Mapping the "Valley of Death": Managing Selection and Technology Advancement in NASA's Small Business Innovation Research Program

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Abstract

We determine the risk mitigation process inherent in managing a portfolio of technologies diverse in both their readiness for infusion and the nature of the performing organization, focusing on the so-called "valley of death" in which the technology's principles have been proven but prototypes have yet to be developed. Using the Technology Readiness Levels (TRLs) of projects funded by the National Aeronautics and Space Administration (NASA) Small Business Innovation Research (SBIR) proposals and awards, we find that the result of selection is a tendency toward larger companies. In the second round of funding, technology maturity is a stronger determinant of selection and company headcount is no longer a statistically significant driver. This combination allows the program to manage risk and deliver real technical advancement from even the smallest companies. We find that technologies typically advance from TRL 2, concept formulation, at the program's outset to roughly TRL 5, component validation, at the program's conclusion; these outcomes precede economic benefits from the subsidy. These findings illuminate a mechanism to address risk as well as demonstrating the technical outcomes of a managed early-stage technology program.

Keywords: TRL, NASA, SBIR, entrepreneurship, innovation, technology maturity

Introduction

The term "valley of death" (VOD) is broadly used to describe funding requirements in transitioning technologies from laboratory to application, and refers to technology readiness levels (TRL) of roughly 2-6. The funding gap becomes most severe for technologies at the validation and prototype phase because it is expensive to advance from one level of maturity to the next, and yet the remaining technical risk is significant enough that project funding is largely inaccessible. However, a manager must support some of these expensive, yet still risky, technologies in order to harvest future potential benefits.

For so-called "deep" or manufacturing-oriented technologies, the problem is particularly acute relative to digital technologies, as prototyping and testing costs skyrocket while significant risks remain. For this reason, many government subsidy programs support research and development at precisely this stage. Often these subsidies are directed toward small and medium enterprises in hopes of stimulating economic and employment growth with the subsidized research.

In the United States, the Small Business Innovation Research (SBIR) program represents a major research and development (R&D) subsidy. While the economic outcomes of the SBIR program have been studied extensively, little is known regarding the actual selection process nor the associated technical advances. We will ask questions including: How does the selection process address the risks of small businesses conducting early-stage research? How do these technologies advance in readiness through the subsidy program? To address these questions, will use previously unexplored data from the National Aeronautics and Space Administration (NASA) SBIR program; the database includes information on the technology readiness levels (TRL), a standard method to assess technology maturity in the aerospace industry. In so doing, we contribute to the literature on subsidies and systems engineering, linking funding to technology advancement and offering new insights for the discussion of innovation policy.

Literature review

In the United States, one mechanism to support R&D in small companies is the SBIR program [1]. Startups contribute disproportionately to economic growth [2], [3] but young, small technology firms may struggle to attract resources from private capital due to high risk, especially in less active investment periods [4]. To remedy this, subsidy programs have developed around the world [5]–[7]. Although funding could in principle "crowd-out" or displace private investment [8], evidence suggests that this is generally not the case [9]–[11] and instead, the subsidy enables the firm to pursue research that would be otherwise discontinued [12], [13] and private investments may follow [14]–[16]. Specific outcomes are linked to the company's prior R&D experience [17], and combinations of public support may decrease the subsidy's effectiveness [18], [19].

The SBIR program has grown in importance because basic research is declining in large companies as it increases in universities and small businesses [20]. SBIR awards have been associated with increases in entrepreneurial activity, venture capital, company growth, high-tech entrepreneurship, patent generation, and incorporation of externally generated patents [21]–[26]. However, the links between the subsidies and the funding agency's mission have not been explored in detail [27], [28], nor have the specific technical outcomes, although some of the formative work behind the SBIR program suggested that small companies are more innovative than large ones [29].

