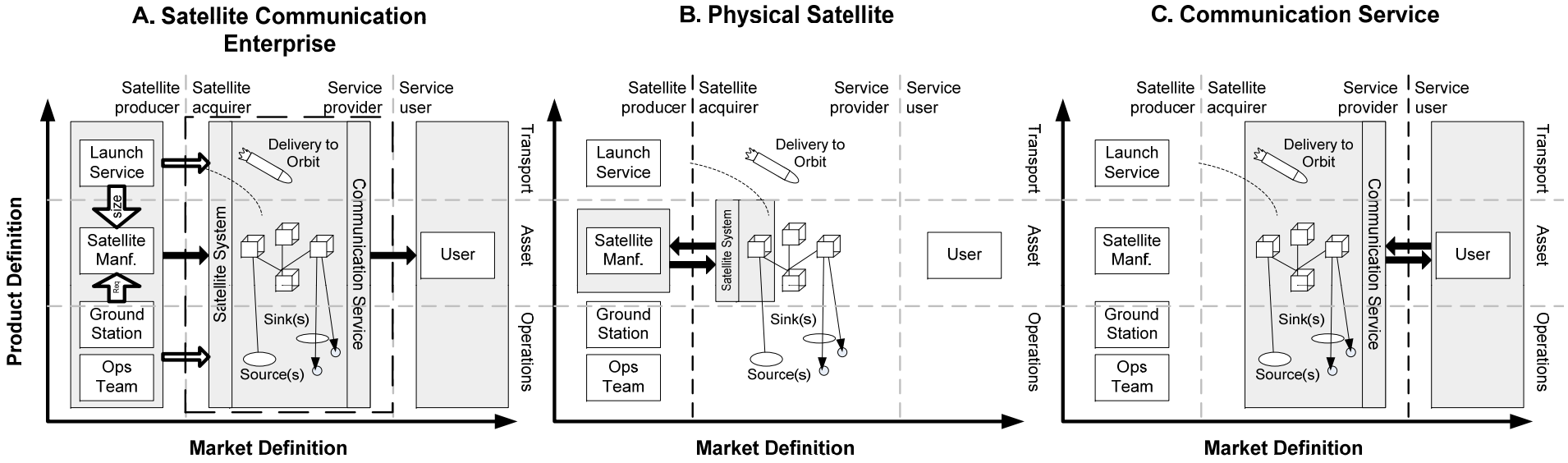
- Input-output definition depends on system boundary



- Given realities of historical data collection, estimators necessary

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)	$f(Is, r, In, Av) / P_{service}$	$MoS / P_{service}$

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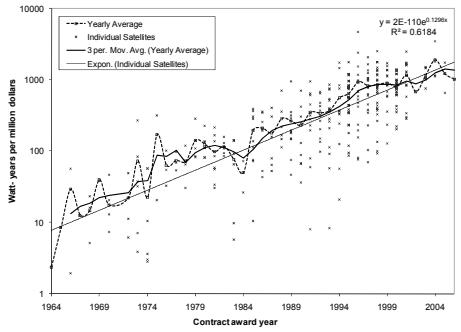
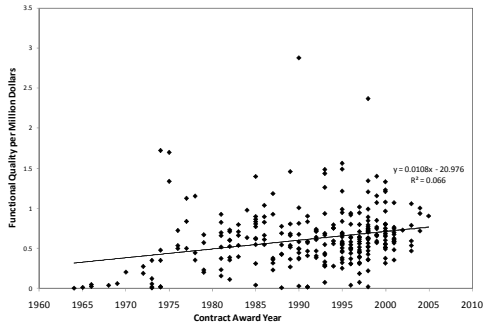
Selecting a Metric for Further Analysis

Paradigm	Metric	Plot	Selection
Communication Satellite Enterprise	$i = \frac{d}{dt}\left[\frac{O(t)}{I(t)}\right] = \frac{d}{dt}\left[\frac{W_{sat} \times T}{P_{contract}}\right]$		✓
Physical Satellite	$i = \frac{d}{dt}\left[\frac{O(t)}{I(t)}\right] = \frac{d}{dt}\left[\frac{\sum_{i}^{n} a_i X_i}{P_{contract}}\right]$		
Communication Service	$i = \frac{d}{dt}\left[\frac{O(t)}{I(t)}\right] = \frac{d}{dt}\left[\frac{MoS}{P_{service}}\right]$	No data currently available Potential for improved estimate	

