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INSTANTIATIONS of GOVERNMENT SPACE INNOVATION SYSTEMS: A COMPARITIVE ANALYSIS

Zoe Szajnfarber
Massachusetts Institute of Technology
Cambridge MA, USA
zszajnfa@mit.edu

Abraham T. Grindle
Massachusetts Institute of Technology
Cambridge MA, USA
grindle@mit.edu

Annalisa L. Weigel, PhD
Massachusetts Institute of Technology
Cambridge MA, USA
alweigel@mit.edu

***Abstract*—This paper is part of a broader research effort which seeks to develop an understanding of the fundamental dynamics that govern innovation in the space sector. Framing the space innovation enterprise as a series of control loops, it highlights the critical functions of project prioritization (which balance science needs, technical feasibility and budgetary constraints) and the strategic orientation of technology development (bucketing funding opportunities in terms of 1) generic technology programs in S&T organizations or branches; 2) advanced technology programs addressing specific future needs; and 3) near term technology maturation programs to support identified gaps for particular programs). It examines each of NASA's, ESA's and the DoD's space innovation systems, providing a preliminary analysis of key differences in their approaches. The paper concludes by laying out the next steps in the overall research project.**

INTRODUCTION

Government space projects have been the source of, and catalyst for, unparalleled innovation. When Apollo 11 touched down on the lunar surface, the whole world watched; marveling at the magnitude of the technological, and human, achievement. Satellites have become indispensable tools in our daily lives, enabling on-board GPS in personal vehicles, global communications, weather forecasts, early warning for natural disasters, etc. More recently, though, government space agencies have become known for their failures as well as their successes. According to the House of Representatives' Report of the Committee on Armed Services, "*simply put, the Department of Defense (DoD) acquisition process is broken. The ability of the Department to conduct the large scale acquisitions required to ensure our future national security is a concern of the committee."[1]*. The same could be said about NASA or the European Space Agency (ESA), citing the large cost overruns and schedule delays of MSL, NPP, SDO, Constellation, Galileo and others. As former NASA Associate Administrator Alan Stern bluntly stated, "*You don't have to know what the abbreviations and acronyms mean to get it: Our space program is running inefficiently*"[2].

Why is it so hard for bureaucratic organizations to acquire advanced space systems effectively? Oft-cited reasons include a failure to mature payload technologies outside of acquisition programs, the decreasing technical competence of the acquisition corps and insufficient emphasis on front-end specification of requirements [3-9]. Other explanations blame inefficiencies inherent in, and resistance to change characteristic of, bureaucracies [10-13]. There is an implicit contradiction in much of this reasoning. On the one hand, there is recognition that top-down acquisition systems do, and must, drive technological progress differently than *normal* markets. On the other hand, the history of acquisition reform tells a recurring tale of efforts to alter these top-down systems to a competitive-like market environment. However, if the acquisition environment is fundamentally different from *normal* markets, perhaps the innovation mechanisms proposed by the business literature (c.f.[14-19]) are not directly applicable to the government space sector. One cannot make that determination without a deep understanding of the fundamental dynamics of innovation in government space sector; something that we do not yet possess.[1]

This research effort seeks to fill that gap by explaining and comparing the "institutional innovation systems" that have evolved within NASA, ESA, and the DoD Space Enterprises to deal with the inherent challenges of innovating in the space sector.[20] Although none of NASA's, ESA's or the DoD's acquisition systems can be construed as ideal examples of

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[1] As evidence of the continued debate, consider that all of the: 1) name; 2) funding level; and 3) location within the organization of NASA's R&T enterprise have undergone 11 major changes since 1992. A similar level of oscillation has been experienced within Military Space.

innovation generators, despite their faults, they have each produced impressive technological advances. Though they share important similarities (e.g., they all employ multi-tier acquisition systems, with at least some technology development separate from approved programs) there also exist important differences (e.g., the DoD acquisition system is driven by emergent threats in the battle theater, whereas NASA and ESA serve the more stable needs of grand scientific challenges). In part because of their historical roots and political entanglements the three organizations have evolved relatively independently. Nonetheless, all three address the same fundamental problem: how to continuously generate and encourage complex product innovation for the space environment in a politically charged monopsony-oligopoly market. It is expected that an analysis of the results of this natural experiment – different organizational instantiations addressing the same fundamental problem – will yield rich insights into the fundamental dynamics of innovation in government space.

Due to the sheer size and complexity of the space enterprise, it would be infeasible to capture the descriptive phase of this research effort in a single paper. Thus, this first paper in the series reports on the organizational layer of the descriptive phase of this study – situating the elements of the agencies innovation systems within the study framework. The follow on papers will add a description of the *shadow* innovation system which connects the elements described herein through informal transient *innovation pathways* as viewed through the lens of carefully selected historical examples. Based on these two complementary views of the organization, an explanatory model of the dynamics of innovation in government space will be presented.

CONCEPTUAL FRAMEWORK: GOVERNMENT SPACE AGENCIES AS INNOVATION SYSTEMS

A core underlying assumption of this research is that *innovation* is an important goal of government space acquisition systems. Innovation as a concept has taken on many, sometimes contradictory, meanings, across a wide range of disciplines. However, two common themes emerge from the debate:

1. Innovation is a process that happens over time, and thus it can neither be observed nor measured through a static lens [21]. Further, it is important to consider the whole picture, as most important innovations are, in reality, the sum of multiple interrelated inventions and improvements that have been integrated into a product over time [22].

2. Second, a new idea or capability (an invention) becomes an innovation once it has been implemented; "new" has no value unless people use it [23-25].

Following these themes, we take innovation in the government space context to be the phenomenon through which the performance outcome (as defined by the user), normalized by resource constraints (as experienced by the producer), changes over time. This can equivalently involve: a) generating a wholly new capability; or b) reducing the resources required to achieve an existing capability (e.g., making the system cheaper or lighter)[26].

In the same way that innovations are often the sum of multiple interrelated inventions and improvements, so too is the process through which innovation happens in a space system. This systems view is illustrated in Figure 1. Taking a control theoretic view of the system, space agencies – which exist to centralize resources and ensure the continued provision of some public good, to meet some perceived public "need" – are continuously seeking to close the "gap" between desired and available capabilities.