To review technical outcomes of any funded technology development program, a general useful tool is the Technology Readiness Level ("TRL") scale ranging from 1 (idea) to 9 (deployed successfully) to compare technologies broadly and assess their readiness for translation [30] (Table 1). The general concept has been extended to automotive manufacturing, Integration Readiness Level, Systems Readiness Level, and Innovation Readiness Levels [31]–[33]. While their use is limited to that of a simple ordinal scale [34], these tools provide important general insight into advancement through a technology-agnostic process. Although many frameworks have been discussed to incorporate prospective benefits in technology assessments [35]–[38], they are not commonly used, and instead those benefits are evaluated separately.

Table 1: Technology Readiness Level (TRL) definitions

TRL	Definition
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment
7	System prototype demonstration in a space environment
8	Actual system completed and ‘‘flight qualified” through test and demonstration
9	Actual system ‘‘flight proven” through successful mission operations

An excellent laboratory to study technology advances, particularly nationally subsidized ones, is the aerospace industry; it is typically viewed as a nationally strategic industry with strong links between defense and civil markets. The industry experiences high development costs and cyclical cash flow, with systems characterized by heterogeneity, low volumes, high performance and reliability requirements, and extreme ambient operating conditions [39], [40]. The high degree of customization leads to extended product life cycles and often to launching variations of existing models rather than new products [41]–[43]. Uncertainty in technology maturation has been recognized as a major constraint in developing broader system-level schemes to integrate various technologies [44]. In addition, if technologies are contributed by various stakeholders, their misaligned incentives may lead to a mismatched and non-optimized system [45]. At the Department of Defense, better guidance on technology maturity could improve schedule changes of weapons systems [46]. In addition, slippages will occur with typical schedule modeling practices, and more sophisticated analyses linking schedule and risk may be needed [47]. At the systems level, low TRL and TRL heterogeneity strongly influence schedule slippage [48], as does complexity in heritage technologies [49]. Technology interaction and coupling effects can complicate high- and low-TRL systems [50].

Many factors inhibit the adoption of new technologies at NASA; the agency experiences cost and schedule slippages from new technology infusion [51], and organizational factors may affect program advancement [52], with key concerns for system complexity, review, and assessment validity [53]. A TRL of 6 is required for a new technology to be considered for infusion into a flight project [54]. As development costs increase non-linearly with TRL [55] , demonstration of technology performance becomes progressively more difficult and may limit further funding [56], which may already be constrained by the small frequency and number of mission opportunities [57]. Thus, federal sources for VOD funding become even more critical [58]–[61].

It has previously been observed that the NASA SBIR selection process identifies quality companies, particularly so-called "microfirms" of 1-5 employees, and that the program does indeed develop technologies of use to the agency [62], [63]. We suggest that NASA carefully curates the pool of small business recipients by managing two sources of business risk: 1) the company size; and 2) the technology maturity, and that the program can be shown to address the VOD.

Empirical model

Our overarching hypothesis is that NASA program managers seek to mitigate both business and technical risk in the selection processes. A possible proxy for business risk is headcount, under the assumption that the risk is highest when the company is at its earliest or smallest stage. The technical risk may be measured by the technology readiness, with earlier stages posing more risk. If these risks may be assessed independently, for a project from a company with headcount h, initial technology maturity M, and anticipated technology advancement δ, the selection probability SP for phase i may be given by:

$$SP_i = f(h_i, M_i, \delta_i, \textit{other variables...})$$

We do not observe program variables such as budgetary limitations, program requirements, or other factors affecting selection.

