Instrument First, Spacecraft Second (IFSS): A New Paradigm In Space Mission Development[1,2]

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Abstract— NASA science instruments have had a history of developmental delays. These development delays can lead to cost growth for the overall mission, as shown in recent studies of NASA missions and a larger historical data set. There are examples of historical missions, such as QuikSCAT and QuikTOMS, that have had shorter development times and less than historical average cost and schedule growth, which had instruments that were largely developed prior to the start of mission development. This implies that a similar approach, labeled instrument first, spacecraft second (IFSS), could provide reduced cost and schedule growth in future missions. To test this idea, an analysis was conducted to determine potential benefits of initiating instrument development prior to full mission development for NASA Earth Science missions. A cost and schedule analysis was conducted for representative Tier 2 and Tier 3 Earth Science Decadal Survey missions to quantify the benefits. The results indicate that the savings resulting from such an approach is on the order of $2B, making more funding available for future missions, while providing a less volatile and more manageable mission portfolio. This paper discusses the cost and schedule growth for historical missions and lays out the approach and results for assessing the IFSS concept.

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1. INTRODUCTION

The development of NASA missions is difficult. Developing world class science instruments that constantly push the state of the art can present a series of developmental challenges that are difficult to both anticipate and overcome. For many NASA missions, the development of an instrument can become the primary key technological challenge for the success of a mission [1]. As such, the difficulty of developing an instrument can lead to delays in delivering the instrument to the spacecraft for system integration [2]. This delay, in turn, can lead to cost growth while the spacecraft, mission and ground system team waits for the instrument to be delivered. The subsequent "marching army" cost can be significant and is one of the primary causes of cost growth for NASA missions [3].

This issue is addressed by hypothesizing that developing the instrument first and bringing it to an acceptable level of maturity prior to procuring the spacecraft and initiating ground system development could provide an overall cost reduction or minimize cost growth for NASA missions. To test this theory, the cost and schedule of representative missions from the recent Earth Science Decadal Survey (ESDS) [4] were analyzed to determine if potential cost and schedule growth could be minimized by developing the instrument(s) prior to starting full mission development.

Section 2 discusses the historic difficulties of NASA science instrument development and the associated cost and schedule growth while proposing a potential approach to reduce this growth for future missions. Section 3 presents the instrument first, spacecraft second (IFSS) methodology and lays out the process for analyzing its effectiveness in minimizing project cost and schedule growth. Section 4 presents the results of applying the methodology to representative ESDS Tier 2 and Tier 3 missions.

2. BACKGROUND

Historically, most NASA missions have had instrument development issues [3]. Specific examples of recent problems include the development of the Cloud Profiling Radar (CPR) instrument on CloudSat, the Geoscience Laser Altimeter (GLAS) instrument on ICESat and the instrument on the Orbiting Carbon Observatory (OCO). Each of these missions experienced significantly more cost growth to the

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project than the cost of the instrument growth alone. As can be seen in Figure 1, instrument development difficulties led to delays in instrument delivery which results in significant cost growth in the instrument and the subsequent total mission cost due to the marching army cost. For the examples shown, the ratio of total mission cost growth to instrument cost growth is on the order of 2:1. Although it is understood that other factors contributed to the cost growth of these missions, the instrument delivery delays were one of the primary contributors.

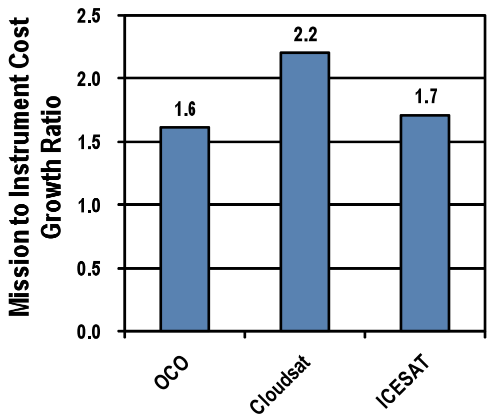

Figure 1 - Ratio of Total Mission Cost Growth to Instrument Cost Growth for Recent Missions with Instrument Difficulties