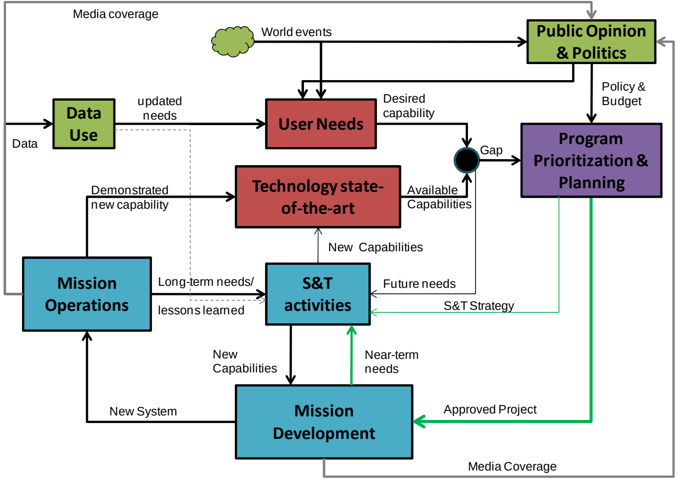

Figure 1: Conceptual representation of the Space Innovation System

However, this gap is not a stationary target. Both user needs and the technology state-of-the-art are continuously being updated through development efforts by the agency and supporting industrial base, as well events in the operational environment. In the DoD context, the public need is national security as provided through the use of advanced intelligence and weapons systems; in the NASA and ESA contexts the fundamental driver is science.[2] This need, in the latter context for new scientific understanding, is satisfied through the acquisition and operation of an advanced technological system. For example, NASA spends billions of taxpayer dollars employing engineers and scientists to develop and send a rover-carrying spacecraft to Mars, so that it can collect data useful (when analyzed by scientists) in answering key scientific questions. Embedded in this simple example are the two categories of inter-related organizational structures which make up the *government space innovation system.*

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[2] While throughout the history of the space age, the case for NASA as a jobs program has often been made, this is a sustaining argument not an existence argument. Specifically, NASA would never have been created as an employment strategy – there are many more financially efficient ways to create jobs when starting from a clean slate.

Namely these structures focus on: 1) prioritizing user needs (e.g., which are the most important science questions to attack next?) based on an estimate of the need-capability gap and in the context of strategic guidance; and 2) technology development, both in terms of developing flight missions and enabling technologies so that future needs can be met. The interplay of these two structures – as mediated by perceived system performance feedback mechanism(s), which, along with world events, drive the strategic and budgetary inputs to the above described systems – determine which ideas get funded; and in an environment where the price of entry is extremely high, securing government funding is a necessary condition for realization of even the best idea. Since the relationships among these decision factors are strongly related to the organizational environments in which they operate, the following discussion will be grounded in three particular space organizations – NASA, ESA and DoD Space.

SYSTEM REPRESENTATIONS: NASA, ESA AND THE DOD

In order to facilitate comparison across the three organizations, for each agency, the below discussion will be structured in terms of the categories described above: 1) Program prioritization; 2) Technology Development. Before delving into the individual descriptions, a few notes on data sources must be made.

One might expect that multiple official maps, or representations, of how these space organizations develop, infuse and utilize the capabilities they develop. However, while partial pictures exist in each of the agencies, a unifying map - incorporating the multi-level processes and programs – does not. This is not merely a lack of graphical representation, given the level of complexity of the systems and the disaggregation of the processes across discipline lines (i.e., science from engineering from planning), it is unclear whether a single entity has taken a top-level integrated view of the system from an innovation perspective. Thus, the representations presented below are the authors' abstractions; built up on the basis of a review of published procedural documents and website content, supplemented by semi-structured interviews and careful observation. The implicit assumption in this approach is that while no one has a holistic view of the process, individuals know their particular piece and its interfaces in detail. Thus, a top-level map can be constructed when the pieces are integrated.

In the case of NASA, a preliminary round of 13 interviews was conducted; eight were with individuals in leadership positions representing each of the NASA mission directorates. These interviews sought to elicit a complete list of technology development opportunities within the agency and understand the intended strategic connections among them. They were also used to better understand the agency's philosophy towards near-term vs. long-term emphasis. Four interviews were conducted with staff engineers and technology focused scientists located at Goddard Space Flight Center. They all had significant experience developing new instrument technology in the NASA context. These interviews focused on the individual's role within the system and who s/he interacted with in terms of both inputs and outputs related to his/her work. Further, multiple questions were asked about how the various technology development opportunities connect to one another in terms of the maturation of a particular technology. More interviews are planned to cover a broader range of the working-level perspective.

In the ESA case, the primary author spent three months in residence at ESTEC (the European Space Research and Technology Center), attached to the Advanced Concepts Team (ACT) explicitly studying technology innovation in ESA science programs. During this time, numerous informal informational interviews were conducted. As well, 13 individuals were targeted for semi-structured longer research interviews. The subjects included, 5 members of the project team (the project manager, systems engineer and three discipline specialists); 2 scientists, one principle investigator (PI) and former member of Solar System Working Group (SSWG – a scientific advisory board to ESA) and one project scientist – the ESA liaison between project and science; 2 members of the prime contractor's project team; and 4 ESA technical experts who had either consulted on, reviewed, or managed technology development activities for the flagship mission that had united the group. An initial conception of ESA as an innovation system was published as ref. [27].

In the DoD context, the documentation is better; many systems representations exist, thus minimizing the data-collection challenge. Also, there is considerable ongoing and recently completed work at MIT examining the defense acquisition system (c.f. [20, 28-30]). In addition, the authors conducted a detailed, interview-based case study of efforts to infuse Internet Routing in Space (IRIS) as a new mode of defense satellite communication.[31] The following representation is the result of a fusion of the insights gained through these various projects

A. NASA's Innovation System

NASA is the US's civil space agency. Its mission is to "*pioneer the future in space exploration, scientific discovery and aeronautics research*." To support this mission, NASA is organized as four mission directorates – Aeronautics Research (ARMD), Exploration Systems (ESMD), Science (SMD) and Space Operations (SOMD) – and 10 centers – Ames Research Center (ARC), Dryden Flight Research Center (DFRC), Glenn Research Center (GRC), Goddard Space Flight Center (GSFC), Jet Propulsion Laboratory (JPL), Johnson Space Center (JSC), Kennedy Space Center (KSC), Langley Research Center (LRC), Marshall Space Flight Center (MSFC) and Stennis Space Center (SSC). The NASA budget is bucketed in terms of mission directorates and theme lines (e.g., SMD divides funding among Earth Science, Heliophyics, Planetary Science, and Astrophysics), but the day-to-day work is conducted at the field center. While the functional expertise of each center tends to be related to the theme lines, many expertises are cross-cutting. For example, JPL specializes in the robotic exploration of the solar system. While this focus is of primary relevance to SMD, robotics also plays a key component of the ESMD mandate. The discussion in this paper will emphasize innovation within the SMD; however many of the concepts are extendable to other mission directorates.