The second study examines how the final technology readiness TR_f varies with these same quantities. What is the final distribution of technology maturities, and how does it depend on the variables that affect selection? In other words, we will examine drivers of TR_f:

$$TR_f = f(h_i, M_i, \delta_{i,}, \textit{other variables...}).$$

Data overview and analysis methods

Applications are publicly solicited for SBIR funding in two consecutive tranches, known as Phases (Figure 1). The award stipulates no rights for the agencies nor a demand for equity or intellectual property. Only Phase I awardees may apply for Phase II funding; roughly 96% of eligible firms elect to do so. The entire award portfolio for the year is selected at once; this is true for both Phases. In the period of this study, awards have ranged from $100 k to $125 k for Phase I and $600-750 k for Phase II.[1] Further funding may follow from other programs at NASA if the likelihood of using the technology in a flight project is sufficiently high. Since 2009, NASA SBIR applications at each Phase have required that the principal investigator (PI) estimate the proposed technology's current status as an initial measured TRL level. Extracted variables used in the analysis include the initial measured TRL (*mi*), the PI's anticipated final TRL (*af*), and employee headcount (*emps*). At the phase conclusion, a NASA representative measures the final TRL (*mfn*). These measurements repeat for both Phases (Figure 1).

[1] The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

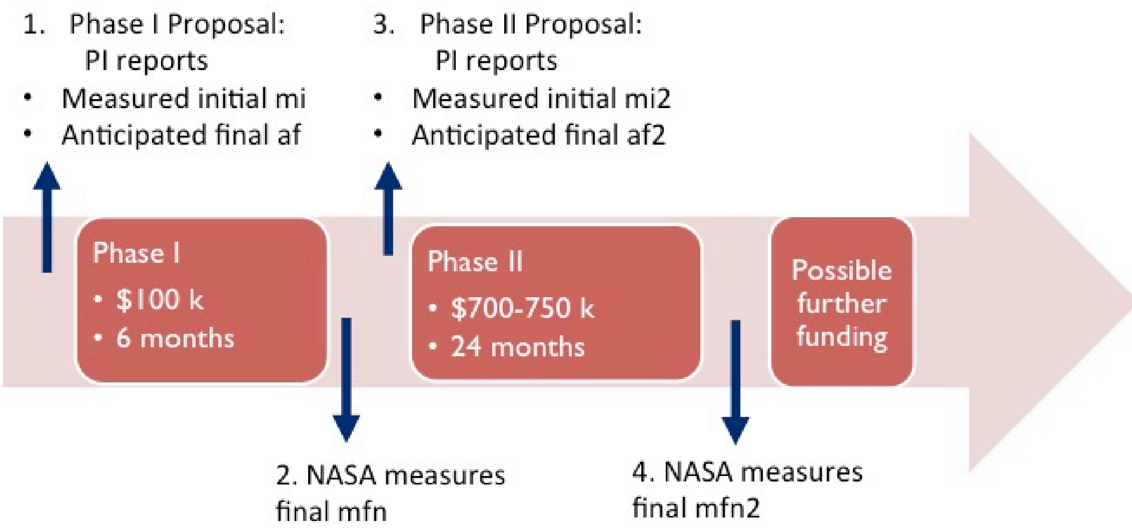

Figure 1. Schematic of program and associated measurements.

In this analysis, we assume that both measurements are equally accurate even though they come from different sources; unfortunately, it is prohibitively expensive in time and money for a NASA representative to formally review each proposal's initial TRL.

Table 2: Award sizes in NASA SBIR program.

Year	Funding per phase ($ k)	
	Phase 1	Phase 2
2010	100	750
2011	125	700
2012-6*	125	750
*No projects were funded in 2013		

Data used for this analysis were compiled from the Electronic Handbook (EHB) for the NASA SBIR program. This data set is searchable over many years of the program for restricted use. To protect the procurement sensitive nature, we compiled data from 2010 to 2016 for all NASA Mission Directorates and divided the pool into two populations for some analyses: the so-called "microfirms" with 1-5 employees and "standard small businesses" (SSBs) with 6-499 employees. Membership in this group is determined at each Phase's launch; roughly 5% of the population moves from one category to the other between the two Phases. Several variables were extracted for the data set, summarized in Table 4. The only calculated variable is the advancement, defined as the difference between the anticipated final measure and the initial TRL.