To understand the impact of instrument difficulties and their contribution to cost and schedule growth relative to a larger data set, a recent investigation of the causes of cost and schedule growth for forty NASA missions shows that over two-thirds of the missions experienced instrument development difficulties [3]. Figure 2 shows the results of this study where a third of the missions had instrument problems only and another 30% of the missions had both instrument and spacecraft development problems. Figure 3 shows the associated cost growth for these missions where missions that only had instrument development problems experienced over twice the cost and schedule growth of missions that only had spacecraft development problems. It is postulated that cost growth for instrument development problems are more prevalent and have higher cost growth because instruments are the primary, challenging developmental items for NASA science missions while spacecraft have less developmental issues. With the availability of standard spacecraft busses through NASA's Rapid Spacecraft Development Office (RSDO) and commercial providers, the complexity of instruments relative to spacecraft is even greater for potential future Earth science missions.

Another recent study examined the average delay and distribution of delays of the planned versus actual delivery times for the instrument. Figure 4 shows a plot of the planned versus actual development time for eighty-four NASA science instruments. The plot shows the planned time on the x-axis with the actual delivery time on the y-axis. The diagonal line on the graph indicates when the actual delivery time equals the planned delivery time. As can be seen, the majority of data points lie above that line, indicating that a delay has occurred. Figure 5 provides further enlightenment by indicating the distribution of the delays. The average growth of the data set is 33%, with almost half of the instruments experiencing growth greater than 30% and 14% of the instrument experiencing growth over 60% of their planned delivery duration.

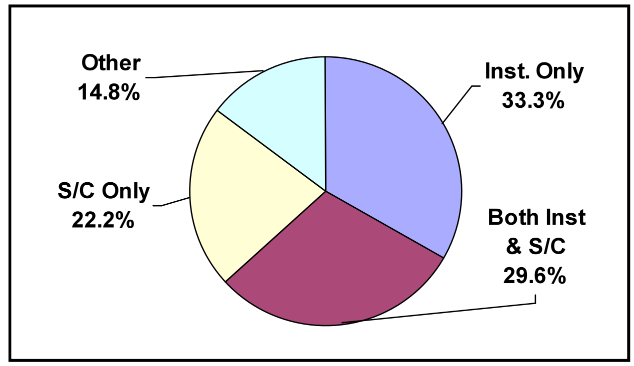

Figure 2 - Distribution of Problems Identified for a Forty NASA Mission Set Studied

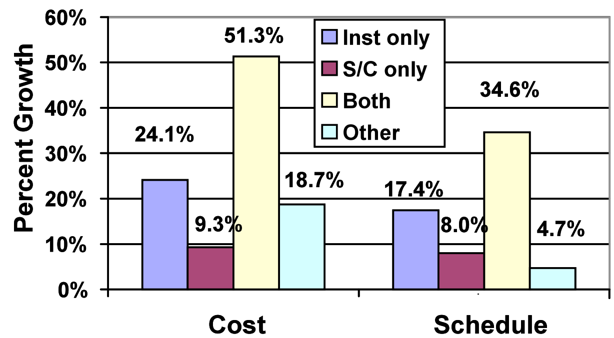

Figure 3 - Associated Cost and Schedule Growth as a Function of the Problems Encountered

Figure 4 - Planned vs. Actual Delivery Durations for 64 NASA Science Instruments

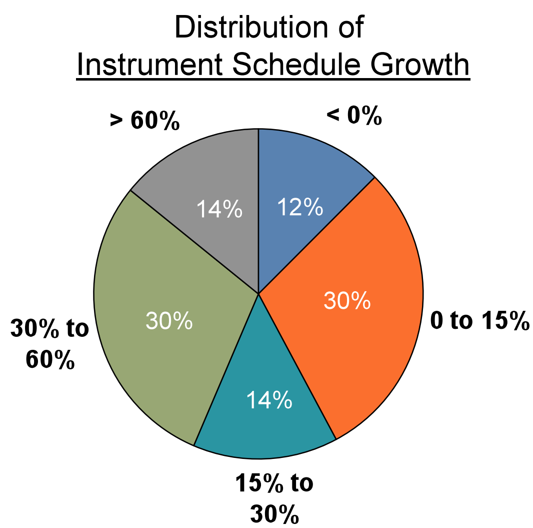

Figure 5 - Distribution of Instrument Schedule Growth for 64 NASA Science Instruments