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Part B: Analysis of History

- **Objective**: Gain a better understanding of how innovation can, and should, be encouraged in the space sector through quantitative analysis

- **Key Questions**:
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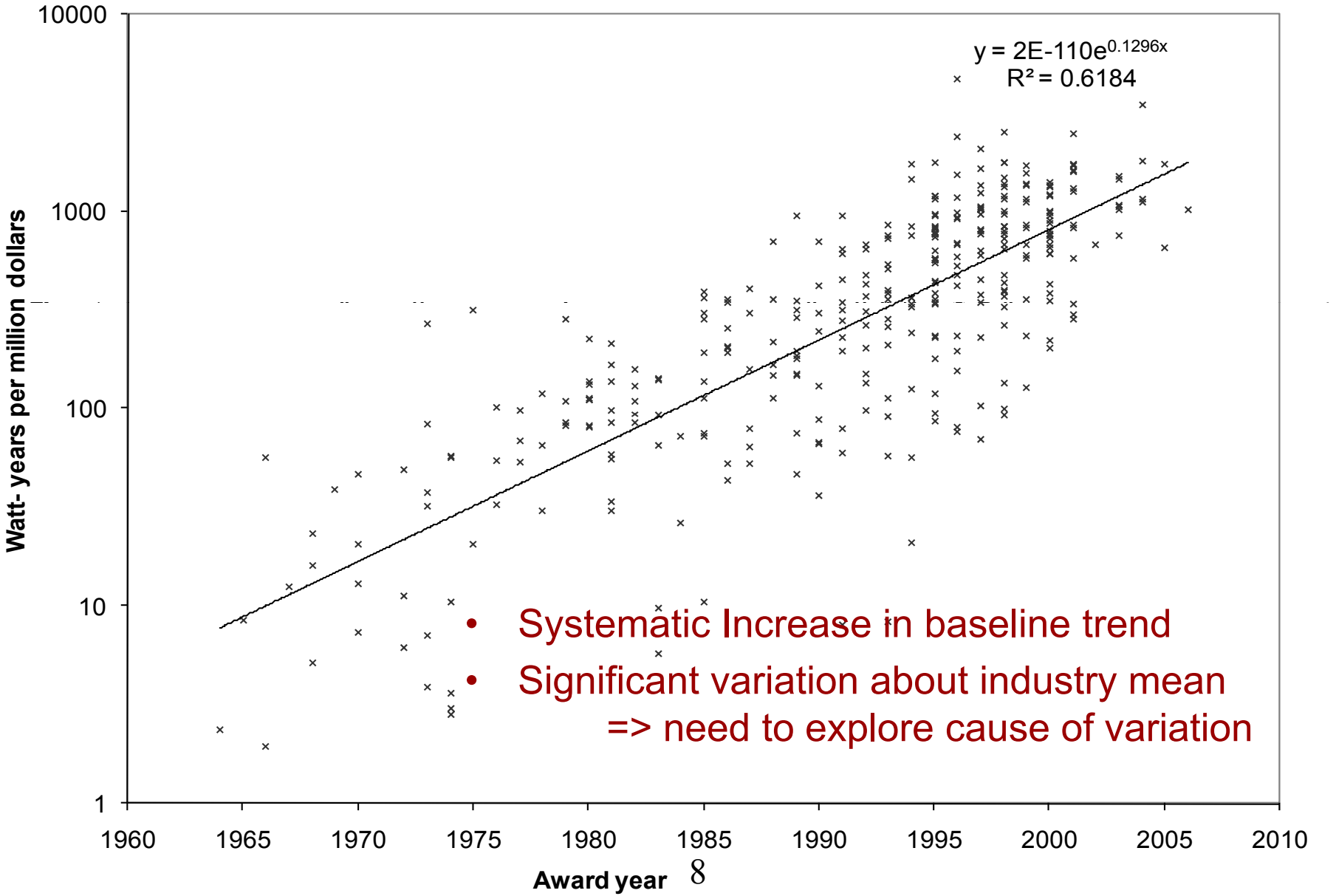
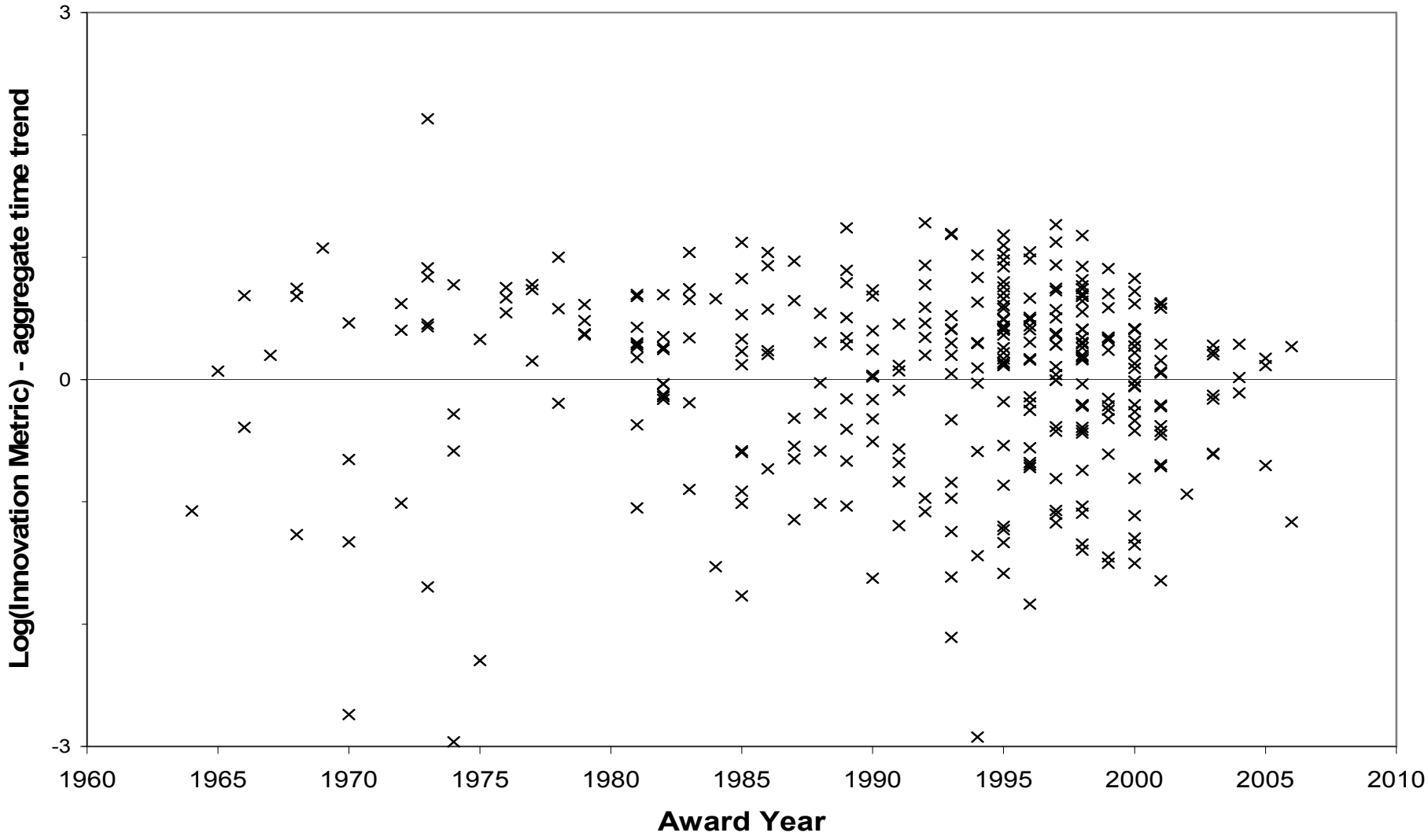
What can be learned from this data?