1) *Program Prioritization at NASA*

At NASA, the program prioritization process is highly iterative and seeks to balance scientific value, technical feasibility and budgetary realities, as illustrated in Figure 2. Initially, prioritization of compelling science questions is left to the scientists. Communities of scientists self-organize to produce a list of priorities, communicated to NASA through Science Advisory Boards and mediated in part, by the National Research Council's (NRCs) decadal survey process. The Decadal Survey presents a list of mission priorities, in each of the broad science themes, in terms of guiding science questions. This list is taken under advisement by NASA as it formulates a budget strategy for the coming years in consultation with the Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB). While the opinions of the science community are taken under strong consideration by NASA, technological feasibility is a much stronger factor in NASAs assessment than it is during the Decadal Survey process.

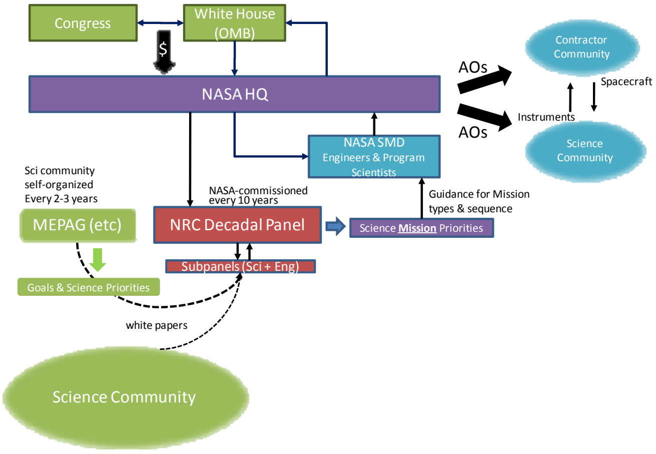

Figure 2 - (Preliminary) Conceptual Representation of NASA's Mission Selection Process

Future missions get slotted into NRC priorities in one of three categories – Explorer, Discovery or Flagship. This classification is nominally a function of the projected cost; however, since cost is highly dependent on technology maturity, in reality the classification process is strongly influenced by where in the technology development process a project is initially approved. And, the perception of this maturity is related to the strength of the political justification for a particular mission. For example, as explained to the authors by one NASA executive, the James Webb Space Telescope (JWST) was ranked first in the last decades Decadal Survey (ahead of Laser Inferometer Space Antenna (LISA)), in part because the rationale for its importance was straightforward. As a "grand observatory," thousands of astronomers will be served simultaneously. Also, the *pictures* it will return will dazzle the public for the foreseeable future. The LISA, on the other hand, which was ranked second in the same category of the Decadal Survey, is arguably a more valuable mission scientifically. However, since the gravitational radiation community is considerably smaller and the measurements more esoteric, a higher threshold of technology feasibility may have been applied to the LISA assessment. LISA has received some amount of pre-Phase A funding this decade at a level suitable for incremental technology maturation and demonstration.

The results of a mission, in terms of the lessons learned through technology development and the scientific data returned, are fed back into future missions, through mechanisms of varying formality. The scientific loop is carefully maintained. Research and analysis of the data is a formal budget line in each of the science themes. As well, the key science questions, as defined in the white papers of science-community groups such as MEPAG (Mars Exploration Program Advisory Group), are revisited on a bi-yearly basis to ensure that they evolve as new knowledge is gained. On the technology and budgeting side, the existence of such formal feedback-loops or learning processes is less clear. It is generally believed that successive generations of missions typically require measurements that are sufficiently different from one another that there is only limited transferability of instrument technology from one to the next.

2) *Technology Development at NASA*

Within SMD, there is no longer any top-level budget line for technology development. This is because, faced with increased budget pressures in the early 2000s, NASA made the conscious decision to significantly reduce cross-cutting early stage technology development and focus efforts on near term mission needs. Technology development efforts have not ceased, they have merely gone underground so to speak, embedded within the extended project development process. Figure 3 enumerates the technology development funding vehicles within SMD arrayed in terms of their TRL focus.

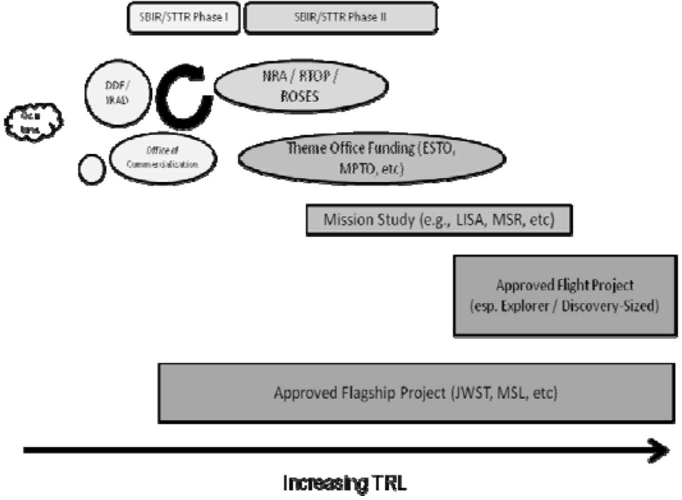

Figure 3 - Landscape of Technology Development Funding Mechanisms with NASA SMD

Within SMD, funding for technology development comes in four main forms: 1) formally unfunded brainstorming; 2) center overhead; 3) mission directorate discretionary funds; and 4) project budgets. The lack of arrows connecting the various shapes in Figure 3 is intentional and illustrative of the lack of formal connections among them in practice. The burden of finding enough funding to keep a concept alive as it matures is largely left to the technologist/inventor. A description of the pathways connecting the various opportunities is left to the follow-on paper. The sections that follow describe the scope of the mechanisms that currently exist.

Since the bulk of SMD funding is allocated in terms of flight projects, and centers are awarded flight projects based on demonstrated competence and expertise, centers often use the Director's Discretionary Fund (DDF) or Internal Research and Development (IRAD) monies to fund early stage concept development. The idea is to identify promising ideas and mature them to a point where they can effectively be competed for more formal funding mechanisms. DDF/IRAD funding tends to be small and short, on the order of $50-100K and for 1-2 year duration. Congressionally mandated SBIR/STTRs (of a similar size and duration[3]) can also sometimes be used to secure sufficient funding to prove the utility of an early stage concept. At this early stage, concepts are not expected to show a direct link to a particular mission, although some mission relevance is seen as a proposal strength. New instrument concepts can often go through several rounds of center level funding before they successfully are transitioned to directorate-level funding.

Discretionary funding is also allocated at the directorate level. NASA Research Announcements (NRAs), of which Research and Technology Objectives and Plans (RTOPs) and Research Opportunity in Space and Earth Sciences (ROSES) are particular types, are effectively grants given to candidate instrument Principal Investigators (PIs) (internal to NASA or not) to further mature promising instruments. They are slightly longer and more substantial than DDF/IRAD grants.