The difficulty of instrument developments versus spacecraft developments can also be seen when investigating resource growth for historical NASA missions. A more recent study reviewing a subset of twenty NASA missions in greater detail demonstrates that instrument resources such as mass and cost grow at a significantly greater rate than spacecraft resources [5]. Figure 6 shows the average percentage mass and cost growth of the instruments and spacecraft from the start of Phase B within this twenty mission data set and shows that the growth for instruments is essentially twice the growth for spacecraft. This incongruity implies that instruments typically are less mature than spacecraft at the initiation of a project, as shown by the differences in mass growth, which leads to cost growth. Again, this additional information supports the idea of developing instruments early, prior to start of spacecraft development, in order to minimize the marching army effect of spacecraft waiting for instruments to be delivered. Based on the immaturity of the initial instrument design, the history of instrument development difficulties and the associated total mission cost growth, an approach that develops the instrument first before the other mission elements, referred to as the instrument first, spacecraft second (IFSS) mission development approach, could potentially provide a reduction in cost growth in the development of NASA missions.

3. APPROACH

Missions where the majority of instrument issues were resolved prior to the start of spacecraft development, such as QuikSCAT and QuikTOMS, are in sharp contrast to missions developed in a more traditional manner. For both of these missions, the instruments for each, SeaWinds for QuikSCAT and TOMS for QuickTOMS, had already been largely developed prior to spacecraft acquisition. Each instrument was able to be integrated with spacecraft and launched in the relatively short time of two years. The reduced development time and integration uncertainty in these missions helped to keep the cost and schedule growth relatively low compared to historical NASA mission averages.

The proposed IFSS approach is a simple idea – developing the instrument early and bringing it to an acceptable level of maturity prior to initiating full mission development. A notional example of the IFSS development approach is shown in Figure 7 where the start of spacecraft development is delayed to more favorably match the historical instrument development delays.

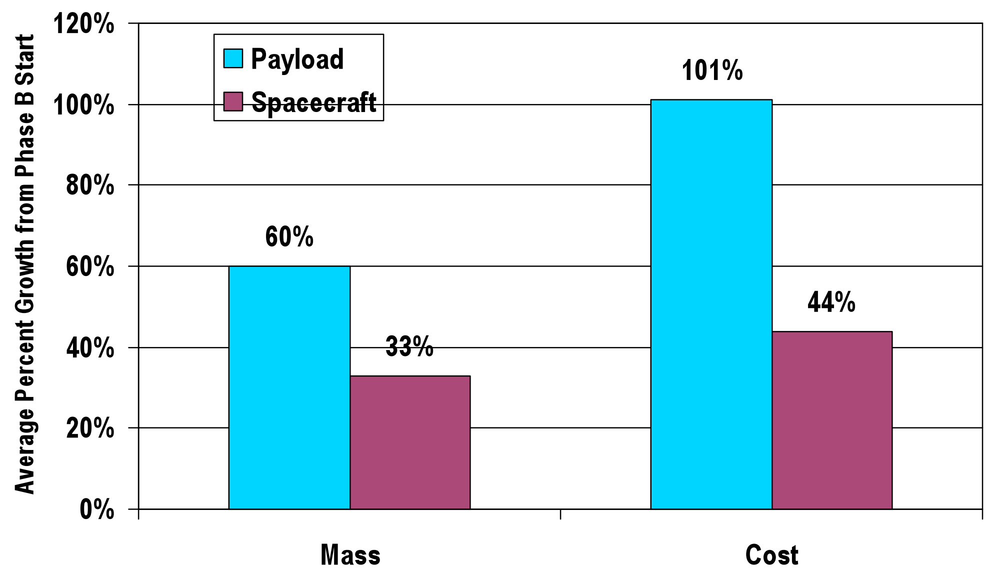

Figure 6: Relative Cost and Schedule Growth, from Phase B Start, of Instrument Payloads vs. Spacecraft