- Systematic Increase in baseline trend
- Significant variation about industry mean
  => need to explore cause of variation

Exploration of differences among customers, contractors and their interactions



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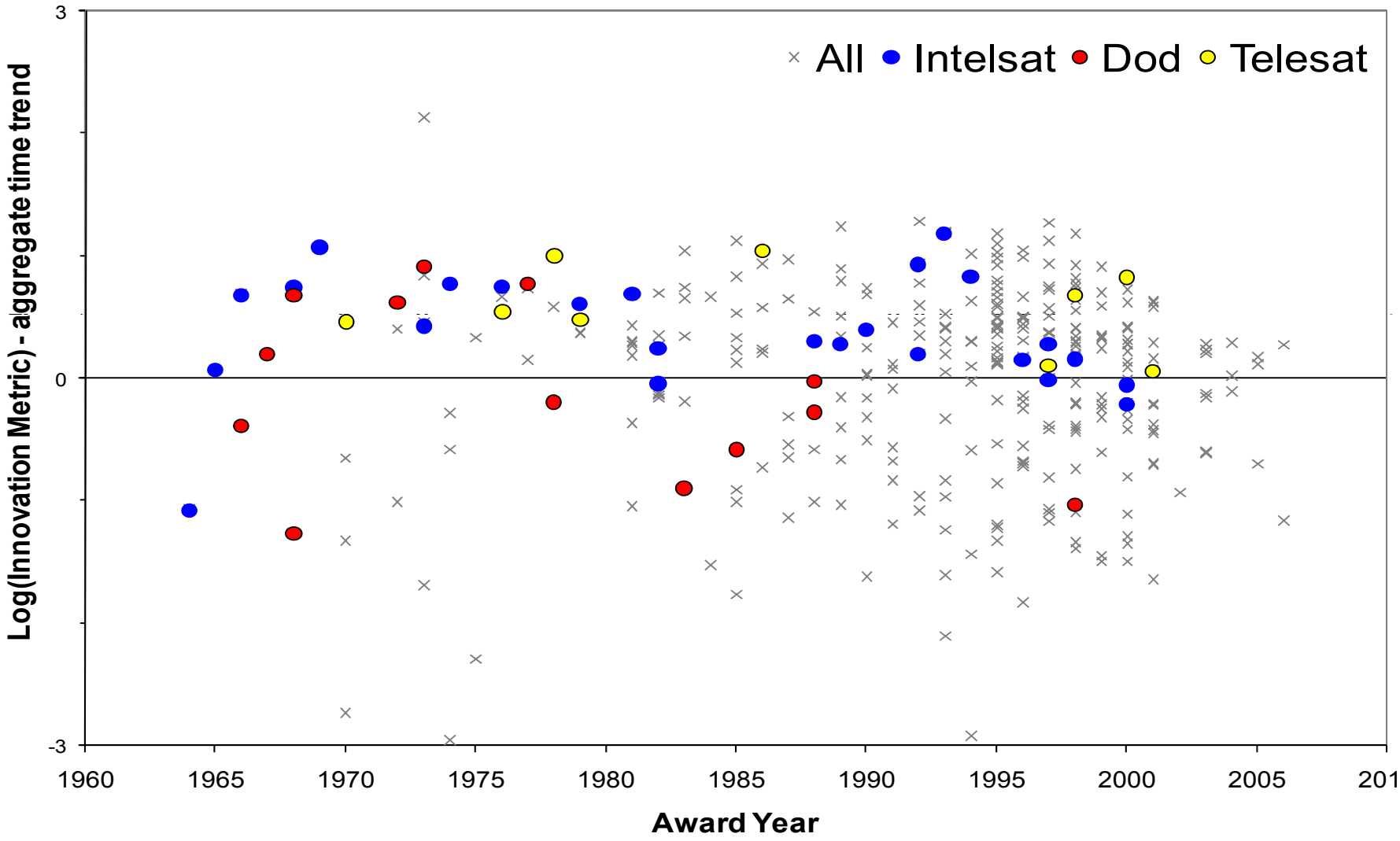