Table 3: Analysis variables

Variable for Phases I, II	Description	Source
year	Fiscal year of analysis	Data
mi, mi2	Measured initial TRL	Data – PI measurement
af, af2	Anticipated final TRL	Data – PI measurement
mfn, mfn2	Measured final TRL	Data – NASA measurement
advance, advance2	Degree of advancement	Calculated as *af – mi*
emps, emps2	Headcount	Data – continuous integer
p1, p2	Selection for a given proposal	Data - Binary

Table 4: Data set for NASA Phase I and II awards 2010-2016

	Phase I (6 months)		Phase II (24 months)	
	Proposals	Winners	Proposals	Winners
Microfirms (1-5 employees)	2,160	380	310	102
Standard small businesses (6-499 employees)	6,339	1,546	1,525	572
All awards	8.499	1.926	1,835	674

Results

Selection processes

To understand the selection probability in Phase I, we estimated the selection probability by conducting a logit regression on the binary dependent variable p_1 (Table 5). Year-fixed effects are important because the relative SBIR allocation (as a function of the agency's R&D budget) increased by 10% during the time of this study [64]. We find that the headcount matters significantly; a tenfold increase in employment leads to a 15% increase in selection probability. The independence of selection with the initial and final TRLs *mi* and *af* are consistent with a program that is not mitigating risk by choosing more mature technologies in the first funding tranche. However, it is interesting that the term *advance* serves as a proxy for the selection of higher quality proposals; increasing the predicted advancement by 1 unit decreases the likelihood of selection by about 8%.

Table 5: Logit regression to estimate the probability of winning in Phase I.

	Dependent variable: Selection in Phase I = p_I					
	(1)	(2)	(3)	(4)	(5)	(6)
year	0.063***					0.060***
	(0.012)					(0.012)
log(emps)		0.156***				0.151***
		(0.019)				(0.019)
mi			0.047*			0.024
			(0.025)			(0.027)
af				-0.036		
				(0.023)		
advance					-0.125***	-0.086***
					(0.030)	(0.032)
Constant	-1.467***	-1.662***	-1.342***	-1.079***	-1.013***	-1.788***
	(0.052)	(0.060)	(0.067)	(0.098)	(0.057)	(0.127)
Observations	8,499	8,499	8,499	8,499	8,499	8,499
Log Likelihood	-4,533.751	-4,514.493	-4,546.563	-4,547.036	-4,539.495	-4,495.040
Akaike Inf. Crit.	9,071.502	9,032.985	9,097.126	9,098.071	9,082.991	9,000.080

*p<0.1; **p<0.05; ***p<0.01
Standard errors given in parentheses below each coefficient

When we repeated the analysis for Phase II (Table 6), we found that the company size was no longer a determinant of the selection probability. Instead, only the initial TRL level *mi2* had a modest effect on selection, but the final anticipated TRL *af* did not. Again, anticipating too great an advancement, or too many TRL steps, was negatively correlated with selection.

Table 6: Logit regression to estimate the probability of winning in Phase II.

	Probability of winning in Phase II = p_2					
	(1)	(2)	(3)	(4)	(5)	(6)
Year	0.125***					0.122***
	(0.022)					(0.022)
log(emps2)		0.008				0.0002
		(0.037)				(0.038)
mi2			0.147***			0.127**
			(0.054)			(0.056)
af2				0.00004		
				(0.042)		
advance2					-0.146***	-0.104*
					(0.054)	(0.056)
Constant	-1.049***	-0.566***	-1.055***	-0.542**	-0.232*	-1.255***
	(0.102)	(0.122)	(0.196)	(0.241)	(0.125)	(0.297)
Observations	1,833	1,833	1,833	1,833	1,833	1,833
Log Likelihood	-1,188.457	-1,205.581	-1,201.901	-1,205.604	-1,201.966	-1,183.222
Akaike Inf. Crit.	2,380.913	2,415.161	2,407.801	2,415.209	2,407.933	2,376.444

*p<0.1; **p<0.05; ***p<0.01
Standard errors given in parentheses below each coefficient

These results are consistent with a simple view of the variation of the selection probabilities with initial TRL, shown graphically in Figure 2; in Phase I, the microfirms show approximately 15% lower selection probability, particularly at TRL 1-4. This difference vanishes in Phase II and replaced with a modest dependence on the technology's initial TRL.