The level of maturity required for a new technology to transition from center or directorate-funded concept into a flight project (the ultimate goal) depends on the priority level of the flight project. NASA flies three classes of science mission – Explorer, Discovery and Flagship. To be designated an Explorer mission, a proposal team must demonstrate that no new technology is required to be developed; i.e., either the technology was previously developed as part of another mission, or more likely, developed through a series of IRAD/NRA opportunities. Flagships, on the other end of the spectrum, are designated as such because they were deemed a sufficiently high priority through the mission selection process to merit some level of technology investment (e.g., JWST discussed above). The result is that significant technology development activities are often conducted as part of the early phases of the mission development (although nominally, all technology must have achieved TRL 6 prior to PDR). In such cases, it's not without precedent for a paper concept (TRL 1-2) to be taken up by a Flagship and matured through the full TRL spectrum.

B. ESA's Innovation System

The European Space Agency is organized as 10 directorates – Earth Observation, Galileo Programme & Navigation-related Activities, Human Spaceflight, Launchers, Legal Affairs & External Relations, Operations & Infrastructure, Resources Management, Science and Robotic Exploration, Technical and Quality Management, and Telecommunications & Integrated Applications – and six Establishments (centers) and Facilities – Headquarters in Paris, ESTEC (the European Space Research and Technology Centre in Noordwijk, NL), ESOC (the European Space Operations Centre in Darmstadt, Germany), ESRIN (ESA's centre for Earth Observation near Rome, Italy), EAC (the European Astronaut Centre in Cologne, Germany), ESAC (the European Space Astronomy Centre near Madrid, Spain and CSG (the Guiana Space Centre in Kourou, French Guiana). Where NASA has chosen to prioritize maintaining *"10 healthy centers" versus only assigning work to the center where the historical expertise for that work resides* –ESA's division of work across the centers is much more strongly correlated to the functional expertise of the center[4].

All the technology development and spacecraft engineering/mission management is conducted at ESTEC. HQ takes care of international relations and legal & administrative matters. ESOC is responsible for all ESA mission operations except launch; everything related to launch is conducted at CGS. ESRIN and ESAC handle analysis and archiving of earth and astronomy & planetary science data respectively. EAC is where astronauts train and find their home base. All agency technology development is consolidated under one budget line, and housed at ESTEC (although in reality the line is more grey, as will be discussed below), as required by the ESA convention.

In order to fully understand the ESA organizational structure, it is important to also consider ESA's relationship with the EU and its member states' space agencies. Where NASA is an executive agency of the US Government, ESA is an intergovernmental organization with no formal link to the European Commission (EC); in fact ESA and the EC have different member states. Where NASA receives its funding appropriation on an annual basis from Congress following negotiations with OSTP and OMB, ESA is funded through a combination of *mandatory* and *optional* contributions from its member and cooperating states. Contributions to mandatory programs are scaled based on the country's Gross Domestic Product (GDP) and cover the General Budget (a major part of overhead) and the Science Programme. The rest of the directorates are financed at the discretion of interested members. Further, where NASA is the sole civil space agency

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[3] A NASA SBIR Phase I award is currently set at a maximum of $100,000 and lasts for six months. A Phase II award is set at a maximum of $600,000 and lasts for a period of up to two years.

[4] In part, ESA has this luxury because it is a younger organization than NASA and has not undergone such massive changes in its mission – ie, from Apollo to post-Apollo/Skylab to Shuttle to ISS to VSE – as NASA.

for its constituents, ESA must coexist with the often substantial space programs of its member states (e.g., CNES, DLR, ASI). In the science context, in order to minimize duplication of efforts, national space agencies are expected to fund instrument development, while ESA develops the spacecraft bus and integrates the system.

This policy of separating instrument and bus development has important implications for the way innovations are conceived in the ESA context. Recall that at NASA the bulk of SMD's innovative efforts are focused on instrument developments. In European, scientists (typically not directly affiliated with ESA) and their sponsoring national space agencies are responsible for instrument development. They will typically contract with specialized machinists as required, but maintain significant oversight of the instruments being developed. Within ESA, there is an Advanced Science and Payloads (AS&P) group that develops model payload concepts and supports scientists for early-stage feasibility studies, but it has limited interactions with the formal project development process conducted in the Technology Directorate.

1) *Program Prioritization at ESA*

At ESA, as illustrated in Figure 4, the space science missions are initiated through a top-down domain specific process (the color code maps to Figure 1 – green is user needs, red is an estimate of the technological state of the art, blue is technology development). Initially, within the framework of the long-term vision for space science (e.g., Horizons 2000/+, Cosmic Vision 2015-2025) ideas are solicited from the science committee at-large and then vetted and ranked via a peer-review process.[5] Once the list of candidate missions has been narrowed to four, missions are assessed for scientific value and technical feasibility. This is done concurrently by 1) a science mission team (including the mission proposer and AS&P support) which defines a model payload; and 2) an internal-to-ESA engineering team which performs a technical assessment. Based on the findings in this exercise, the peer-review process is recommenced,[6] culminating in the down-selection to one candidate mission to be promoted to the definition phase.

The definition phase is conducted in three parts. First, an industrial proposal competition is held, leading to the selection of two serious candidates for the eventual industrial contract. Next, the spacecraft's scientific payload is finalized through a peer-review process (involving the science advisory structure and technical consultation). Finally, two concurrent (and competitive) detailed industrial studies of the actual mission (including the payload) are conducted. At the end of this phase, the Science Programme Committee (SPC), part of ESA's international governing body, decides whether or not to recommend that the Council fund this mission through implementation. Since Science Missions tend to require multiple advanced technologies, the SPC has historically approved missions which require multiple technology development contracts to be initiated (these contracts, known as Technology Development Activities (TDAs), will be discussed more below).

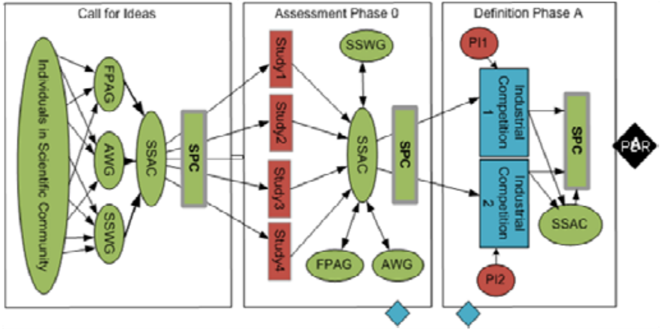

Figure 4 - ESA Mission Selection Process

2) *Technology Development at ESA*

ESA has a relatively extensive and coherent technology development strategy, which nominally balances basic phenomenological exploration with program specific technology development. To this end, ESA has four generic technology programs – Basic Technology Research Programme (TRP), General Support Technology Programme (GSTP), Technology Transfer Programme (TTP), European Components Initiative (ECI) - eight domain specific technology programs – Earth Observation Envelope Programme (EOEP), Advanced Research in Telecommunications Systems (ARTES), Global Navigation Satellite System (GNSS) evolution, Transportation, Human Exploration, Science Core Technology Programme (CTP), Mars Robotic Exploration Preparation Programme (MREP) and Future Launchers Preparatory Programme (FLPP) - and one on-orbit demonstration platform (Proba). These are shown in Figure 5. As with NASA, the discussion will focus on the mechanisms particular to Science.

