Innovation Pathways in Bureaucratic Organizations:
A Process Study of Technology Infusion at NASA

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ABSTRACT

This paper uses a longitudinal case study of the infusion of new infrared sensor technology at NASA to illustrate limitations of current conceptual models of the innovation process in large bureaucratic organizations. Based on in-depth interviews with key participants, supplemented by a review of project reports, contract archives, publications and press coverage, the paper constructs a detailed process history of the multi-decade "innovation pathway" taken by the new sensor as it was matured from initial demonstration of the relevant scientific phenomena (conceptualization) through implementation on an earth observation satellite (actualization). This case illustrates that maturity is not always a monotonically increasing attribute of the technology, as assumed in current practice; it also explains how informal mechanisms (e.g., personal relationships) can serve as important enablers of transitions among different phases of the formal technology development process. Implications of these findings are discussed and a strategy for a more targeted follow-on study is outlined.

1 INTRODUCTION

In 2008, a Quantum Well Infrared Photodetector (QWIP)-based Thermal Infrared Sensor (TIRS) was chosen, as a late addition, for implementation on the Landsat Data Continuity Mission (LDCM) – a joint NASA-US Geological Survey mission that will continue a 30+ year legacy of geospatial data [DOC#11].[3] Over its history, Landsat Data have enabled agricultural, forestry, air quality, and geological activity monitoring among other societal benefits. The new QWIPs technology will continue this legacy in the thermal infrared band, with improved sensitivity. The planned 2012 launch will mark the first implementation of a QWIPs-based sensor on a space-based platform, and one of the first applications of QWIPs principles in an infrared camera system in the relevant wavelength (8-12 μm) [DOC#12, INT#1]. The QWIP innovation provides sensitivity at manufacturability (i.e., cost-schedule) improvements over previous sensors, and has potential applications to a wide range of space and terrestrial missions [DOC#11].

The decision, for an operational satellite program, to infuse an unproven (and therefore perceived risky) new technology is never taken lightly. In this case, the intersection of three sequences of events forced the infusion decision. First, a problem stream: the originally baselined TIRS instrument ran into serious technical challenges. At the systems requirement review (two years before the planned launch), it became clear that the planned technology would not be flight ready

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[3] Reference material from interviews (INT) and archives (DOC) are detailed in Tables 1 and 2 below.

in time [DOC#12, INT#7, 10]. As a "data continuity mission" launch timing was an important mission driver; a decision was made to remove the TIRS instrument from the manifest in order to salvage the rest of the science return. Second, a solution stream: in the intervening time since the original selection of the TIRS instrument technology, significant scientific progress had been made on QWIPs devices [DOC#11, 12]. Made from mature semiconductor materials (and the corresponding mature processing technology) and boasting a working prototype, QWIP-based TIRS was now the lowest-schedule-risk alternative. Third, a window of opportunity: in addition to the 30,000+ publications that have resulted from Landsat science data, the turbulent launch history of the previous 7 Landsat missions has brought together a cohesive Landsat lobby. It was the lobby that ensured that a LDCM would fly in the first place, and the decision to de-manifest TIRS sparked another round of heated debate [DOC# 14, 15]. In the end, the FY2009 Appropriations Act explicitly included $10M for a TIRS, officially legitimizing the risk.[1] The FY2010 Appropriations Act provided another $150M for the TIRS instrument, to ensure the schedule was met.

Told this way, the infusion of QWIPs is a classic tale of an "idea [technology/policy] whose time has come"[2]. However, where the bureaucratic decision making and agenda setting explanations break down is in the technology solution side of the story. While it may be impractical, and of little value, as Kingdon argues, to attempt to trace a causal chain of events in a socio-political *primordial soup*, there is significant path dependency, and a series of necessary stages, in a technology development process. Further, while the existence of a continuous flow of new concepts and capabilities, generated by independent actors on the supply-side, can be appropriately assumed by decision makers in a competitive market context, these dynamics are fundamentally different in the monopsony markets characteristics of the space sector [3, 4]. Specifically, since many of the new technologies which are critical enablers of future space science missions have limited or no near-term commercially viable applications on earth, the necessary R&D investment will be underprovided by industry without the combination of government patronage and explicitly articulated future need [5, 6].

The need to pre-invest in technology development in advance of explicit mission-level needs is well recognized within the space community and all national space agencies engage in some level of technology roadmapping and innovation investment (e.g., NASA technology roadmap, ESA Cosmic Vision).[4] However, there is only limited consensus on how much relative investment is required at different maturity levels and how the different buckets of funding should be connected. In fact, a review of NASA's historical technology strategy (Figure 1) shows an oscillation from emphasis on basic research to investment exclusively in project specific technology development. This illustrates a recognition of the necessity for both types of development but a lack of clear understanding of how to find an appropriate balance.

In the current instantiation of NASA's innovation system, both types of development are nominally represented. In theory, promising ideas are initially explored through basic concept development. Next, the most promising of those concepts are further matured through applied R&D. Finally, a very small subset of those are infused into flight projects and undergo project-

[4] See [7] Z. Szajnfarber, A. T. Grindle, and A. L. Weigel, "Instantiations of Government Innovation Systems: A comparative analysis," in *International Astronautical Congress* Daejeon, S. Korea: IAF, 2009. paper for review of different agency strategies

specific development. In theory, the flow from new concepts to implementation on flight projects is controlled by a series of gates – decision points, where progress is reviewed and the set of maturing capabilities that will go on to the next level is selected. The goal is to develop enough new capabilities now, so that future projects will be able to draw upon mature (i.e., low technology risk) versions of the capabilities they will require. In practice, the process is much less linear. Funding mechanisms are used flexibly as governed by personal relationships and seemingly chance encounters; and this informal system remains without description or documentation.

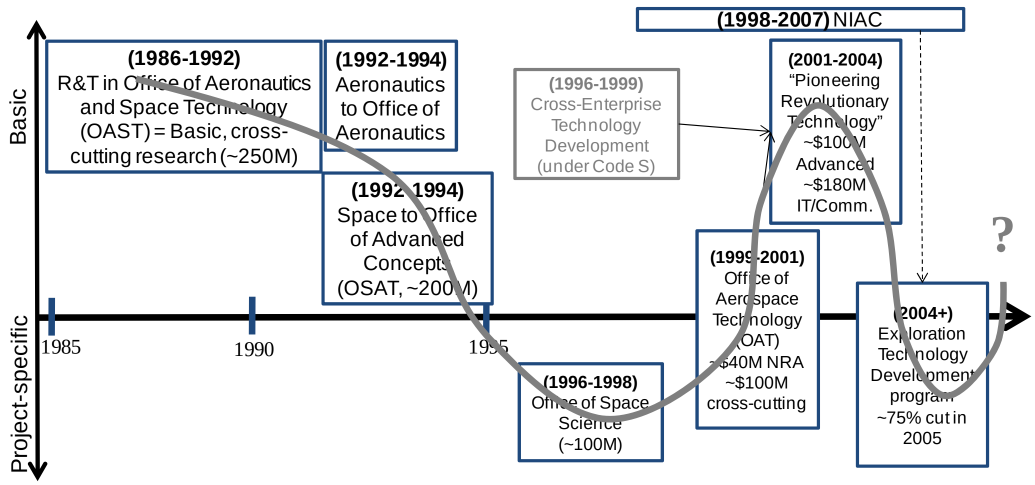

Figure 1 – History of NASA’s Technology Strategy

Yet if we want to improve the system, we first need to understand how it is actually working and why. This paper reports on the first stage of a broader research effort which seeks to develop this requisite understanding; specifically, this first piece uses a detailed longitudinal case study of the infusion of the QWIPs-based TIRS technology at NASA, to test the limits of existing theory and conceptualizations of the innovation process in large bureaucratic organizations. The goal of this first stage is to demonstrate the incompleteness of our current understanding, highlight the implications of the differences and focus the follow-on work. After detailing the research design in section 2, this paper is organized into four main sections, inductively building an understanding of the system. First, an analytical chronology of the QWIPs case is presented; next, the set of formal mechanisms involved in maturing the technology are identified and characterized in terms of the components of NASA’s innovation architecture; third the path taken by the QWIPs technology is explained in terms of the informal mechanisms that influenced the path; finally, the implications of these observed dynamics are discussed in terms of practice and theory.