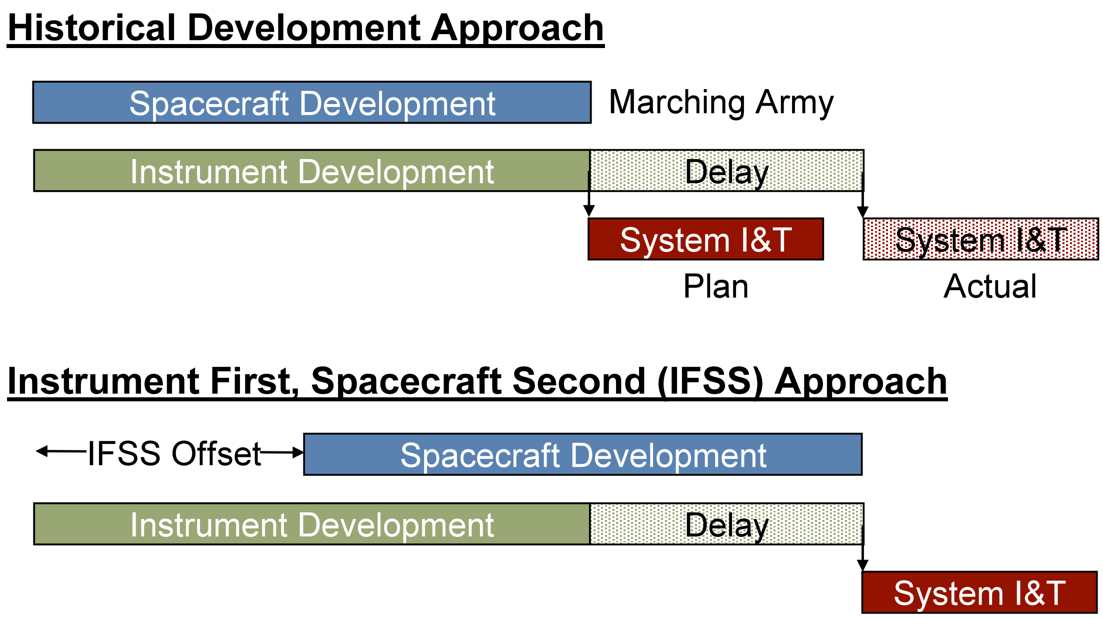

Figure 7 - A Notional Comparison of Traditional Development with Delays versus a Possible IFSS Approach

4. Assessment Approach

To test the hypothesis that IFSS could lead to a decrease in cost and schedule overruns, a quantitative process was needed. Realistically, it should use plausible missions that are under investigation for future flight. It was decided that the Tier 2 and Tier 3 Earth Science Decadal Survey missions would be used. The Earth Science Decadal Survey mission were chosen because there was a good amount of public data, both cost and technical, to use in the analysis and the Tier 2 and Tier 3 mission are currently under study for flight in the next decade. A multi-step process was undertaken to generate portfolio costs to compare the development costs for the Tier 2 and Tier 3 under the current paradigm and under IFSS. Figure 8 provides an overview of the process that was used.

For each of the Tier 2 and 3 mission, the available technical data was used to develop "-like" missions. These missions are not the exact current concepts, but are representative of what would be flown. It was necessary to develop these detailed designs so that a cost estimate could be generated for each mission. The detailed designs were generated using a concurrent engineering methodology (CEM) model. The CEM model used is a single page spreadsheet that uses mission design and instrument technical parameters to size the spacecraft bus (mass, power and various technical parameters).

With the detailed designs in hand, the cost estimates for each mission were developed. Though cost estimates for each mission are available publically, the available information is only the system-level cost and is not at a low enough level to be useful in the study. For this study, costs at the level of the spacecraft and individual instruments were required to understand the cost impact of delays for each of these elements. These costs were then laid out over a baseline schedule. This provides a funding profile from which expenditures by phase can calculated and used in the simulation that was run to quantify possible schedule delays. The baseline schedule was a notional timeline based the planned development time for each mission. To quantify possible overruns for the instrument developments, historical developments times for analogous instruments were needed. Analogies for each instrument to be flown on a mission were identified and the range of times used in the simulation.