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[5] Respected scientists from the community serve as members on domain review committees in the areas of Fundamental Physics (FPAG), Astrophysics (AWG) and Solar System (SSWG). These committees are subordinate to the Space Science Advisory Committee (SSAC). Selection and duties are similar to journal review boards etc.

[6] Depending on the results of the studies, concepts may be returned to the discipline committees several times, with the goal of modifying the scope of the mission so that it fits the cost envelope, without losing sight of its scientific basis. The cost envelope in particular is quite rigid. ESA science missions are funded through the "mandatory programs" budget, meaning that their total resources are effectively fixed between 10 and 15% of ESA's operating budget in any given year. In an effort to simultaneously support multiple scientific communities and maintain funding through public interest (and the public responds to frequent milestones), the total budget translates into approximately two Class M (~600M€) and two Class L (~300M€) projects every 6 years.

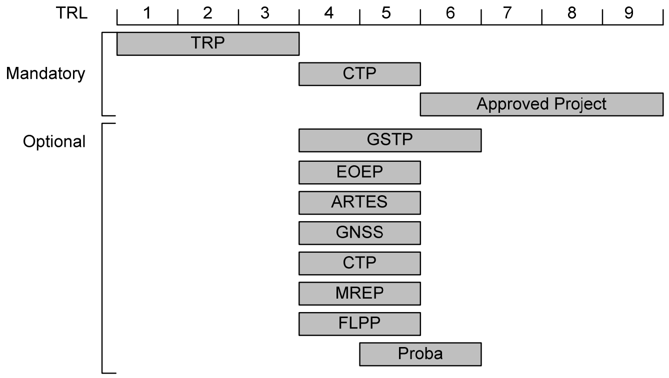

Figure 5 - ESA Technology Development Landscape[7]

The Technology Research Programme (TRP) funds very early stage development (TRL 2-3) across all mission areas. TRP is a mandatory program which means that all ESA Member states are required to contribute to it on a yearly basis. It runs on a three-year work plan, drafted by groups of senior ESA experts, with reference ESA's ten-year technology roadmap. In addition to funding technologies relevant to particular mission areas, the TRP allocates a third of its effort to so-called "Generic Technologies[8]." Two notable initiatives within TRP include the "Star Tiger scheme," which involves the rapid development and prototyping of advanced technology - typically 'spin-ins' from non-space sectors – on a timescale of months rather than years, and the "Innovation Triangle Initiative," which accepts unsolicited innovation proposals focused on non-space technologies to solve space problems.

Some subset of successful TRP projects will receive follow-on funding through mission directorate specific "advanced technology" programs (i.e., CTP, EOEP, ARTES, GNSS, FLPP and MREP). For example the Science Core Technology Programme (CTP) focuses on advanced concepts particular to science missions (TRL 4-5). It represents the next stage after TRPs for science specific developments. In order for technologies to be selected for CTP funding (expect in certain exceptional cases), in addition to successfully demonstrating utility through a TRP, a case for direct (critical) applicability to a future mission must also be made. However, given that CTP equivalent technologies are many TRL levels too immature to be explicitly considered for mission use, this creates a catch-22.

The General Support Technology Programme (GSTP) is the other main path to fill the technology development gap from TRP to mission funding. It nominally funds promising engineering concepts (TRL 4-6) as they transition into mature products suitable for application in a wide range of mission areas. The GSTP is an optional program (i.e., there is no requirement for members to contribute). It operates on a five-year work plan organized around 1) General Activities; 2) Building Blocks and Components; 3) Security for the Citizens; and 4) In Orbit Demonstrations. The program boasts a permanently open, Announcement of Opportunity (AO). However, as an optional program, funding is relatively limited.

In practice, this catch-22 is overcome by personal relationships among technical directorate staff (D/TEC) and members of the ESA project team. One experienced D/TEC reported spending as much as 30% of his time securing funding for his development projects. This involved advertising the results of his latest development projects to his colleagues on the project side, while simultaneously listening carefully to design problems that had arisen in the flight projects for ideas for future technology development efforts. Thus, while in-project, technology development will not typically be supported unless the mission "cannot be achieved without it," fortunately (from the point of view of innovation) missions often require technology development in at least some area, and are forced to initiate Technology Development Activities (TDA), a generic term used to describe any of the above mentioned funding mechanism. While TDAs do serve as mechanisms to pull successful TRPs out of the capabilities pot, some TDAs are used to space qualify mature non-space technology. D/TEC staffs report being continuously on the look-out for the emergence of a new capability in a related ground-based field that might be relevant to a future space-based need.

Thus, while the multiple tiers of technology development exist, the extent to which they provide distinct cultures of "push" vs. "pull" focus is limited by the realities that funding is so rigidly tied to particular projects. In the end, whether and which particular new capabilities get incorporated into a project is often a matter of timing. This process is driven by the confluence of a project need and the sufficient maturity of the requisite capability, catalyzed by the legwork of a number of key individuals.

C. US National Security Space Innovation System

The US National Security Space enterprise is considerably larger and involves many more organizations than either NASA or ESA. The organizational structure in Figure 6, reproduced from the Allard Commission report [33] gives a top-level view of the wide range of government and non-government organizations responsible for providing and operating space-based capabilities serving both military and Intelligence Community needs. Broadly speaking the various agencies fall into the categories of planning/coordinating agencies/components, user agencies and components, acquisition agencies, and science and technology (S&T) organizations.

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[7] Adapted from [32] M. Guglielmi, E. Williams, P. Groepper, and S. Lascar, "The Technology Management Process at the European Space Agency," in *International Astronautical Congress* Glasgow, Scotland: IAF, 2008.

[8] Generic Technologies are those that are either of use to multiple missions or are advanced basic technologies of common interest to all applications (e.g., component design, spacecraft propulsion or power generation.)