2 RESEARCH APPROACH

Innovation, particularly in the context of complex products and organizations, is a difficult phenomenon to study. It happens over an extended period of time (multiple decades is not uncommon) and experiences extremely high sample mortality (on the order of one out of a hundred concepts are actually flown); it involves multiple actors, institutional mechanism and exogenous factors interacting in ways that make it difficult to define a system study boundary *a* *priori*; there is a paucity of directly relevant existing theory by which to guide the investigation;[5] and the mechanisms that have been identified (e.g., catalytic events which break down bureaucratic barriers[8]) involve complex interactions, not readily measurable with structured (e.g., survey) instruments.

In order to deal with these research challenges, this study takes a process tracing approach. Scholars have argued that it is more appropriate than other methods for the study of phenomena characterized by complex causality [9] because it allows for the reality of feedback loops in social phenomena to be considered endogenously [10]. Process tracing is both a philosophy about what data to collect, and how to analyze it. Mohr [11], in his classic text on organizational theory, makes a strong distinction between "variance" theory (which explains phenomena in terms of relationships among dependent and independent variables) and "process" theory (which seeks to specify the sequence of events which lead to types of outcomes). Specifically, the process tracing method, by going back in time to identify the key events, activities, or decisions that interact in probabilistic ways to link hypothesized causes to the outcomes of interest, allows the researcher to specify the mechanisms linking causes and effects [12].

In order to achieve the rich detail required to generate process theories, studies often trade sampling breadth for depth. Hall suggests that, if falling on the small-N end of the sampling spectrum "*is the price we pay to understand complex causality, the trade-off is worth it*" ([12] citing [9]). In this paper we use a single, detailed longitudinal case study of the infusion of the QWIPs-based TIRS technology at NASA, to test the limits of existing theory and conceptualizations of the innovation process in large bureaucratic organizations. The goal of this first stage is to provide an existence proof of the limitations of our current understanding, highlight the implications of the differences and focus the follow-on work.

2.1 Data Sources

Constructing each individual innovation pathway requires that the sequence of events, processes, and decisions that link the initial new concept to the eventual infused technology be identified. Yin[13] identifies 6 sources of data useful in building evidence in case study research: Interviews, Documents, Archival material, Observations – both direct and indirect – and Artifacts. Each of these data sources has strengths and weaknesses with respect to validity and reliability. Better confidence can be achieved by triangulating multiple data sources. In the context of this study, elite interviews and documents formed the primary data sources, with archival material (including programmatic records and published scientific material) and observations supplementing to a certain extent.

Interviews with key participants were conducted on-site at the NASA Goddard Space Flight Center (Goddard or GSFC), the Jet Propulsion Laboratory (JPL) and the small business involved with the project. They were used for two purposes. First, a subset of initial interview accounts served to create a sketch of the critical events, helping to focus the document search that

[5] Ref [8] Z. Szajnfarber and A. L. Weigel, "Stiching the Patchwork Quilt: Integrating the Diverse Literatures Relevant to Complex Product Innovation in a Government Monospony," in *Atlanta Conference on Science Technology and Innovation Policy* Atlanta, GA, 2009. provides an overview of the related theory and empirical work. It shows that most of the work is at a much higher level of analysis and doesn't address the particular challenges of technology development pre-infusion.

followed. Primary records, like contract documents were then used to validate the details of the timeline, since decade-old memories are fallible. The second round of interviews was then used to probe the motivations of the actors and understand why particular pathways were taken at different times. Interview subjects were selected initially based on introductions from the Goddard's office chief technologist; as the research progressed, more subjects were identified who could provide complementary perspectives. This strategy of snowball introductions was pursued until all the key individuals involved in this particular innovation pathway had been interviewed. Table 1 provides a list of the participant interviews, identified by their functional roles. All interviews were digitally recorded, with permission, and transcriptions were made of all relevant portions.

Table 1 - List of Participant Interviews

Interview #	Functional Role
1, 7	Goddard Technologist (30 mins, 45 mins)
2	Small Business CEO and Technologist (1.5 hrs)
3	JPL Scientist (30 mins)
4,5	ESTO funding manager (1hr, 20 mins)
6	Innovative Partnerships Program staff (20 mins)
8	IRAD funding manager (20 mins)
9, 10	Landsat/HQ program perspective (1 hr/20 mins)
11	15 contextual interviews were conducted with an even mix of managers and technologists (12 hrs)

Documents in the form of journal articles, contract proposals and reports, internal records, legislative actions, and news coverage were used to validate events described by the interview subjects. One advantage of studying a bureaucratic agency is that records exist for most activities. However, given that hundreds of small R&D contracts are awarded on a yearly basis, without pointers, like names and key words from the interviews, it would be nearly impossible to construct the pathways from documents alone. Financial records were provided by some programs, but the reporting was found to be somewhat inconsistent. Table 2 provides a summary of the documents consulted in this work.

Table 2 - List of Document Categories

Ref #	Source Type	Doc Reference
1-5	Contract awards	2x EST: ATIP-99-0100; ACT-02-0005; 1x SBIR: SBIR-06-1-S4.02-8429; Lab book notes for DDR and SDI; financial data provided
6-10	Contract materials	"Quad charts" final presentation for each contract, accessible at http://esto.gsfc.nasa.gov/ and http://sbir.nasa.gov, more details obtained from the personal records of the technologists
11	Scientific publications	Multiple publications consulted, main source [14]
12	Internal presentations	More than 10 internal review meetings re: include TIRs or not (e.g., "Landsat Data Continuity Mission HQ Actions/Issues"[15] and "QWIPs-based Thermal Infrared Sensor for the Landsat Data Continuity Mission"[16])

13	Websites	LDCM home page: ldcm.nasa.gov
14-15	Legislative discussion	Debate archived at: http://www.idwr.idaho.gov/GeographicInfo/Landsat/landsat-thermal-band.htm; Landsat remote sensing act of 1992
16	Press material	Press releases when QWIPs was inducted into the Space Technology Hall of Fame, Successful contract results etc.

In the following discussion, statements will be cited based on the interview or document reference in the above tables to maintain traceability to the sources, while preserving some level of anonymity for the interviewees.

2.2 Sensemaking Strategy

The data collection described above yields an immense amount of qualitative and quantitative data; as famously stated by Pettigrew (1990), the researcher is at risk of "*death by data asphyxiation*." [17] The challenge of sensemaking is one of how to move "*from a shapeless data spaghetti toward some kind of theoretical understanding that does not betray the richness, dynamism, and complexity of the data but that is understandable and potentially useful to others*." (p. 694) [17] To this end, different disciplines use "process tracing" to make sense in different ways.

For example, for Lindsay[18], studying military innovation as a political scientist, process tracing means constructing a single detailed historical narrative of a particular technology trajectory using multiple sources of data. Allen[19] on the other hand, studying the origin of new capabilities in the firm setting as an organizational scientist, studies multiple, paired, cases, quantifying key parameters in his process data to facilitate meta-analysis. In fact, in an excellent methodological review paper, Langley[17] suggests that there are at least seven contrasting strategies for "sensemaking" from process data. Her categories range from historical narratives (like Lindsay's), to temporal bracketing (e.g., phase models of the process), through visual mapping (e.g., [20]) to quantification (like Allen's). The relative strengths of the different methods depend on tradeoffs among accuracy, simplicity and generality in the resultant theory.

Langley notes, that the sensemaking strategies are not mutually exclusive. In fact, since the different strategies use different anchors to organize the analysis (e.g., temporal bracketing assumes sequential stages in the process, where quantification uses outcome categories), they can be used to complement each other[17]. The point is that the more different lenses used to make sense of the data, the better[21]. Also, narrative accounts can often be helpful in taking the first cut at the data, to be further analyzed using one of the more synthetic methods.

This research follows the above advice. Specifically, the analysis was conducted in four stages, mirrored by the sections in the remainder of this paper. First, in section 3, an analytical chronology of the QWIPs case is prepared, as suggested by [22] to "get on top of the data, to clarify sequences across levels of analysis, suggest causal linkages between levels, and establish early analytical themes" (p.280). Those initial themes were then coded, and abstracted, more systematically using what Langley calls visual mapping. This was done in two phases: in section 4 the set of formal mechanisms involved in maturing the technology is identified and characterized in terms of a NASA innovation architecture; then, in section 5, the path taken by the QWIPs technology is explained in terms of the informal mechanisms that influenced the path. This strategy of graphical representations allows a large number of dimensions to be represented simultaneously and concisely. The visual map is an intermediary step – performed on individual process histories - between raw data and the more abstract theory that is the goal. Finally, in section 6, the observed dynamics were compared and contrasted to existing theory.