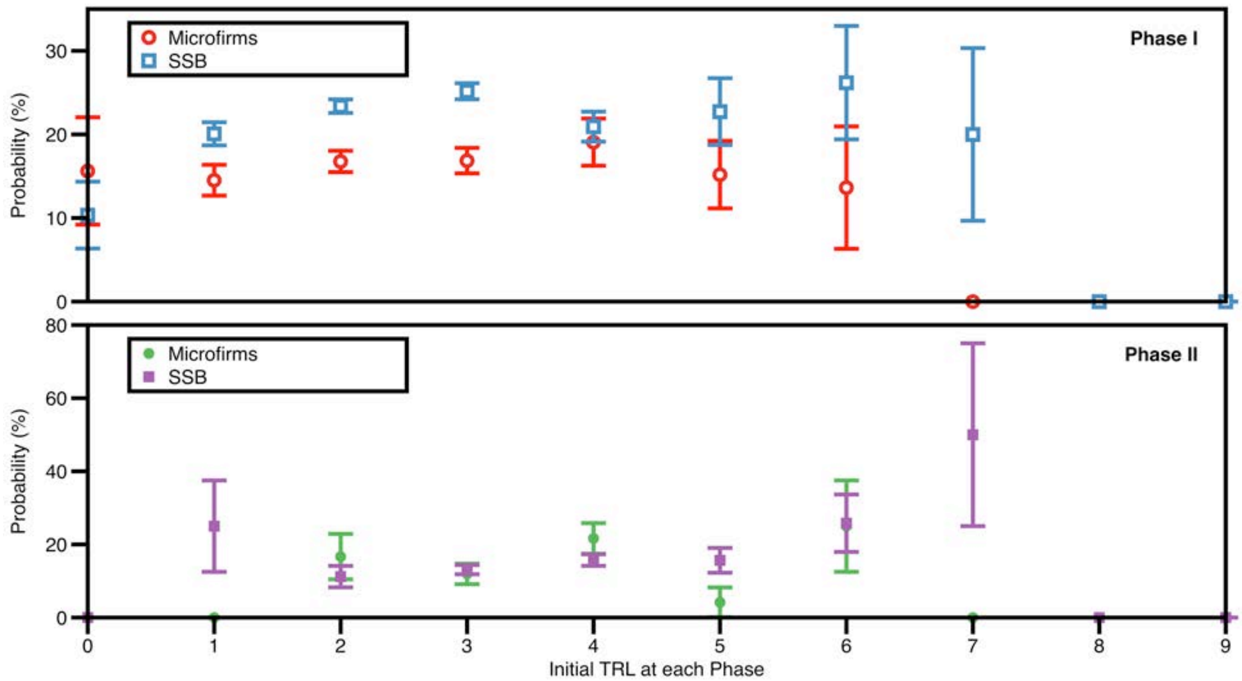

Figure 2. Selection probabilities for Phase I (top) and Phase II (bottom).

Technical outcomes

We explored the actual outcomes of the funding process through the distributions of the final TRL measured by NASA at each Phase's end (Figure 3). The severe skew at the program's beginning is transformed into a more symmetric distribution at the end of Phase II. The shapes of Figure 3 prompted us to ask if microfirm and SSB distributions were in fact statistically equivalent. To test the hypothesis that the microfirm and SSB shapes did not come from the same parent distributions, we conducted Kolmogorov-Smirnoff and Anderson-Darling tests on various pairs of TRL distributions (Table 7). At the program's outset, the initial TRL *mi* distributions appear to be different according to the Anderson-Darling test, which is more sensitive to tails [65]; and yet, as the program evolves, the microfirms and SSB distributions cannot be shown to stem from different distributions. In other words, the initial *mi* differences do not persist in the program.