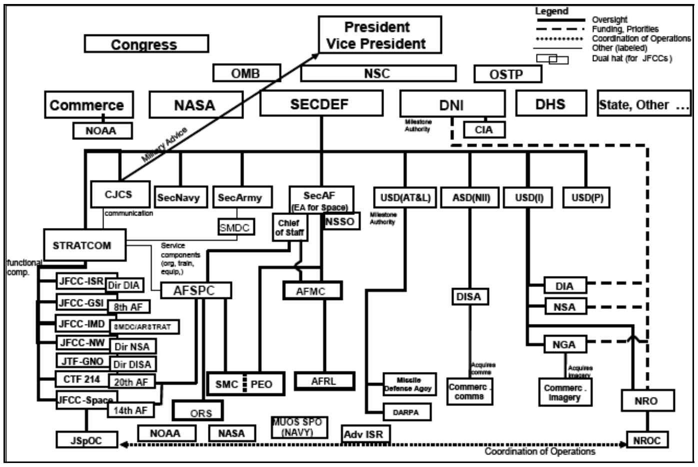

Figure 6 - The Current Organization of National Security Space. Acronyms: Office of Management and Budget (OMB); National Security Council (NSC); Office of Science Technology Policy (OSTP); Secretary of Defense (SecDef); Director of National Intelligence (DNI); Department of Homeland Security (DHS); Chairman of the Joint Chiefs of Staff (CJCS); Secretary of the Air Force (SecAF); Under Secretary of Defense, Acquisition, Technology and Logistics (USD(AT&L)); Assistant Secretary of Defense for Networks and Information Integration (ASD(NII)); Under Secretary of Defense for Intelligence (USD(I)); Under Secretary of Defense for Intelligence USD(P); Strategic Command (STRATCOM); Space and Missile Defense Command (Army – SMDC); Joint Force Component Command (JFCC); Global Strike and Integration (GSI); Network Warfare (NW); Space Operations (SP); Network Ops (GNO); Missile Defense (IMD); Air Force Space Command (AFSPC); Air Force Material Command (AFMC); Defense Information Service Agency (DISA); Defense Intelligence Agency (DIA); National Security Agency (NSA); National Geospatial Intelligence Agency (NGA); Operationally Responsive Space (ORS); Space and Missile Systems Center (SMC); Program Executive Office (PEO); Air Force Research Lab (AFRL); National Reconnaissance Office (NRO); Joint Space Operations Center (JSpOC)

For historical reasons detailed in [34], National Security Space activities have been divided between *military space* "white programs" and *intelligence space* "black programs." Planning for white programs (e.g., space-based capabilities for communications, early warning, weather, surveillance, space control, precision navigation and timing, and launch) is the sole purview of the SecDef, with responsibility shared among many DoD components including OSD, Joint Staff, defense Agencies, Combatant Commands, the Military Services (Army, Navy, Air Force) and DARPA. Planning for black programs (reconnaissance and related satellite systems) has been jointly shared between the SecDef and the DNI. Other organizations with space responsibilities include NASA (typically contributing some technology development), Department of Commerce (NOAA's weather satellites), the Department of Energy and the National Labs, the Department of Agriculture (U.S. Geological Survey and LANDSAT), the Department of Homeland Security (National Applications Office), the National Science Foundation (Space Weather), Department of State, Department of Transportation, National Security Council, Office of Science and Technology Policy, Federal Communications Commission, and the satellite systems and activities of US allies, all contribute under their own budget lines and planning authority.

In the national security context, the term *space user* accurately describes a number of different communities. Warfighters from all Military Services extensively use data derived from satellites while deployed as part of component commands (e.g., for ISR, weather forecasts, positioning and navigation and communication). The Army is currently the largest space user and is working to become more sophisticated in that use. Satellite-derived data is also used for strategic decision making for military operations. The intelligence community is also a large user of reconnaissance data, acquired by the NRO and processed by the NGA for use by the CIA and DIA/NSA.

1) Program Prioritization within the DoD

The DoD takes a more concurrent approach to needs prioritization than either NASA or ESA, as executed through the Joint Capabilities, Integration and Development System (JCIDS) process. As illustrated in Figure 7, the process is initially, guided by i) national security strategy, and ii) a concept of operations (ConOps) generated by one of the forces (i.e., Army, Navy, Air Force), or a joint operating concept (JOpsC) if it is generated by the USJFCOM, the existence of a joint[9] need and gap (i.e., an effect required by the warfighter to meet his/her mission that cannot be achieved using existing resources) must be identified and validated. This is accomplished by three sequential steps – FAA,[10] FNA[11] and FSA [12] – which essentially involves an analysis of the effectiveness, costs and risks of all available alternative solutions to the warfighting gap. These analyses are performed by a high performance team (HPT) which draws members from the championing force provider, technical consultants, Defense Acquisition System/Planning Programming Budgeting and Evaluation (DAS/PPB&E) officers and towards the end, representatives from other services.

Before an Integrated Capabilities Document (ICD – the major output of a capabilities based assessment) is approved and the Joint Requirements Oversight Council (JROC) initiates a formal acquisition process, all of the services and COCOMs must agree that the capability will in fact fill a joint need. The mechanism for this consensus building is to send a draft ICD to the various stakeholders for comment, which often leads to JCIDS actions; and multiple time consuming iterations.

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[9] The term "joint" is used to indicate an expectation that solutions which cut across service lines be considered (e.g., if the army requires more bandwidth to support strategic communications, air force satellite resources will be allocated rather than developing an army specific satellite).

[10] Functional Area Analysis (FAA): identify operations, conditions, and standards needed to accomplish objectives

[11] Functional Needs Analysis (FNA): assess ability to meet objectives given future and planned systems

[12] Functional Solutions Analysis (FSA): selection of systems that best address capability gaps

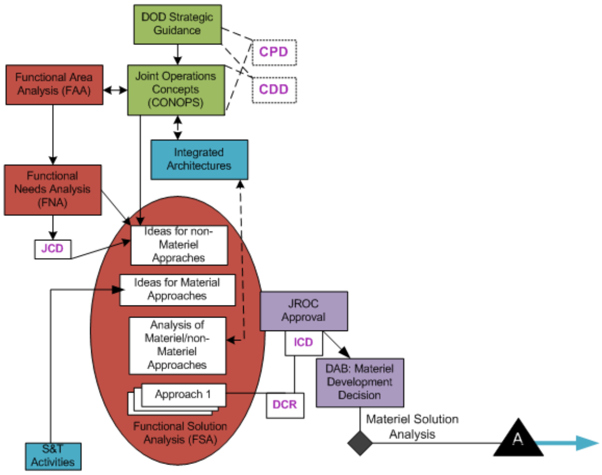

Figure 7 - DoD Mission Selection and Prioritization Process

2) *Technology Development in Miltiary Space*

Within the Military Space enterprise, new capability development is conducted through a two-tiered organizational structure focused on (1) research and development and (2) formal acquisition programs. Initially, basic phenomenological investigations are conducted within the Air Force Office of Science Research (AFOSR)[13] and to a certain extent, the Defense Advanced Research Projects Agency. The nature of the work is exploratory and the expected time frames for results relatively long (*i.e.*, 15-20 years, although more emphasis has been put on near term focus, 5-10 years, of late.[35] As the concept mature, the emphasis on military usefulness increases. Projects are expected to show obviously useful areas of application; as a result, there is pressure to focus on near term development. For both the fundamental and applied research, projects are siloed by discipline and collaboration across disciplines is limited. As these S&T organizations demonstrate concept feasibility, technologies are transferred to the Service Laboratories for further development, maturation, and demonstration of capability.