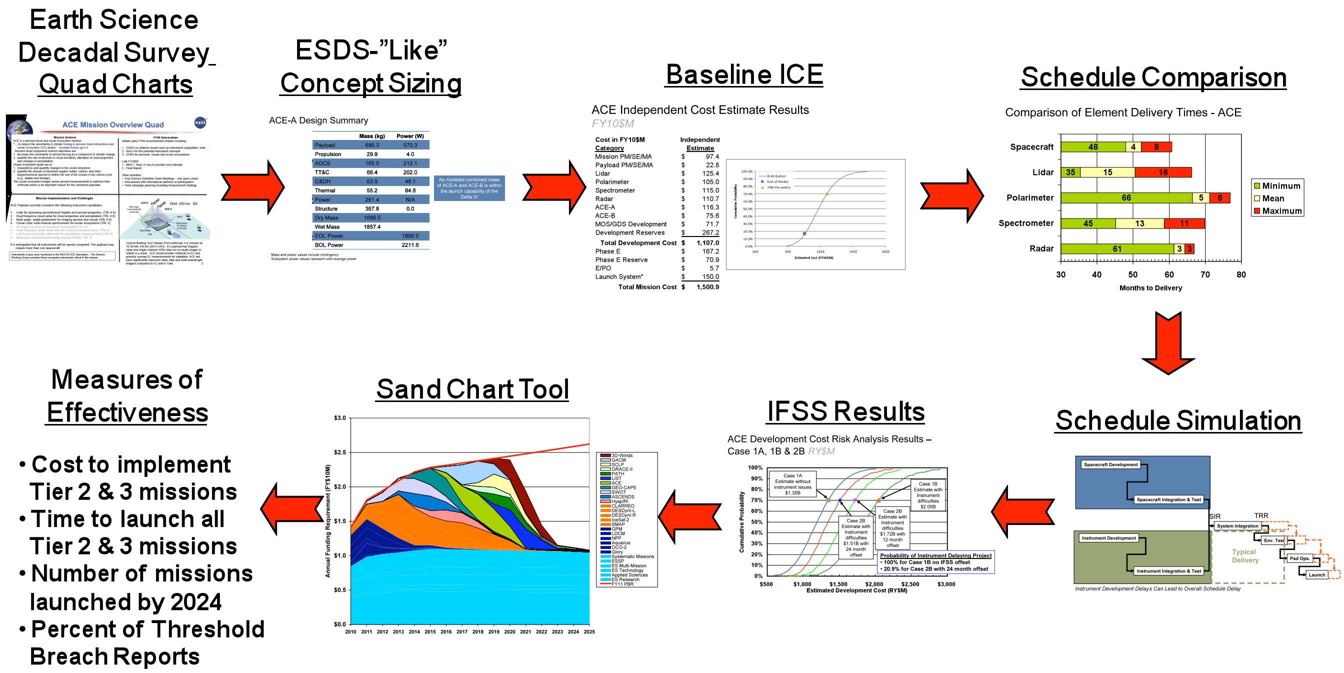

Figure 8 – Process to Investigate Possible Cost Savings from the IFSS Development Approach

In order to assess the impact of potential instrument delays on the cost of a mission, a simulation was developed that uses a distribution of historical development durations for analogous spacecraft compared to the distribution of historical development durations for analogous instruments for the missions to be investigated.

Figures 9 and 10 show the primary basic test which drives the simulation. For each, a Monte Carlo draw is made for both the spacecraft development duration and instrument development duration(s) to determine if the spacecraft will be ready for system testing prior to the instruments' availability for integration to the spacecraft. Figure 8 shows a case in which the instrument development duration is greater than the spacecraft development duration. In this case, a "marching army" cost, identified as the average monthly cost expenditure (i.e., "burn rate") from the time of initial assembly to test, is incurred by the complete project until the instrument is ready to be integrated. Figure 9 shows the case where the instrument development is started earlier than the spacecraft – by the corresponding "IFSS Offset" – and the instrument is delivered prior to the spacecraft being ready for test. In this case, a burn rate associated with the instrument integration and test team, which is much smaller than that for the complete project, is applied as a penalty for early instrument development. The simulation is run for 10,000 cases providing a statistical distribution of potential outcomes allowing for an assessment of the benefit or penalty of different IFSS offsets.

Once all the simulations were complete, the results from the current development paradigm could be compared to those from the IFSS approach to see if there is any savings from starting the instrument development early. The individual mission results were then used in a tool called the Sand Chart Tool. This tool provides the ability to visualize the portfolio as a whole and use metrics other than cost (such as total time to launch all missions) to compare the performance of the two different approaches.