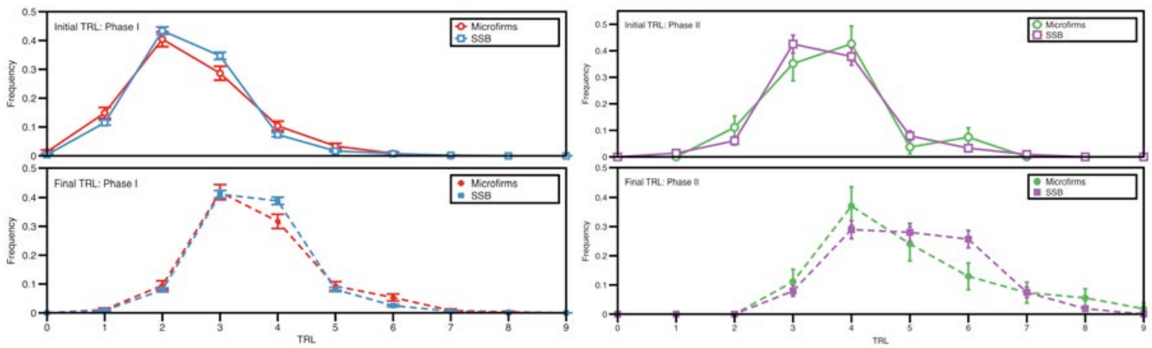

Figure 3. Left (right): Phase I (II) technical advancement; with initial (top) and final (bottom) TRL for microfirms and SSB.

Table 7: Tests to compare similarities of TRL distributions. All tests compare the microfirms and SSBs selected for the program.

Microfirm-SSB distribution comparison	Kolmogorov-Smirnoff		Anderson-Darling	
	Score	p-value	Score	p-value
Phase I: Initial TRL *mi*	0.05	0.34	3.32	0.02
Phase I: Final TRL *mf*	0.05	0.61	1.69	0.14
Phase II: Initial TRL *mi*	0.06	0.89	0.50	0.75
Phase II: Final TRL *mf*	0.10	0.76	1.35	0.22

We then explored drivers of the final TRL, as measured by NASA, via linear regressions (Table 8). It is not surprising that the initial TRL is a strong driver in both Phases because clearly one who starts further ahead is more likely to end in a more advanced state. However, we find that the smaller companies progress further in Phase I but not in Phase II. In other words, even after controlling for the initial TRL level, the smaller companies are linked to greater advancement – but only in Phase I. An interesting note is that the year-fixed effects are linked to Phase I selection, but not Phase II.

Table 8: Linear regressions of the final TRL, as measured by NASA

	Phase I				Phase II			
	NASA measurement of final TRL *mfn*				NASA measurement of final TRL *mfn2*			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
year	0.065***			0.061***	-0.011			-0.001
	(0.019)			(0.020)	(0.079)			(0.079)
mi		1.108***		1.110***				
		(0.053)		(0.053)				
log(emps)			-0.070**	-0.091***				
			(0.033)	(0.034)				
mi2						1.032***		1.030***
						(0.134)		(0.135)
log(emps2)							0.092	0.064
							(0.087)	(0.087)
Observations	1,826	1,826	1,826	1,826	268	268	268	268

*p<0.1; **p<0.05; ***p<0.01
Standard errors given in parentheses below each coefficient

Tables 9 and 10 show the complete transition probability matrices for the microfirms and SSB, respectively, and reveal several differences. SSB show a modestly broader *initial* distribution of TRL, with some proposals at higher initial TRL (6, 7) selected for further funding; on the other hand, microfirms present a broader *final* distribution, with some final TRL of 8 or 9. For the most part, the matrices are remarkably similar given that the available resources may differ by a factor of 100 between the two organizations, if resources scale with headcount.