3 THE QWIPs INNOVATION PATHWAY: *From promising science to satellite sensor*

The QWIPs innovation pathway begins in the late 1980s, when the potential for quantum wells to be used in far IR photo detectors was demonstrated through a unique collaboration between scientists at AT&T/Bell Labs and the NASA Goddard Space Flight Center (GSFC) [DOC#16, INT #7]. During their year-long contract, funded at ~$100K under the infamous strategic defense initiative (SDI) [INT#7], they incorporated a QWIPs-based photodetector array into a camera system and performed airborne imaging with it [DOC#16]. However, despite the early promise of the new technology, the project essentially terminated with the contract, and the collaborating organizations went their separate ways. For Bell Labs, it was a strategic decision that QWIPs detectors did not align with their commercial portfolio. For the GSFC technical team, their other flight project responsibilities won out, leaving the QWIPs detector arrays in the proverbial "sandbox." [DOC#16, INT #7, 3]

Although Bell Labs as an organization moved on, many of the young scientists involved with the project maintained interest in the nascent technology [DOC#16]. Recognizing the enhancements that QWIPs could offer to space-based imaging, in 1992, the Jet Propulsion Laboratory (JPL), another NASA center, acquired both the technology and many of the original scientists [DOC#16, INT #3]. There they started the Infrared Focal Planes & Photonics Technology Group, where they have continued to push the scientific state-of-the-art in both space-based and earth IR imaging technology.[6]

In the late 1990s, the original collaborators were reunited for another reason. Believing that NASA as a whole would benefit from more collaboration among its centers, the GSFC and JPL groups were "encouraged" to find a basis for collaboration [INT#1, 3, 7]. Encouragement in this context means that scarce R&D resources were earmarked for collaborative projects. So, the GSFC team spent a week on-site at JPL discussing potential common projects. It turns out that QWIPs detectors were the most promising area for collaboration between the groups and the outcome of that week was one of the concepts that is now – 10 years later – being developed for the TIRS instrument [INT#7].

The team moved forward under a sequence of back-to-back Earth Science Technology Office (ESTO) grants, supplemented by a short Director's Discretionary Fund (DDF) contract on the GSFC side [INT# 1, 4, 7, DOC#1, 2]. In the first tranche of funding - $140K over 3 years from 1999-2002 from ESTO's Advanced Technology Innovation Program (ATIP) and $80K for the first year of DDF [INT #7, DOC#6, 9] – they developed hyperspectral QWIPs sensor array [DOC# 6], useful for remote sounding of numerous geospatial quantities. This work showed sufficient promise to secure another three years of funding, again from ESTO, now under the Advanced Component Technology (ACT) bucket. In this round, they requested $1.2M over 3

[6] See http://scienceandtechnology.jpl.nasa.gov/people/s_gunapala/ for more details

years through 2005, and built a 1Kx1K detector array and the corresponding read-out circuit [INT#7, DOC #2, 7]. As listed in the project report, the first contract matured the capability from TRL (technology readiness level) 2 to 6 [DOC#6] and the second contract from TRL 2 to 5 [DOC#7], illustrating the flexibilities of the definitions of TRL. These contracts enabled the technologies to be matured to the point that there was no new science left to be worked out; the remaining investment would target space qualification and engineering progress, the role of technologists and engineers more than scientists.

Enter the phase of development sometimes referred to as the valley of death. The name refers to the fact that there is no clear path between ESTO development funding and project applications; and there was no immediate flight opportunity available within the space context. However, having made significant progress during these 7 years, the technologists were excited to find practical applications to further their work, including medical imaging and terrestrial caves, which served as partial bridge funding [INT#7]. An opportunity presented itself to re-open the flight trajectory shortly thereafter, when the Goddard technologist and the CEO of a small business began chatting at the technical conference [INT#1, 3, 7]. It turned out that the company had been doing some groundwork on manufacturing a QWIPs-based camera, but had been struggling to secure funding. In fact, they had already submitted three blind proposals to NASA's SBIR program (a congressionally mandated innovation funding mechanisms) [INT#3], but despite success with the Army version of SBIR, all three NASA proposals had been rejected; the CEO was about ready to give up on NASA [INT#3].

However, by the end of this informal chat, the two had come up with a proposal strategy with a well defined concept [INT#1]. Another *coincidence* further ensured the success of the company's fourth SBIR proposal. The relevant subtopic manager – the individual in charge of soliciting reviewers and technical contracting officers for the SBIRs – had an office down the hall from the Goddard technologist [INT#1, 7]. Thus, upon returning to Goddard, the technologist indicated to his friend, the subtopic manager, that there might be a QWIPs proposal coming in, and if so he would be happy to review it. The subtopic manager agreed "*because it's really hard to find reviewers so if someone volunteers it's very hard to say no…*" [INT#1] and assigned himself as the second reviewer [INT#7]. Both technologists were suitably impressed; the contract was awarded in September of 2006 and the GSFC technologist became the contracting officer's technical representative (COTR) [DOC#3].

The output of the phase I contract was a prototype QWIPs-based camera; an excellent result for the 6 month 100K contracting mechanisms [INT# 1, 3]. Despite the success, the phase II bid was rejected for reasons that seemed baffling to the team [INT#1]. Outraged by what he saw as a clear failing of the system, the Goddard technologist made a series of phone calls to his colleagues in programmatic roles [INT#1]. As told from his perspective, within a few weeks, the funding managers realized their mistake and righted the wrong by securing enough funding (~$300K) to "*keep us both [him and the small business] alive for another 18 months, which turned out to be enough.*" [INT#1, 7] The funding came from a partial SBIR phase II and a partial ESTO grant – redistributed at the discretion of the program office [INT# 4]. In this case, the role of technology portfolio management for the SBIR phase II awards, and ESTO program manager were held by the same individual, a colleague of the Goddard technologist's [INT#1, 4].

As recounted by the ESTO fund manager, the initial phase II rejection shouldn't have been surprising at all [INT#5]. The way the transition from phase I to phase II SBIR awards is structured, center-level boards rank their own center's finishing phase Is; and that ranking forms the basis for NASA-wide SBIR portfolio planning for phase II [INT#5, 11]. In the case of QWIPs, the Goddard ranking was quite low, so it would have been inappropriate, from a process point of view, for the ESTO fund manager to recommend that it receive follow-on funding. In his view, the low ranking was because of a lack of advocacy in the review meeting by the Goddard technologist/project COTR [INT#5]. While advocacy is not explicitly a necessary part of the process, a short presentation by the COTR is the primary basis for the committees decision and, all things being equal, enthusiasm about the recommendation plays an important role.

The Goddard technologist hadn't appreciated the importance of his advocacy role; he believed that the capability was so obviously an important enabler of future missions that it should speak for itself [INT#7]. This was not the first funding proposal on this innovation pathway that had been turned down for lack of *salesmanship*. A previous Internal Research and Development (IRAD) proposal had been rejected because the link to future missions hadn't been effectively communicated [INT#8]; similarly, the earlier SBIR phase Is hadn't shown clear flight project ties. However, at this time, the Goddard technologist felt strongly enough about the efforts of the company to *play the game* [INT#1, 7]. Retroactively, he was able to convince the funding manager and secure the follow on funding. At the same time, he supplemented the SBIR/ESTO combination with Goddard's internal R&D funding (IRAD) [INT#1, 4, 7, 8].

However, even before the IRAD could be completed, the original SBIR team was drawn into a project-specific development contract to develop a QWIPs-based TIRS (Thermal Infrared Sensor) instrument for the Landsat Data Continuity Mission (LDCM) [INT#1, 7]. As described in the introduction, the politically charged LDCM mission was facing major technical difficulties with its baselined TIRS instrument [DOC #12 -15]. Whereas in the original TIRS technology tradestudies in 2000 and 2007, QWIPs weren't even considered, due to insufficient data about their performance in the required wavelengths [DOC#12, INT#7]; a year later, however, after significant investment through ESTO, SBIR and internal Goddard R&D, QWIPs were now the least programmatically risky choice going forward.