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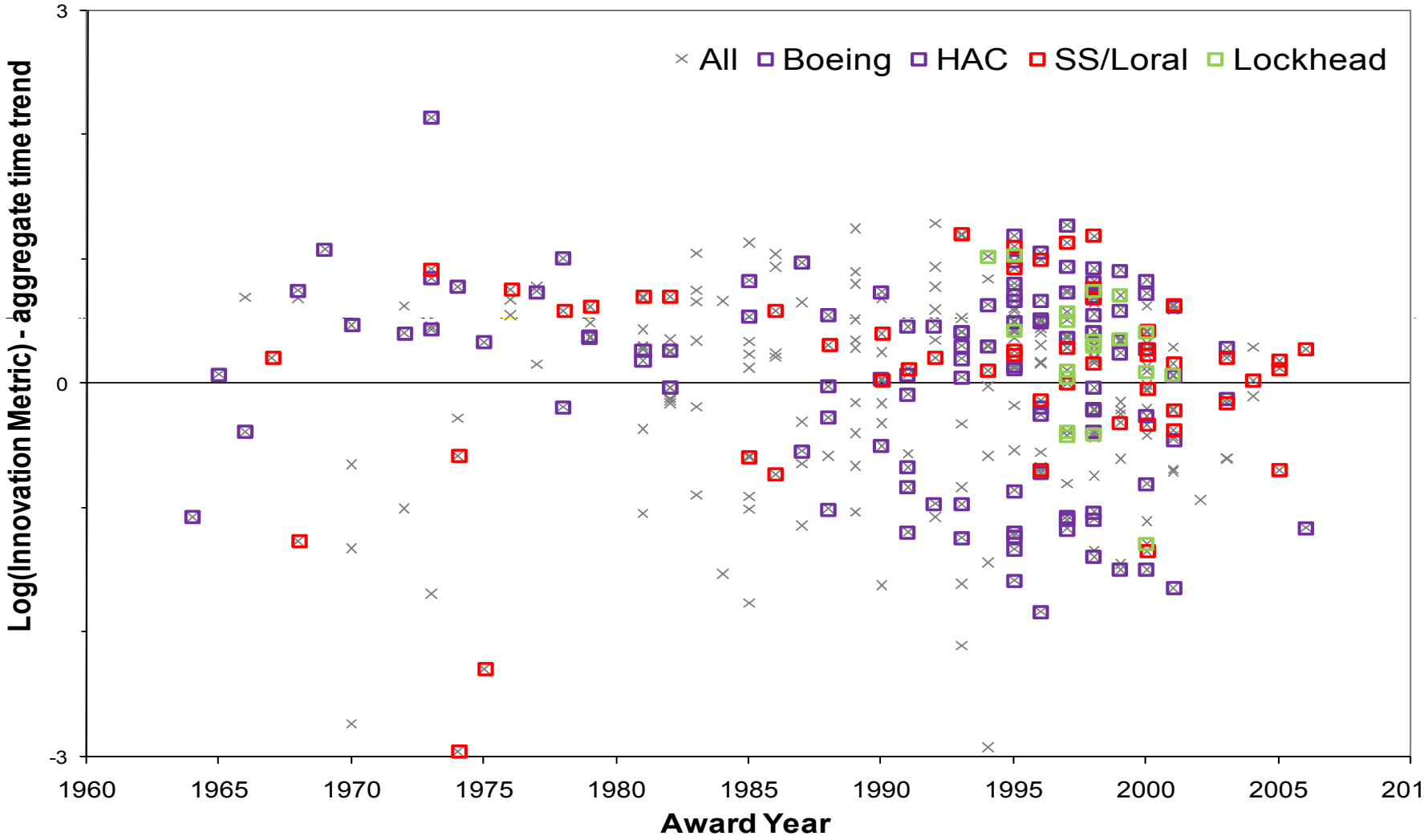