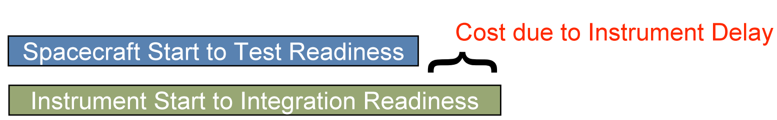

Figure 9 - Typical Development Leading to "Marching Army" Cost Due to Instrument Delays

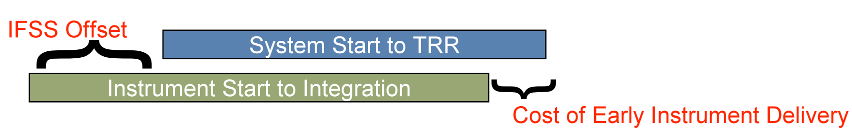

Figure 10 - Applying the IFSS Offset to Reduce the Potential Cost Due to Instrument Delays

4. Results

The simulation was applied to representative designs of the eleven Tier 2 and Tier 3 Earth Science Decadal Survey missions. For each of the missions, public documentation was used to identify instrument resources, such as mass, power, pointing requirements, data rate, etc., and a spacecraft sizing routine was used to size the spacecraft to satisfy the mission and instrument resource requirements. The goal was to develop ESDS-like missions for which an independent cost estimate could be developed for use in the simulation. The independent cost estimate was developed to assess the baseline cost of the mission assuming that the instruments could be delivered on time with no developmental difficulties. Table 1 shows that the "-like" missions are representative of the proposed ESDS missions.

Table 1. Comparison of Tier 2 & 3 Mission Public Costs vs. Independent Estimate for ESDS-like Missions

Mission	Public Cost (FY10$M)	Aerospace Estimate (FY10$M)	Difference
Tier 2			
HySPIRI-like	$ 433	$ 451	4.2%
ASCENDS-like	$ 455	$ 510	12.1%
SWOT-like	$ 652	$ 808	24.0%
GEO-CAPE-like	$ 1,238	$ 677	-45.3%
ACE-like	$ 1,632	$ 1,285	-21.2%
Tier 2 Total	*$ 4,409*	*$ 3,731*	*-15.4%*
Tier 3			
LIST-like	$ 523	$ 683	30.7%
PATH-like	$ 459	$ 387	-15.7%
GRACE-II-like	$ 454	$ 280	-38.3%
SCLP-like	$ 449	$ 552	22.9%
GACM-like	$ 988	$ 830	-16.0%
3D-Winds-like	$ 760	$ 856	12.6%
Tier 3 Total	*$ 3,632*	*$ 3,587*	*-1.2%*
Total	**$ 8,042**	**$ 7,319**	**-9.0%**

Costs shown in Table 1 do not include Launch Vehicle and Public Costs come from NASA Earth Science Decadal Survey Implementation inflated to FY10$M

Historical development times for instruments analogous to those for each of the specific Tier 2 or Tier 3 missions investigated were gathered and used in the simulation to provide the basis for the instrument development durations. These historical instrument development durations should therefore be representative of the challenges facing these types of instrument developments. The cost of the baseline mission, with and without instrument difficulties, was compared to similar conditions for missions developed with an IFSS offset to determine if savings could be realized.

Figure 11 shows the results of the simulation for a HyspIRI-like mission using the historical development times. Case 1A shows the baseline cost distribution assuming that no instrument developmental difficulties arise (i.e., that the instruments are delivered on schedule). Case 1B shows the same case when historical instrument developmental difficulties are introduced using the instrument development duration distribution based on historical analogous instruments. The cost difference between Case 1A and Case 1B indicates a potential $90M cost growth could occur if the mission was planned such that the spacecraft and instrument developments were started at the same time. Applying an IFSS offset of 18 months in Case 2B results in a potential cost growth of only $10M or a savings of $80M over Case 1B. This same methodology and approach was used for all eleven Tier 2 and Tier 3 missions to identify the total cost growth savings that could be achieved for a portfolio of missions. Based on the simulation results over all Tier 2 & 3 missions, the IFSS approach saves on the order of 30% compared to the typical development approach.