Now in the TIRS baseline, the original QWIPs team, and additional engineers, have been pulled into the LDCM project and are operating under a stable, legislatively guaranteed ~$10M, project-specific funding with a clear very near-term mission objective. The Goddard technologist believes that an important difference between the ESTO product, which did not convince the TIRS team and the SBIR output, which did, was the involvement of a commercial company [INT#1]. From the project perspective, the difference was as much a matter of evolving priorities. [7] As of the time of writing (early 2010) the final space-qualification and development

[7] A more complete history of the TIRS instrument is beyond the scope of this paper but a few key points provide important background. In 1992 the Land Remote Sensing Act guaranteed a data continuity mission to follow Landsat 7. However, although Landsat 4, 5 and 7 image in the thermal band, because the users of this thermal data are a small niche community and since these types of measurements are difficult (i.e., expensive) continuity of thermal imaging has never been popular in Washington. From the perspective of TIRS, LDCM has undergone X major reformulations. In the mid 90s, LDCM was investigated as a series of industry studies, with TIRS as an optional extra; they came up with huge cost estimates based on heritage microbolometers. None of the studies were selected and following a National Security Council-led interagency review, the LDCM functionality was relegated

are currently being pursued as two parallel projects [DOC#11]. The first is a collaboration between the Goddard Space Flight Center and the US Army Research Laboratory (ARL) seeking to design and fabricate a corrugated QWIP array based on the concepts proven in the ESTO contracts. The second is a team consisting of the SBIR small business, with support from GSFC/ARL to develop a grating based QWIP array. The LDCM mission is scheduled for flight in 2012[14].

4 Formal Mechanisms in the NASA Innovation Architecture

In the above description, a number of institutional mechanisms, designed to support technology and system development, were mentioned. This section revisits and categorizes them in terms of their stated and effective role in NASA's innovation system. Figure 2 presents a conceptual overview of how the different mechanisms are arrayed in terms of emphasis as well as funding size and duration of support. There is an expectation that new concepts move through the system from left (novel concept) to right (implemented on scientifically important flight mission) requiring an order of magnitude of more funding resources at each stage of maturity. The number of funded technologies is expected to be winnowed down at each stage, with only a few of the hundreds of concepts that enter the system finding use on flight projects. The following sections describe each of the funding "decades" and the extent to which there are explicit connections among them.

4.1 Brainstorming

In this context, brainstorming refers to the informal activities that precede formal applications for technology development funding. Since there is a certain cost associated with proposal writing (in terms the opportunity cost of writing the proposal vs. working on other projects) and there is an inherent uncertainty as to whether that proposal will be funded (and if the idea will go anywhere), scientists and technologists tend to spend some time on *back of the envelope* calculations designed to convince themselves that they have a concept worth pursuing [INT#11]. There is no direct funding for this type of activity, but a few mechanisms do exist to encourage these creative interactions. For example, in the QWIPs case, the GSFC technologists were sent to JPL to brainstorm and find an area for collaboration. Similarly, trips to conference meetings are an important (funded) opportunity to brainstorm and cross-pollinate ideas.

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as one of the many NPOES instruments. That program ran into difficulties and in 2005 OSTP released a memo directing NASA to reinstate LDCM as a free-flying mission. Thus, NASA released a request for proposals (which included the possibility of a TIRS instrument). By that time, scientists in Idaho had found a way to use Landsat thermal data water resource disputes (an important and expensive issue in the Midwest U.S.) and had established a powerful lobby. In 2007 NASA conducted an in-house concept study of a TIRS instrument. Believing that coming up with a reasonable cost estimate was the most important factor for TIRS inclusion; they turned to commercially available microbolometers. However, a year later a closer look revealed that microbolometers were not an adequate solution and the TIRS instrument was de-manifested to preserve schedule. However, in 2008 at the systems requirement review, the project was projected to be at least 6 months behind schedule. This created a new opportunity for a TIRS instrument to be manifested. HQ asked Goddard, the systems integrator if a new instrument could be furnished. They responded "yes, but only if we can use QWIPs and develop it in-house." HQ conceded and QWIPs was baselined. At this point, the decision was one of expedience. During the previous 8 years, Goddard had developed the in-house capability of manufacturing QWIPs devices, eliminating the need for time consuming procurement, and making the extremely aggressive two year timeline realistic. [INT#10, DOC#13]

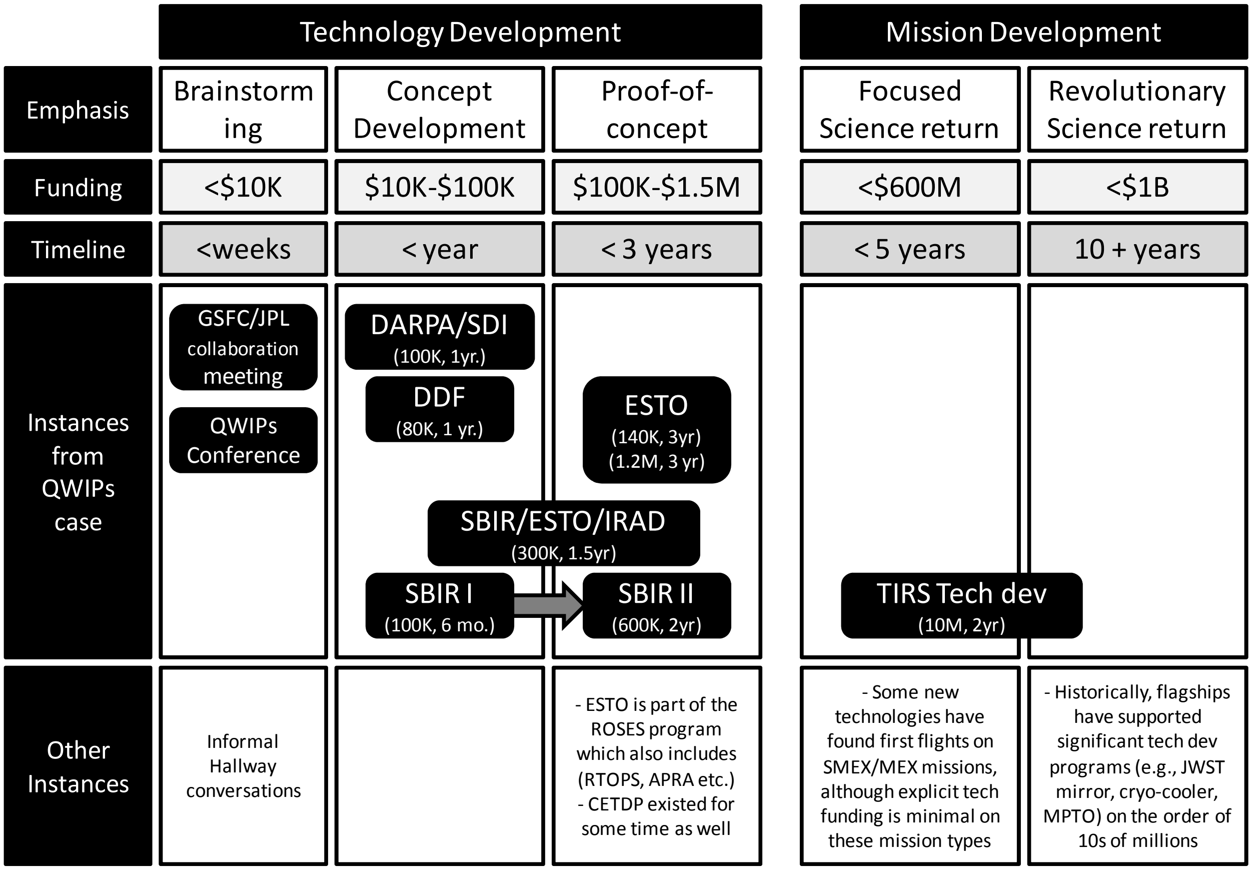

Figure 2 – Map of Formal Institutional Mechanisms Employed in QWIPs Case

4.2 Concept Development

Once an idea has been fleshed out, a small amount of seed funding is needed to develop the concept so that it can be pitched to the larger, more stable technology development funding. Uses for these $10 – 100K include buying parts for breadboards, machine shop time, and paying civil servants' salaries.[8] Investment in this early stage concept development is currently left to the discretion of the NASA centers. They exist at the discretion of the center director, which means that there's no explicit NASA-level funding line for them; rather, on a center by center basis, management has decided that investing in promising ideas is "*more important than cutting the grass as often as we'd like.*"[INT#11] This speaks to the reality that early stage funding is currently minimal and highly variable across centers. At Goddard, over the last few decades, this funding has existed in two forms: the DDF (the director's discretionary fund) and IRAD (internal research and development). Although they cover a similar place in the maturity spectrum, they employed quite different operating philosophies. DDF was designed with a high-risk, high-reward mindset, administered by the senior science fellows within the center. There was limited traceability in funding decisions and follow-up, and the perception is that the programmatics emphasized trust in the judgement and expertise of the individual recipients [INT#8, 11]. IRAD on the other hand, which has superseded DDF, is administered by the Chief Technologists Office. It serves as strategic funding designed to win future missions for Goddard as a center. As

[8] As civil servants, NASA employees are required to account for all their hours with charge codes; and time spend developing new concepts needs to be charged to something. IRADs are one way of covering this cost.

a result, proposers are expected to demonstrate clear links to (potential) future missions, even for early-stage developments.