Table 9. Transition probabilities for microfirms advancing through both Phases.

		Phase 2 final TRL, measured by NASA								
		1	2	3	4	5	6	7	8	9
Phase 1 initial TRL, measured by PI	0	-	-	-	-	1.9 ± 1.8	-	-	-	-
	1	-	-	1.9 ± 1.8	9.3 ± 3.9	3.7 ± 2.6	1.9 ± 1.8	-	-	-
	2	-	-	3.7 ± 2.6	14.8 ± 4.8	13.0 ± 4.6	1.9 ± 1.8	3.7 ± 2.6	-	-
	3	-	-	1.9 ± 1.8	13.0 ± 4.6	3.7 ± 2.6	7.4 ± 3.6	3.7 ± 2.6	-	-
	4	-	-	3.7 ± 2.6	-	-	-	-	1.9 ± 1.8	-
	5	-	-	-	-	1.9 ± 1.8	1.9 ± 1.8	-	3.7 ± 2.6	1.9 ± 1.8
	6	-	-	-	-	-	-	-	-	-
	7	-	-	-	-	-	-	-	-	-
	8	-	-	-	-	-	-	-	-	-
	9	-	-	-	-	-	-	-	-	-

Table 10. Transition probabilities for standard small businesses advancing through both Phases.

		Phase 2 final TRL, measured by NASA								
		1	2	3	4	5	6	7	8	9
Phase 1 initial TRL, measured by PI	0	-	-	-	-	-	0.5 ± 0.5	-	-	-
	1	-	-	0.9 ± 0.7	4.7 ± 1.4	1.9 ± 0.9	1.4 ± 0.8	-	0.5 ± 0.5	-
	2	-	-	4.7 ± 1.4	12.1 ± 2.2	10.3 ± 2.1	8.9 ± 1.9	3.7 ± 1.3	0.5 ± 0.5	-
	3	-	-	1.9 ± 0.9	11.2 ± 2.2	12.6 ± 2.3	8.9 ± 1.9	1.4 ± 0.8	0.5 ± 0.5	-
	4	-	-	-	0.5 ± 0.5	2.3 ± 1.0	5.1 ± 1.5	1.9 ± 0.9	-	-
	5	-	-	0.5 ± 0.5	0.5 ± 0.5	0.5 ± 0.5	0.9 ± 0.7	-	-	-
	6	-	-	-	-	0.5 ± 0.5	-	-	0.5 ± 0.5	-
	7	-	-	-	-	-	-	0.5 ± 0.5	-	-
	8	-	-	-	-	-	-	-	-	-
	9	-	-	-	-	-	-	-	-	-

Discussion

To our knowledge, this is the first study of SBIR to focus on the technical outcomes rather than the economic measures typically used to examine government subsidies. This is important because these outcomes are realized immediately during the program, rather than the later economic signals such as revenue and employment growth. We confirm that the SBIR program helps technologies address - but not necessarily span - the "valley of death", advancing TRL roughly from 2.5 to 4.5. However, this may be insufficient to reach TRL 6, the maturity required for infusion into a flight project. As TRL 6 is a reasonable proxy for commercial readiness, it is likely that these technologies are also closer to, but not entirely ready for, commercial deployment.

Importantly, the headcount effect observed in Phase I may appear *de facto*, but is not by design. Instead, the program managers are selecting for fixed criteria applied to the full proposal pool, and the proposals from microfirms are generally of different quality than those from larger firms. The selection tendency toward larger firms is an outcome and not a goal of the selection process. As a result, the model appears to partially disaggregate the maturity M such that it is managed more directly in a later stage, as suggested in Figure 5. This process sheds new light on the typical invention-to-product cycle in which technical risk is retired prior to business validation [61]; indeed, the ongoing business-technology interaction leads to particular challenges in interacting with small businesses.