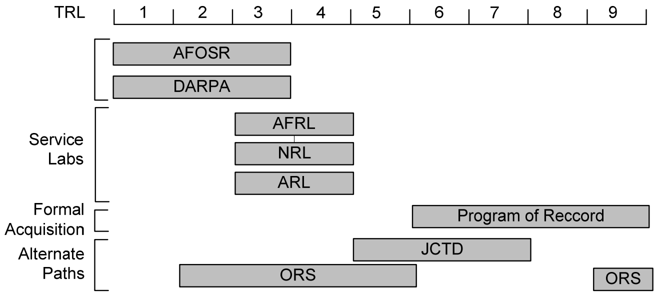

Figure 8 – DoD Technology Development Landscape

The Air Force Research Lab (AFRL) Space Vehicles Directorate has primary responsibility for space related technology development and is organized around three themes. First, the Battlespace Environment Division, if focuses on means to eliminate/mitigate the full range of natural and man-made threats to air and space support systems. Second, the Integrated Experiments and Evalutation Division develops, incorporates and demonstrates emerging military space concepts. Finally, the Spacecraft Technology Division conducts technology research which seeks to revolutionize space capabilities. It operates centers focused on space-based infrared technologies, as well as advanced power, structures and controls. Once these technologies have been matured to the point where they can be realistically assessed for cost, schedule, and performance contributions to a given set of program requirements, they may be considered as part of the Joint Capabilities and Integration Development System (JCIDS) process.[14] Since AFRL reports to the AFMC and SMC reports to the AFSPC, the transition efforts (of technologies into formal programs) are coordinated through the Space Development and Test Wing (part of SMC). Co-located with the AFRL it tests and evaluates Air Force space systems, executes advanced space development and demonstration projects, and rapidly transitions capabilities to the warfighter.[15]

As in the cases of NASA and ESA the vast majority of DoD investment in developing new capabilities is associated with formal programs, which follow the traditional systems engineering phases. Once a formal program has been initiated the majority of the development work is contracted out to the industrial base. Compared to ESA and NASA, the DoD is the most reliant on industrial contractors. Over the years, these contractors have invested fairly significantly in their own internal R&D. For example, Boeing's Phantomworks and Lockheed's Skunkworks have famously been the source of multiple radically innovative systems.

Recognizing that JCIDS may not be an appropriate transition mechanism for some technologies, alternative technology development paths have been developed in recent years. One such route is through the Joint Capabilities Technology Demonstrations (JCTD) office which was stood-up in 2006[16] to provide emerging technologies and innovative concepts to the warfighter as quickly as possible. JCTDs focus on resolving joint needs within a one-to-three year timeline, by creating opportunities for technology and operational demonstrations of mature technology/solutions (TRL 5-7). JCTDs are designed to fill the gap between S&T and acquisition – they don't replace either. The funding for JCTDs is relatively modest – $2 to $3 million – and short term – typically three years, at the end of which successful demonstrations are actively transitioned into programs of record.

Another alternate route is through the Operationally Responsive Space (ORS) office. The purpose of ORS is to

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[13] http://www.wpafb.af.mil/AFRL/afosr/

[14] *technology developed in S&T or procured from industry or other sources shall have been demonstrated in a relevant environment or, preferably, in an operational environment to be considered mature enough to use for product development in systems integration*

[15] http://www.kirtland.af.mil/library/factsheets/factsheet.asp?id=6881

[16] Replacing the Advanced Concepts Technology Development Program, which began in 1995

reduce the time constants associated with space system acquisition, design, and operation to allow the national space architecture to keep pace with changing missions, environments, and technologies. The fundamental idea is to trade off the reliability and performance achieved by existing spacecraft for the speed, responsiveness, and customization which may be achieved by architectures that incorporate elements such as small, modular spacecraft and low-cost, commercial launch vehicles.[4] The plan is to leverage COTS parts and commercial launch services coupled with model of seed-funding rather than development contracts. ORS is typically grouped into the category of technology development; however its functions really span both the roles of technology development and spacecraft acquisition.

VARIATION ACROSS RELEVANT DIFFERENCES

The introduction to this paper suggested that differences in the way NASA, ESA and Military Space organize their innovation systems has created some level of quasi-experiment in terms of how strategic/organizational decisions impact innovation. While the above discussion was focused on conceptualizing and representing the structure of the three space enterprises as innovation systems – itself an important contribution – some of the major differences were highlighted along the way. This section consolidates those points to argue that differences in these organizations create a fertile basis for future cross-case comparison. It is broadly organized in terms of the structure of the prioritization process (subdivided as the constituent challenges of A. needs representation and B. capability assessment) and technology development strategy (subdivided as the constituent challenges of C. resource allocation and D. separation of exploration from exploitation).

A. Needs Representation

The fact that the Government buyer is not a coherent decision making entity and as a result does not always “know” what it “needs,” leads to a need for a complex needs representation process within government acquisition agencies.[20] Differences in the approach to concept selection and approval, taken by each of the space agencies, stem from the relative priority given to the different knowledge types involved. Specifically, on the needs side, determining what next to acquire is a prioritization process involving knowledge of 1) operational utility (e.g., a desired effect in the battle space); 2) the of overall budget portfolio; and 3) the status of developments along the technological roadmap.

At ESA and NASA, within the context of chronically over-constrained budget envelops, selection priority is given to scientific experts, with engineering considered subordinate to science needs. The ESA deference to the initial science advisory board filter is slightly stronger than at NASA, but they fall on similar ends of the spectrum. The DoD takes a more concurrent approach to needs prioritization. Compared to ESA and NASA, where the users are scientists who have a high degree of domain-specific expertise and credibility, independent of any nationally mandated strategy, DoD warfighters are different type of user. Their needs are directly related to the National Military Strategy they are sworn to execute. While there is increasing recognition of the value of operational knowledge – gained in the field – in defining future needs, the warfighter surrogate on the HPT is often several tours of duty removed from his/her warfighting experience. This setup implicitly subordinates user needs to top-level strategy and technical judgment. More recently though, programs like Operationally Responsive Space – which emphasizes near-term tactical control for the warfighter – have sponsored efforts to solicit direct input from the warfighter.