The other main source of concept development funding is from the small business innovation research (SBIR) program. SBIR is a congressionally mandated program[9] which is administered at NASA by the Agency-wide Innovative Partnership Program (IPP). The program requires that NASA technologists work with small businesses on innovative, low TRL concepts.[10] The phase I awards are designed to prove-out the concepts and determine if the relationship is worth pursuing.

4.3 Proof-of-concept

Within the Science Directorate, the first stage of formal technology funding is covered by NRAs (NASA Research Activities), with the PI led grants administered through ROSES (Research Opportunities in Space and Earth Sciences). ROSES encompasses a number of theme specific (i.e., Earth Science vs. Astrophysics) funding programs including RTOPs (Research and Technology Operating Plans), ESTO (Earth Science Technology Office) and APRA (Astronomy and Physics Research and Analysis). These are peer-reviewed, multi-year grants, on the order of $100K to $2M, designed to support the pre-development of flight instruments for future missions. There therefore needs to be a clear mission application expressed in the proposal. Centers tend to have small amounts of money to support proposal development for these types of awards.[11]

Phase II of the SBIR program also falls into this category, funded at $600K over 2 years. Companies are often expected to develop prototypes in this phase in order to prepare for follow-on commercialization or infusion into NASA missions.

4.4 Flight Mission Development

NASA flies a mix of mission classes, differentiated primarily by funding level (e.g., in the astrophysics context, Flagships are more than $1B, explorers (SMEX/MidEX) are low hundreds of millions and medium missions are in between). However, the price differentiation also corresponds to risk acceptance and technology development investment. Specifically, explorer missions are not *allowed* to require any new technology development (with the exception of one planned "miracle" that won't interfere with overall mission success if it fails [INT#11]). Flagship missions, on the other hand, are expected to revolutionize a branch of science, and therefore invest heavily in technology development. With 10-plus year development cycles, they can support fairly major long-lead technology development initiatives, and recent missions have invested tens of millions in this effort. It should be noted that the LDCM $10M investment in TIRS and QWIPs is slightly different. LDCM isn't really a flagship mission, and the tech development wasn't initiated early in the program as a planned innovation mechanism. Nonetheless, it is fulfilling the same function of stable, substantial, project-specific technology

[9] For an overview of the SBIR program see [23] NRC, "SBIR and the Phase III Challenge of Commercialization: Report of Symposium," T. Committee on Capitalizing on Science, and Innovation, National Research Council, Ed. Washington, DC, 2007.
[10] For an overview of the Technology Readiness Levels see [24] J. Mankins, "Technology Readiness Levels," Advanced Concepts Office, NASA1995.
[11] For example, Goddard has a small proposal support office.

development funding. One clear difference between project specific funding and the other stages of funding is that individual scientists and technologists cannot bid for it. The resources are allocated by the project to baselined instruments that are deemed to need it.

4.5 Connections among mechanisms

It is noteworthy that there is only one explicit arrow connecting any two funding buckets in Figure 2. In the context of SBIR, there is indeed a clear mechanism for how a successful phase I contract should receive follow-on funding as a phase II. As described above, there are a series of review stages where COTRs advocate for the companies and outputs are ranked. The overall allocation is managed as a portfolio at the agency level. There are no similar mechanisms connecting any of the other funding buckets. In fact, Figure 3, reproduced from the NASA systems engineering handbook, shows the assumed fluidity of how the system is presumed to work. Using Figure 2 above as a basis, the next section will explore how the system is actually traversed in this case and why.

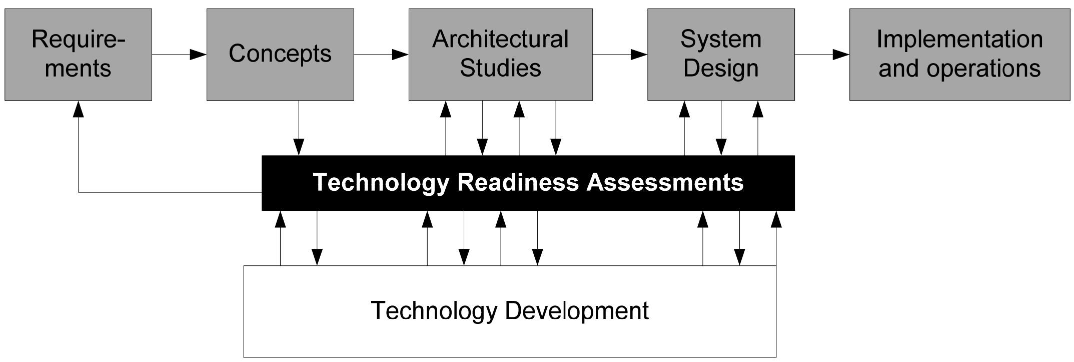

Figure 3 - Conceptualization of NASA Technology Infusion Process

5 Informal Mechanisms that Shape the Innovation Pathway

Having outlined the components of NASA's innovation system in the previous section, the QWIPS innovation pathway described in section 3 can now be plotted. Figure 4, illustrates the process history both in terms of funding buckets and time. The first clear observation from the figure is that the pathway doesn't follow the nominally expected linear progression through the phases of funding and maturity. This *loopiness* is not on the surface an unexpected result – the linear model of innovation has long been discredited. However, the assumption in the phased NASA innovation system is not that innovation is a linear process whereby successful brainstorming leads directly to a proof-of-concept that can be matured as a flight instrument; rather that once a concept has been proved-out (however that happens), the next step involves flight qualifying not a return to concept development. It is the latter assumption that is challenged by this *loopiness*. In order to investigate the nature of that challenge, this section explores the rationales and informal mechanisms that shaped the QWIPs innovation pathway in this way. The following sections focus on the particular mechanisms that drove each transition for this particular case and discuss the broader categories of informal mechanisms they represent. A discussion of the implications of these dynamics and potentially general categories of informal mechanisms are left to section 6.

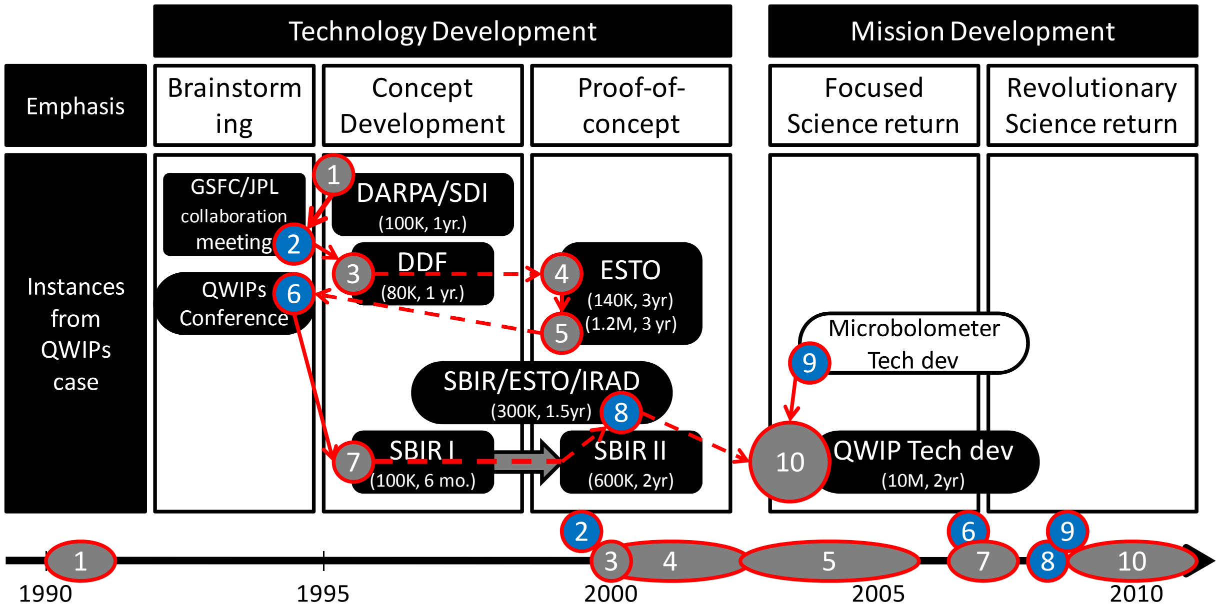

Figure 4 - Illustration of QWIPs Innovation Pathway

5.1 Nominal Transitions (2-3-4-5)

Within the overall innovation pathway, the progressions from steps two to five are fairly nominal, direct transitions. Potential collaborators were brought together and given seed funding (DDF) to flesh out their good idea. Early in the fleshing-out process they applied for a modest (by ESTO standards) amount of follow-on funding to ensure that the project would continue if they were successful. Through the combined DDF and first ESTO grants, the utility of the concept was demonstrated, making follow-on more substantial, funding from a second ESTO natural. They were already familiar with the process (low overhead of re-applying to the same mechanism), and were nowhere near the upper funding limits with their first proposal.