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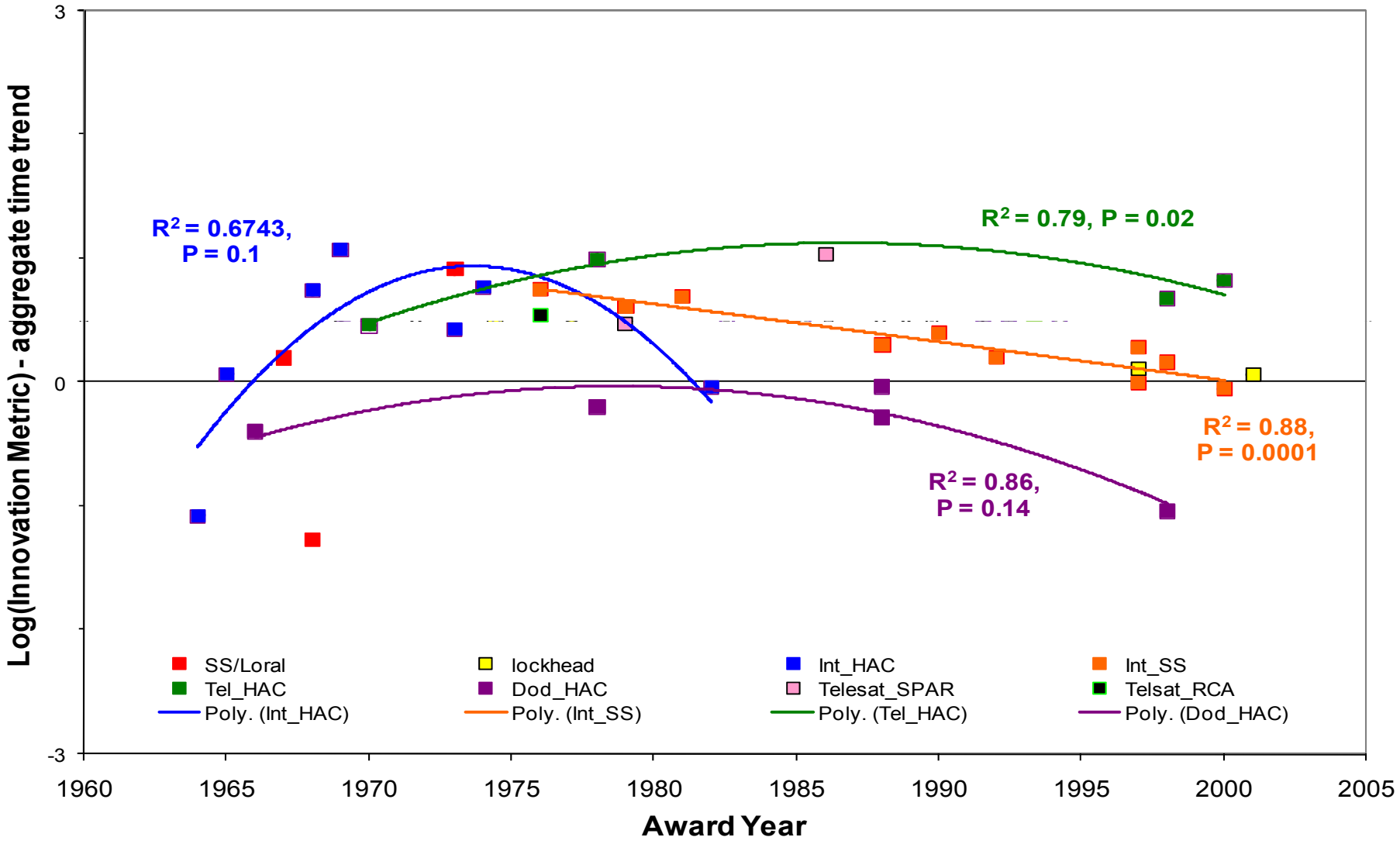

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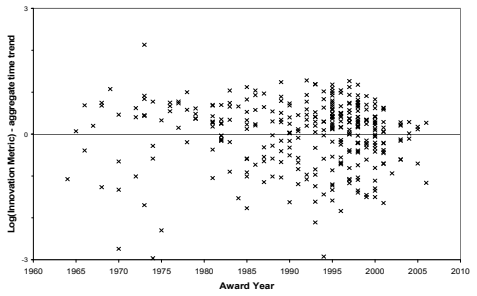
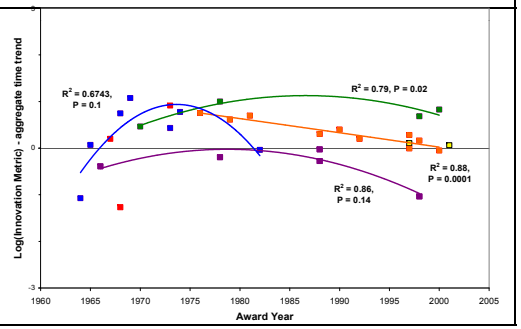
Summary of Results

Method		Results	
Data Mining	$IM = \alpha_0 + \alpha_1 t + \beta_1 g_1 + \ldots + \beta_n g_n + \gamma_1 C_1 + \ldots + \gamma_n C_n$	• Significant contractual Parameters (G_n) • Insignificant generational Parameters (C_n)	Eliminate time trend 
Hypothesis Testing	$H_0 = \Delta$Customer $H_1 = \Delta$Contractor $H_2 = \Delta$Pair	• customers equivalent • contractors equivalent • Pairs different • 2nd order trend	

$$\ln[I(t)] = c_0 + c_1 t + c_{2(i,\bullet)} + \sum_{i=1}^{n}\sum_{j=1}^{m}\left(c_{2(i,j)} + c_{3(i,j)} t^2\right)$$

The industry innovation baseline is increasing exponentially over time

Acquisitions by the US government yield a statistically different innovation outcome

Different customer-contractor pairs exhibit statistically different relative innovation performance.

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Contributions

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.