B. Capability Assessment

In order to “specify innovation[17]” effectively, one needs to be intimately familiar with the realm of the possible in all aspects of the design – something that is practically impossible. As noted by von Hippel (1988) there are multiple sources of innovation – new ideas come from users, manufacturers, suppliers [19] – and the insights and opportunities that enables each type of innovation can be quite different [15]. In the space acquisition context, the extent to which responsibilities are fragmented across bureaucratic organizations, the inherent complexity or the products being developed and the politics which encourage contracts to be spread over regions and continents (in the case of Europe) result in an exceedingly fragmented knowledge base. Thus, although a relatively small set of individuals are tasked to define the frontier of the possible, they cannot have the all the knowledge required to do so.

Recognizing this limitation, space agencies define specifications through an iterative process which seeks to integrate the relevant knowledge areas on a per-project, as-needed basis. The needs representation part of this process was discussed above. This tradeoff focuses on how operational requirements are defined leading into the project development phases, and controlled throughout the development process. In particular, one key question which has been debated extensively over the years is how much in house technical expertise does the project team require? The fundamental tradeoff here, is between duplication of effort on the one hand, and full reliance on the benevolence of industrial contractors on the other. With the three agencies under study herein, nearly the full spectrum is covered.

Specifically, NASA centers build some portion of advanced spacecraft themselves and let internal research grants to enable NASA scientists to develop advanced instrument concepts. They operate under the philosophy that industry is better at repeatable, nearly commercial aspects of space exploration, while NASA *should* develop the “only-in-space” aspects themselves. In the ESA context, instruments – typically the most advanced aspect of the spacecraft – are wholly developed by the PI’s team. On the spacecraft technology side, in

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[17] Define a requirements specification that is just in advance of the state-of-the-art; that is ambitious enough that it cannot be met without innovating, but close enough to feasible that it can be done in the allotted time.

addition to project engineers in a range of disciplines, ESA maintains in-house technical experts to adjudicate between the project team and contractor on technical disputes. They typically have doctoral degrees in a related area and continue to do research, attend technical conferences and generally stay in-touch with the leading edge of their respective fields while at ESA. The DoD falls on the other extreme of the spectrum from NASA. In recent years, the technical competence of the acquisition workforce has degraded significantly as the DoD has shifted from a model of "oversight" to "insight," forcing a heavy reliance on external contractors.[4, 6, 8, 9, 33]

C. Resource Allocation: S&T vs. Projects

That government space markets are discrete and specific[20] has several important implications for how government space agencies manage the health, and capabilities, of their industrial base. Since space agencies often define system requirements in advance of the technological state-of-the art, for each next acquisition, they would either need to a) support the development of all the innovations required to achieve the required functionality (*e.g.,* in 1963, Project Apollo prototype construction accounted for 60% of the national production of the then nascent integrated circuit technology [36]) or b) support technology development activities between major acquisitions, as a more continuous process.

Despite the success of the crash programs of the 50s and 60s, which employed a type-a approach (innovate when needed), given the associated exorbitant costs and risks, it is generally recognized that such a strategy is unsustainable. Modern government agencies seek to implement a type-b approach (develop technologies in advance); all three agencies investigated herein have separated their formal acquisitions from their technology development tiers to some extent and advocate a philosophy of maturing technologies outside of the acquisition process. However, given the inherent uncertainty in planning innovation, the reality is that most acquisition programs end-up with a mixed strategy (using mostly mature technologies, but investing in several risky technology development efforts as needed) [3, 8, 9]. The interesting differences among the agencies lie in where along the spectrum they fall.

Specifically, NASA funds significant within-project development on flagship missions (one a decade per theme) and almost no within-project development for explore class missions. ESA takes a similar strategy of mixing the portfolio of big and small missions; however, where NASA encourages pre-technology development for explorer mission, ESA tends to leverage technology developed for past big missions to bring down costs on future small missions. Further, ESA favors more medium sized missions compared to NASA's one flagship a decade. From a doctrinal point of view, the DoD has the strongest emphasis on a two tired technology development/formal acquisition process of the three agencies. However, the funding priority given national security programs has allowed DoD acquisitions to deviate significantly from this philosophy. In fact, many of the cost overruns and schedule slips experienced in recent years have been attributed to overreliance on high-risk within-project technology developments [3, 8, 9].

D. Isolation of Exploratory Technology Development from Project Application

Given that project development efforts require that the constituent technologies they use are mature in advance of the project initiation, and that industrial contractors have limited incentive to invest in developing technologies that may not be used, government sponsored R&D is an important source of space-relevant innovation. This fact was demonstrated empirically through Project Hindsight [37]. However, the extent to which these efforts are differentiated, connected and formalized varies significantly across NASA, ESA and the DoD. The fundamental tradeoff here is evocative of the age old exploration vs. exploitation debate – which, recast in the space system development context was expressed eloquently in a recent congressional testimony by Dr. Raymond Colladay as the need to set "up a healthy tension in an organization between technology push focused on long-term research and technology pull from programs [38]."

While each of the agencies fund technology development in three main ways: 1) generic technology programs in S&T organizations or branches; 2) advanced technology programs addressing specific future needs; and 3) near term technology maturation programs to support identified gaps for particular programs; the extent of separation among these activities – both institutionally and in terms of staffing – varies significantly. At NASA, nearly all technology development is funded through projects; thus concepts must argue a link to near-term utility almost from their inception. As a consequence, the inventor is often involved in the development of instruments from conception to flight. At ESA, the TRP program does encourage some level of generic technology development, conducted in a separate directorate from flight projects. However, for a new capability to be infused into a project requires that it be designated a critical enabler quite early in its maturation process. While the inventor is rarely involved in the eventual implementation of the capability, the transition burden of championing the new idea to project teams is carried disproportionately by successful ESA technologists. The DoD maintains the strongest distinction between basic phenomenological investigation, advanced technology development and projects. Yet, while it employs formal transition programs, projects often engage in separate within-project developments because of their near term focus.

CONCLUSION

As an initial step in a broader project which seeks to develop an in-depth understanding of the fundamental dynamics of innovation in government space, this paper has described and represented the elements of NASA's, ESA's and the DoD Space's innovation systems in terms of how they select projects and conduct technology development in support of those selections. It further outlined the key differences among the agencies in terms of the fundamental tradeoffs governing the selection and development process.

However, in order to fully represent each of the Space Agency Innovation Systems, an explanation of how each of the above described funding vehicles and mechanisms are connected in practice is required. To uncover these *innovation pathways* requires detailed historical process tracing of the paths taken by particular technologies as they matured overtime, spanning different types of innovations and infusion into different types of project. This piece of the work is in progress and will be reported on in a follow-on paper. It is hoped that an analysis of the combined, organizational structures (presented in this paper) and informal pathways of the space innovation systems (presented in the next), will enable the in-depth understanding and explanation of innovation in the space sector that is sought.

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