It's worth noting that ESTO was not the only proof-of-concept funding bucket available to the QWIPs development. Although QWIPs was eventually infused into LDCM, and Earth Science mission, the technology is equally applicable to the Astrophysics mission area. Several factors contributed to the decision to pursue ESTO. Firstly, although ESTO is a "level 2" (i.e., agency wide) funding mechanisms, the program office is physically located at Goddard; this enables informal discussions that might otherwise not happen. Allen[19] has written extensively on the importance of informal social interactions. It's difficult to characterize the importance of this type of factor, but records show that many ESTO funded Goddard technologies eventually get infused into other mission areas (i.e., not just Earth Science missions, which one would expect) suggesting that it is a go-too funding source; as well, the technologists we interviewed seemed to view ESTO as less of a black-box application process (part of which is certainly attributable to the process itself).

That QWIPs stopped the *normal* trajectory at step 5 is not uncommon. There is no direct link from ESTO to any project. This is intentional. While the ESTO program prides itself on high infusion rates, ESTO managers see their role as providing unbiased assessments to HQ, rather than advocating for any particular technology that they have funded. Thus, although proposers are encouraged to illustrate direct links to future projects, there is no transition support provided by the ESTO office. They limit their follow-up to collecting infusion records and advising flight project planners about new capabilities in the pipeline, when asked.

5.2 "Backwards" Transitions (1-2; 5-6; 7-8)

As shown in Figure 4, the QWIPs innovation pathway followed unexpected trajectories at a few key points: the reinvigoration of an old partnership, the transition from an ESTO success to a phase I SBIR and the transition from an excellent phase 1 SBIR to a one-off ESTO/SBIR bridge. The first "backwards"[12] transition was explained in detail above, so the major points will only be outlined briefly here. The 1991 SDI contract didn't move forward for a series of practical considerations including strategic choices and competing priorities. While the specifics of its innovation may have become obsolete in the intervening 8 years, the trust-based working relationship it created endured and influenced many of the later activities in this story. Given the extent of advances in the field, and the new application area, that the previous work was revisited as a conceptual brainstorming exercise should not be surprising. That an agency policy decision catalyzed the reunion of a high functioning team is, however, worthy of some note.

For the second backward transition, as described above, there is no natural next-step after ESTO grants; technologists are left to their own devices to find flight opportunities. Since there was none immediately available for QWIPS, the technologist/champion sought other non-space demonstrations. For example, the technology was used for medical imaging (certain diseases can be diagnosed based on imaging in the far IR), and in collaboration with the US Geological Survey to map terrestrial canyons (a similar function as what might one day be relevant for Mars exploration). Each of these applications forced the team to mature the concepts further and enabled them to gain additional risk reduction credibility for whenever the next flight opportunity would arise.

The apparent backward step to the SBIR contract was not actually a loss in maturity; rather it was more a tangential opportunity that could bolster the overall flight case. The opportunity came about because of a "chance encounter" at a conference. Given the small size of the QWIPs community, once at the conference, the fact that the Goddard Technologist and the small business CEO got to talking is not surprising. Though, it's worth noting that authorization to attend conferences cannot be taken for granted in the NASA context. There are recent examples where NASA has put all conference travel on hold for months at a time. In this case, had the two not met at this time, the small business would likely not have submitted a fourth blind SBIR proposal and the Goddard technologist may not have been selected as COTR had it been selected.

In terms of the decision to collaborate, from the perspective of the Goddard technologist, in a funding and time constrained environment, SBIRs (money that they have to spend anyway) provided an opportunity for a small business to work on something in which they had a comparative advantage, and that he wanted done anyway. The actual work focused more on a new way to manufacture the devices (now serving as one of the parallel developments), highlighting an important difference between the "basic R&D" done by small businesses under

[12] "Backwards" is used here because the sequence of funding buckets appears to proceed in reverse maturity. However, as discussed in section 6, the backwards-ness relates to imprecision in the term maturity. It is expected that has this research moves forward, the concept will be refined considerably.

SBIRs and the phenomenological physics "R&D" that was conducted in-house earlier in the process.

From the perspective of the small business, the decision to contract with NASA (and the government in general) was a reluctant one. Started in the early 2000s by a few engineers from a "big three" Defence Contractor, they had left the firm due to frustration with government contracting practices, hoping to make their mark (and fortune) in the commercial advanced optical technologies world. Eventually, they found a niche and were doing fairly well commercially; however, as the market has softened in recent years, they've taken *shelter* in the government contracting sector; now, SBIR contracts from several government agencies form a staple income stream. They do continue to pride themselves in delivering more than they promise and have developed a strong reputation in the fairly small QWIPs community.

That they developed a camera prototype in response to the phase I contract was in keeping with this operating style. However, they were able to do this in part because they were already relatively experienced in the area – they started with a phase I because there's no mechanism to jump straight to a phase II in the SBIR program. Viewed this way, the backwards step was, at least partially, procedurally coupled with a need to find bridge funding somewhere.

The third nominally backwards transition, failing to proceed from a phase I to phase II SBIR award, resulted from a lack of sufficient salesmanship on the part of the Goddard technologist. What's interesting here is the expectation that technologist COTRs will advocate for the small businesses and that this plays an important role in the decision process. On the flip side, the flexibility of the system to fill-in for the lost phase II follow-on is remarkable. The funding managers reported that it is extremely rare to exercise this flexibility to fund losing contracts in other ways; in this case, it was achieved with expedience. This is another area where the fact that the ESTO office is physically located at Goddard came into play. The history of previous in-person interactions between the technologist and funding manager contributed to the frank discussion of priorities which enabled the gap-filler funding.

5.3 Transition to Flight (8 and 9 to 10)

To have a legislative action be sufficiently detailed to target an instrument on a particular mission is to our knowledge unprecedented. As explained by one NASA executive *"A lot of people [on the LDCM project] felt like they had QWIPs rammed down their throat."*[INT#10] But, as an instance of the high activation energy required for a flight project, and particularly an operational mission, to take on the risk of a new technology is a well-documented dynamic (c.f., Sapolsky[25] re: Polaris; McDougal[26] re: Apollo). In this case, the directive to fly <u>some</u> TIRS instrument certainly created the opportunity needed for QWIPs to achieve its first flight. It was chosen over other alternatives because it was the only device that could be ready soon enough.[13] This would not have been so without the ten years of concerted effort and support from pre-mission funding mechanisms that predated the opportunity.

[13] Recall that HQ reversed a previous decision not to include a thermal instrument a mere 2 years before the required launch date. At that point, schedule was the driving factor, and QWIPs was the only chance, and therefore deemed worth the risk.