Figure 4. Management model

In addition to exploring the selection process, we find that the Phase I outcomes differ for both sets of firms in that microfirms advance further than the large companies with an initial modest tranche of funding, consistent with the formative Edwards and Gordon work suggesting that small companies are more innovative [29]. One possible reason may be that the organization is better suited to "make do" with a small tranche of funding; similarly, the incentive for advancement may be greater as the \$100 k award is likely a larger fraction of the total resources. There may also be a selection effect, as the awards already preferentially go toward larger firms; for that reason, the microfirms that do survive the Phase I selection process may be of higher quality. This is consistent with the general reasons that startups are of interest: The option value is much higher because the uncertainty (variance) is so high. Another study showed that microfirm recipients of the NASA SBIR Phase II awards are of higher quality and generate disproportionately more patents than SSBs [62].

This represents a novel empirical study to underpin a cost calibration of the TRL curve, confirming that \$100 k advances a project from TRL 2 to 3, and \$700 k funds advancements to roughly 3.5-5. The large range of final TRL reflects the broad nature of the funded technologies; computational tools (machine learning, artificial intelligence, etc.) may reach a more advanced state with a lower capital infusion than manufactured technologies, such as radiation-hard electronics or a new material for spacecraft.

We also indicate how SBIR can potentially signal firm quality. Government grants can increase a firm's probability of obtaining resources [12], [66], [67], directly by funding technology development rather than through a certification effect [25]. SBIR grants are linked to venture capital, but not angel funding, for academic spinoffs [68]. If firm quality is defined as advancing the technology, then the microfirms' high rate of advancement suggests that the process does indeed identify technologies produced by strong standard small businesses, and even more so by microfirms.

Limitations and future directions

This study is limited in several ways. First, we did not control for the nature of the technology; computing technologies may have lower risk and advance further than manufacturing-oriented ones. In addition, we assume that all the TRL measurements are precise and accurate, and that all the assessments by the PI and NASA are correct. However, behavioral or organizational effects could impact selection, and further research could illuminate this. Indeed, we may see a funding profile resulting from a strategic game, in which both parties make decisions based on assumptions regarding the next step. The link of Phase I selection with decreased values for the projected advancement suggests that overly ambitious plans may be discredited in selection.

While the narrow window in time (2010-2016) examined here should help constrain the year-to-year variation in the selection process, the overlap of the year-fixed effects with the changing program architecture call for further study. The final TRL in the smaller Phase I were correlated with the program year, whereas in the next Phase this effect was not seen. Is the higher budget only funding research to an intermediate phase? What is the optimal allocation between the two Phases, or between the two groups of companies?

A previous model for this program indicated that from a straight financial perspective of real options analysis, a rational economic agent would not pursue the average project [13], and therefore government funding is critical. NASA's SBIR program seeks to fund technologies that will both advance and are likely to be infused. While SBIR economic objectives have been clearly defined, the goal of "supporting innovation" is more nebulous. Should the program advance all technologies by one step, or should it maximize the number of projects advancing to high (TRL>6) maturity? These questions can be explored in an optimization model.

Summary

By studying the advancement of technologies in NASA's Small Business Innovation Research program, we find that rather than reduce risk by funding heritage technologies, the program guides the majority of opportunities at least partly across the "valley of death" to TRL 5. Roughly 10% advance fully to TRLs qualifying for infusion, whereas another 10% still remain at the levels of fundamental discovery rather than readiness for exploitation. We show that the SBIR program produces real technical outcomes in addition to, and likely earlier than, the economic outcomes previously reported.

Managers considering how to disaggregate business and technical risk may consider aligning them independently with the two funding tranches, and reviewing the planned level of advance as well.

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