In the context of modern NASA, the difficulty of transitioning from technology development to flight manifestation stems from a clash of cultures and priorities between the technologists working to push the state-of-the-art, and project engineers focused on accomplishing extremely challenging missions with limited risk, as well as the difficulty of managing the interface between them. The following two quotes illustrate the contrasting perspectives. As articulated by an experience centre chief engineer who spent his life working on the flight projects:

> *"there is not a dearth of ideas; [that's not the problem, the problem is that] there is a sad lacking in the understanding of the ramifications of carrying the idea through to its conclusion. So the ability of a human being to sort through 100s of ideas to find the one or two that might be a useful nugget is a very difficult. […] in general, there are more technologists with ideas looking for a place to apply them, than there are people who are flying flight missions looking for ways to solve problems that they have with new technology."*

An important point to realize about this statement is that NASA is typically the sole near-term customer for those one or two nuggets, and if a flight project does not choose to infuse them, they will be shelved before their broader utility is ever realized. This is the perspective of an experienced technologist who has spent more than two decades developing optics technologies for space applications:

> *"Technology takes years to develop - from when you have a good idea to when you have an applicable product even to a single government use, never mind commercial - so to have a coherent plan, what you need is a vision for the technology needs that is stable compared to that timeline. It's not. We don't know what we're doing for years and years at a time, and by the time we do, the technology that's in the pipeline is misdirected. That doesn't always happen, [but] that happens enough that it seriously detracts from the utility of the program. And people at my level are essentially reading tea leaves and putting fingers to the wind trying to figure out where the wind's shifting to try and leverage the opportunity towards something useful. And sometimes it works… surprisingly! but a lot of times, [you find that] you built a widget that has no applicability."*

An irony in this process is that as soon as a new (useful) technology achieves its first flight baseline (not necessarily flight) other projects start seeing it as an incumbent and are quick to include it as the default choice. In the QWIPs context, although LDCM won't fly until 2012, other technologists were already mentioning their efforts to unseat the default QWIP-based approach. Future cases will be required to determine if this dynamic is more generally observed.

5.4 Types of Informal Mechanisms

Having discussed the reasons the QWIPs innovation pathway took the form that it did above, this section identifies the types of informal mechanisms that drove the process. It presents a preliminary set of categories, which will serve to focus, while being refined by, the planned follow-on work. These categories are summarized in Table 3.

Interaction events describe instances when individuals from distinct subunits of NASA's organization (and/or external collaborators) have an opportunity to interact informally. This could equivalently include meetings in a shared coffee room, or discussions at common technical conferences. They are one-off occurrences (i.e., not reoccurring formal interactions); and are not sought out by either party for an explicit project-oriented purpose (distinguishing them from backchannel communications).

Advocacy describes instances where an individual or group makes an explicit effort to make their (supportive) opinion heard by another individual or group with actionable authority. Internal advocacy refers to advocacy carried out by someone intimately involved with the project (not necessarily within NASA). While external advocacy is carried out by someone without direct ways to impact the project (i.e., the lobby will use data once the satellite is built, but aren't directly involved with its development).

Backchannels describe a subtle form of advocacy. While it can fulfill a similar function of communicating in order to support to decision makers, it is done behind the scene and not always directed at changing decisions.

Discretion is used here to describe instances where flexibility in the system is actively exercised. For example, the ESTO program has some program funds that are not distributed as part of the standard resource allocation. This funding can be used by program managers, as they see fit. When they choose to allocate these resources to provide bridge funding to a promising technology, we call this the mechanism of discretion.

Table 3 – Informal Mechanisms in the NASA Innovation System

Mechanism	**Description**	
Interaction events (A)	QWIPs Example(s)	• Goddard/JPL collaboration brainstorming • QWIPs external conference
	Function	Collaborating across traditional disciplinary boundaries is known to stimulate creativity and innovation in general. In the NASA context, involving multiple collaborators opens up additional institutional funding mechanisms, keeping projects moving forward
Internal Advocacy (B)	QWIPs Example(s)	• Lack of championing at SBIR transition • Active promotion of QWIPs through outside demos (medical, underground caves etc.)
	Function	Funding decisions are made by busy non-experts, advocacy on the part of technologists makes sure they have the right information to make a favorable decision
External Advocacy (C)	QWIPs Example(s)	• Congressional lobbying led to line item in appropriations bill
	Function	Science community interest groups centralize opinions and communicate priorities and user needs to decision makers. The act of lobbying also indicates future directions to the technologists to help them "read the tea leaves"

Backchannels (D)	QWIPs Example(s)	• Goddard technologist suggesting to his colleague that he'd be willing to COTR "if" a QWIPs SBIR came in • Off-the-record discussion between COTR and ESTO fund manager
	Function	Grease the formal mechanism: allows the information, that can't be discussed in open forums, to get communicated candidly, to make everyone aware of what they need to know.
Discretion (E)	QWIPs Example(s)	• The existence of IRAD • The use of ESTO program funding to support QWIPs
	Function	Resolves "catch-22s" in the system: new technologies need to be mature before they can be baselined in flight systems (or even get development funding), but they can't be matured without funding. Small amounts of IRAD fill this hole.

Overall, these types of informal mechanism serve to compensate for inefficiencies in the system. This observation does not imply that these informal mechanisms should be institutionalized. However, since they do play an important role in shaping the innovation pathway, it's important to recognize their existence and analyze the extent to which their use can be promoted as appropriate. Figure 5 illustrates their impact on the trajectory.

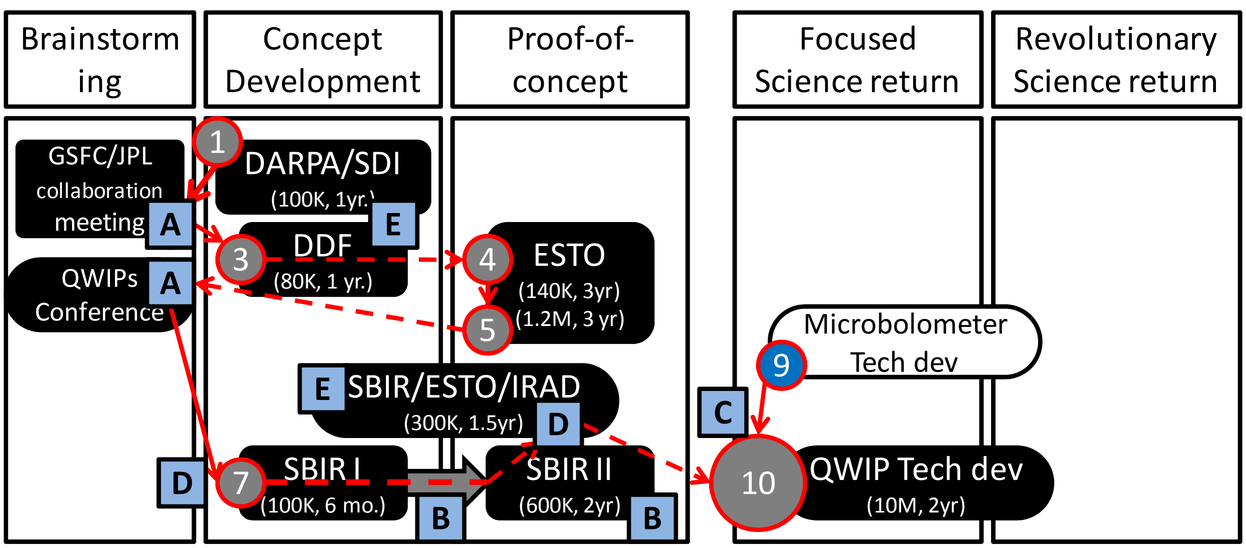

Figure 5 – Map of Formal and Informal Mechanisms in the QWIPs innovation pathway

6 Implications of this case: practice and theory

One of the directives in President Obama's FY2011 NASA Budget Proposal is for NASA to reorient itself as an R&D organization. There is significantly increased funding directed towards basic research and there are plans to bring back some of the old R&D infrastructure. However, as discussed with respect to Figure 1, the historical oscillations are correlated with reactionary swings in policy direction. Called punctuated equilibrium in the exploration v. exploitation literature (see [27] for a recent review article), NASA has previously spent periods of time focusing resources on basic cross-cutting research until it was criticized for spending too much time in the "sandbox." Then began an era of exploiting all those enabling technologies, until they ran out of technologies to exploit, and were criticized for stagnating and forgetting how to innovate. This cycle has repeated itself several times in recent history. The current administration is committed to investing in cross-cutting R&D with a purpose, hoping to find a balance of sufficient investment in basic research, while leveraging that investment on ongoing projects. While a noble goal, it will be a formidable challenge not to fall into the same pattern of over-shooting and focusing too narrowly on exploration. If a sustainable balance is to be achieved, major structural changes are required; and to understand the future implications of those changes requires a better understanding, than we currently have, of the way the system is actually working.

On a practical level, this work contributes directly to that goal. The current operating assumption at NASA is that technology research links to project development as a stage-gate process, with occasional jumps, skipping the development over normal steps, as illustrated in Figure 6.

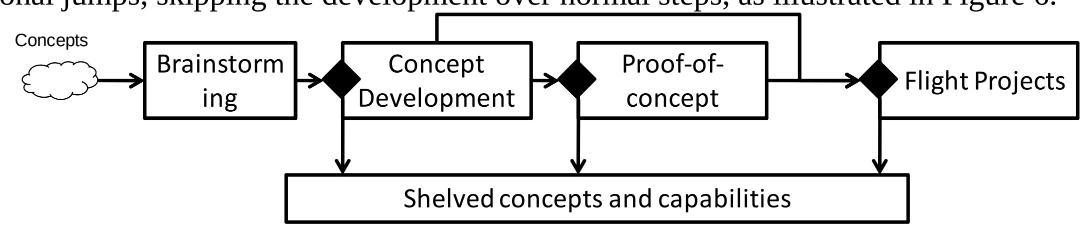

Figure 6 – Baseline conceptualization of NASA's innovation system

Conceptualized this way, NASA's innovation system is a series of stages (during which technology is matured) separated by gates (decision points, where progress is reviewed and the set of maturing capabilities that will go on to the next level are selected)[28, 29]. The innovation management problem thus reduces to a design problem: optimize the gate criteria to achieve the desired flow of new capabilities. What the QWIPs case shows is that the technology flow through the system is not always a progression from right to left, which has important implications for how the system should be improved.

There are at least three plausible explanations for the non-linearity of the process. Firstly, technology maturity may not be a monotonically increasing attribute of the technology, as has been assumed. Second, embedded flexibility in the implementation of the system may account for the observed non-linearity. Third, project goals may simply have changed, causing the idea to literally return to the drawing board. In the QWIPs case, elements of the first two explanations provide partial explanations. Among space technologies, QWIPs is fairly (in terms of integrative complexity) simple. Nonetheless, the physical phenomenon that enables its use can be implemented in multiple different ways, and each implementation presents different manufacturing challenges. Thus, while the transition from the ESTO completion to SBIR phase I was on some level a return to conceptual design, the "return" was on a different, but related, trajectory from the work done under the ESTOs. In other words, while maturity wasn't lost on the ESTO development, another aspect of the design needed to be investigated from concept through to manufacturing. As complexity of the device increases, this type of distinction becomes more relevant and raises a broader insight. In the space context (and complex products more generally), innovation happens at multiple units of analysis (e.g., Henderson and Clark's quad chart[30] must be replicated at every level of integration). As a result, the innovation system components must be sufficiently flexible for multiple development trajectories to be pursued simultaneously.

With respect to the second alternative, the SBIR program, like many other technology development funding mechanisms in the current system, is fairly flexible. That SBIR, IRAD and others can be (and are being) used strategically is an important aspect of what makes the current system work. Strategically in this context, it means that the nominally early stage IRAD can sometimes be used to support a "balloon test" if it is the last step necessary to win an agency-wide bid. Further, while the contracts are typically small, there is flexibility to provide more substantial support in exceptional circumstances. One way to interpret the fact that flexibility plays such a prominent role in the current system is that it allows individuals to compensate for an otherwise broken system; the implication is that if the organization was better designed there would be no need for flexibility to be built in and leveraged. While this is an enticing notion, in fact, innovation is well-recognized to be a messy process. No matter how well the system is designed, it is unlikely that it can fit all innovation pathways simultaneously and, thus, requires some flexibility to accommodate the inherent idiosyncrasies. The point is that flexibility, and the act of exercising it, is not inherently bad; the Agency must be cautious in overly defining and regulating the roles of the different funding mechanisms moving forward.

In terms of fundamental understanding, the QWIPs case and the observed backwards transitions illustrate the need to develop a more meaningful definition of maturity in the context of complex systems. The Technology Readiness Levels (TRLs) currently employed are clearly insufficient in that they confound both component and system maturity and are also associated exclusively with a prescribed sequence of tests, rather than fundamental attributes of the technology. A complementary System Readiness Level (SRL) scale has been proposed[31] but it is built on similar principles and only differentiates on two levels of complexity. As this research moves forward, one important contribution maybe a clearer understanding of how maturity actually accrues in this context. It is believed if that a more general and operationalizable definition of maturity can be posited, an improved NASA innovation system can be built around it.

From a theoretical point of view the concepts of policy windows in agenda setting and inherent trade-offs in balancing exploration and exploitation within the context of the firm, provide useful lenses through which to consider the challenges facing NASA. At the same time, because of the nature of NASA's problem, it provides a fertile empirical basis for testing the implications and extending the constructs put forward in those literatures.

As alluded to in the introduction, the policy windows perspective conceptualized change in bureaucratic decision making systems as the intersection of separate problem streams and solution streams, brought together when a window of opportunity opens up, allowing a problem and a solution to combine and yield a new status quo [2, 32]. In this view, progress should happen incrementally, except when an opportunity for a step-change is seized. Improving the system then becomes a matter of using windows effectively. Many past studies of innovation in government agencies have been done in the context of military innovation by political scientists; considering innovation as a step-change process. Consequently, they have focused on identifying the catalysts of windows (c.f., [26, 33, 34][14]) or the implications of their opening (c.f., [25, 35][15]). While the NASA process is in many ways similar to political agenda setting, the realities of path dependency and significant lead-times in technology maturation limits the explanatory power of these constructs in this context. Specifically, the assumption that solutions generally exist but just aren't being used; and that they will continue to exist until a need finds them, does not hold. While it may be true for policy alternatives, it isn't true for the cutting-edge technologies of interest to NASA. As demonstrated by the QWIPs case, significant pre-development in advance of project "windows" is necessary. Further, contrary to the fatalist assumptions of the policy window model (that, as a technologist, one essentially needs to wait to fit one's widget into whatever flight opportunity arises) the QWIPs illustrated multiple instances where individuals used informal mechanisms to create mini-windows or act in advance of future ones. As the broader study proceeds, there is potential to extend this model to include technology-intensive solutions in bureaucratic organizations.

In addition, the need to balance the competing goals of exploration (seeking radical innovation through the pursuit and acquisition of new knowledge) and exploitation (leveraging existing capabilities to enable incremental improvements) (see [36] for March's initial treatment or [27, 37] for more recent discussion) is by no means unique to NASA. However, studies suggest that characteristics of a firm which enable exploration tend to limit exploitation and vice versa [38]. Two strategies for promoting both kinds of expertise have been proposed. So-called ambidexterity[39] advocates for combining exploration and exploitation through loosely coupled organizational sub-units and so-called punctuated equilibrium[40] suggests that functions can be temporally sequenced (e.g., long periods of exploitation, followed by short bursts of exploration). However, few empirical examples of ambidextrous organizations exists in which to test the emerging theory.[38] To this end NASA provides a unique opportunity to study the trade-offs empirically because a) its plans explicitly bundle a combination of exploratory and exploitative missions; and b) advanced space science is a nearly closed market environment (the vast majority of relevant R&D is funded by government grants) creating traceable links between resource allocation decisions and innovative outcomes. As illustrated in the QWIPs case, at an organizational level, NASA's history shows a pattern of punctuated equilibrium. However, at the project level, NASA seeks to connect a technology development process (focused on exploration) to a project enterprise focused primarily on exploitation. The tensions between these competing objectives are clearly apparent in the QWIPs case, and are remedied to a large degree by the informal mechanisms described above.

As a single longitudinal case study, the main value of this first stage of the work is to illustrate limitations in current conceptualizations and show their potential implications. To this end, the QWIPs case raises some important cautions relevant to NASAs innovation redesign. The current funding buckets are extremely flexible, allowing perceived maturity loops which involve technologists finding unorthodox ways to secure the required funding from multiple locations. If this were to change, calibrating the relative investment needed to prove-out different aspects of

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[14] For analyses of the perfect storm of geopolitical events which enabled Kennedy's moon speech to have the impact that it did, or how the partnership between civilian leadership and a champion within the military allowed the British Air Force to innovate between wars.

[15] In addition to looking at how the window was opened, these works look at how importance/urgency changed the way projects were managed and the relative access to talent and resources compared to other projects.

the development will become critical, otherwise enforced rigidities may worsen the system rather than improve it. Further, while it is difficult to quantify the importance that informal mechanisms play in driving the system, they were observable in multiple instances. At minimum, the role they currently play must be understood, and considered in the discussions of how the system should evolve. In this area in particular, the follow-on research will help establish the more general functions that these informal mechanisms serve. Thus going forward, cases have been chosen to explicitly contrast technologies infused into stably-funded large missions with fixed price small missions; focused, relatively simple sensor technologies, with cross-cutting technology driven satellite bus technology. This will allow us to test and refine these initial ideas about the role of informal mechanisms in driving the current system, and the meaning of maturity in this context.

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