Additionally, the potential cost savings for the portfolio of Tier 2 and Tier 3 missions that use an IFSS approach was assessed. This assessment used The Aerospace Corporation Sand Chart Tool (SCT) which simulates the effect of cost and schedule growth of missions on subsequent missions in a mission portfolio. SCT is a dynamic simulation that uses heuristic algorithms to fit projects into an annual budget profile by delaying projects that have been planned and haven't started yet or projects that have started but are currently in the preliminary design phase (Phase B). This simulation emulates historical cases like the effect of cost and schedule growth of missions such as Cloudsat and Calipso causing the cascading cost growth and schedule delay of the Aquarius and Orbiting Carbon Observatory (OCO) missions. SCT was used for the two cases of development with and without IFSS. Four measures of effectiveness were developed to compare the SCT results: 1) Cost to implement ESDS missions, 2) Time to launch ESDS missions, 3) Number of missions launched by 2024, and 4) the percent of time that missions exceed their baseline cost by 15% resulting in a threshold breach report. The results for each measure are shown in Figure 12 and indicate that, for all four measures, IFSS provides better results.

The results of the SCT portfolio simulation show the effect of the traditional approach of developing the instrument and spacecraft concurrently in a compressed time and the inefficient cascading effect this approach has on future missions. The IFSS approach allows for late instrument delivery thereby realizing less "marching army" cost growth within a mission and subsequently less impact on future missions. The implications of the analysis are significant in that the results show that the Tier 2 and Tier 3 ESDS missions could be implemented at less cost, allowing more missions to be executed earlier while maintaining the projects within their agreed upon development funding. Although the analysis only considered the Tier 2 and Tier 3 missions, the ability to fund the missions at a $2B savings allows for future missions to be funded at an accelerated pace which will increase future science return.

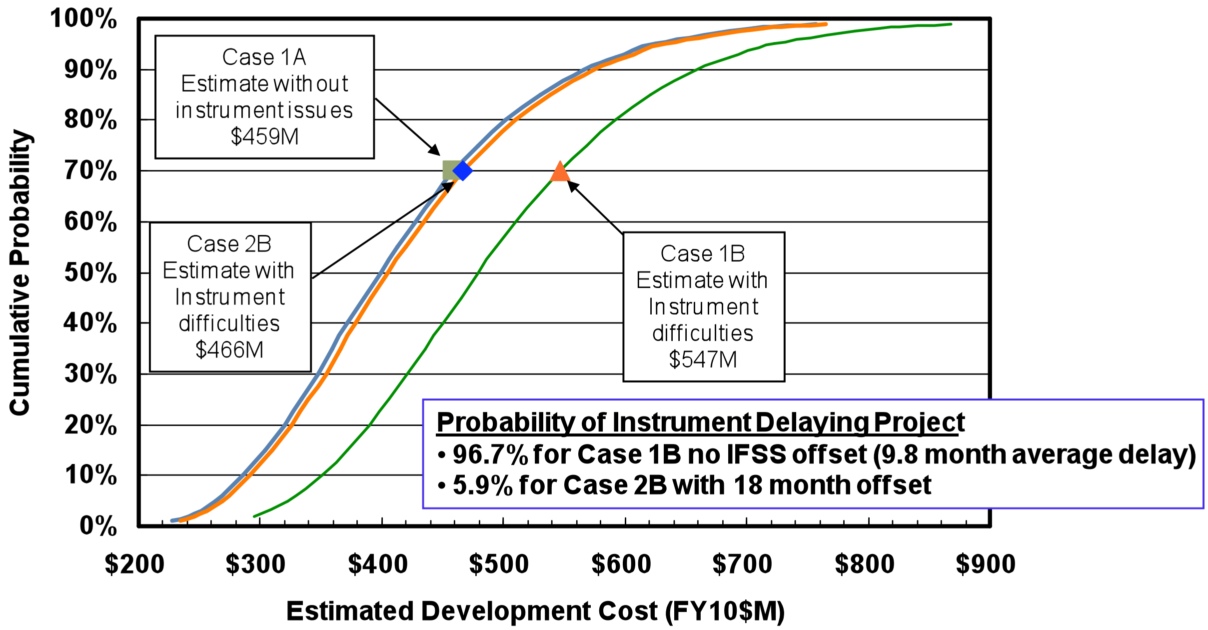

Figure 11 - HyspIRI-like Development Cost Risk Analysis Results

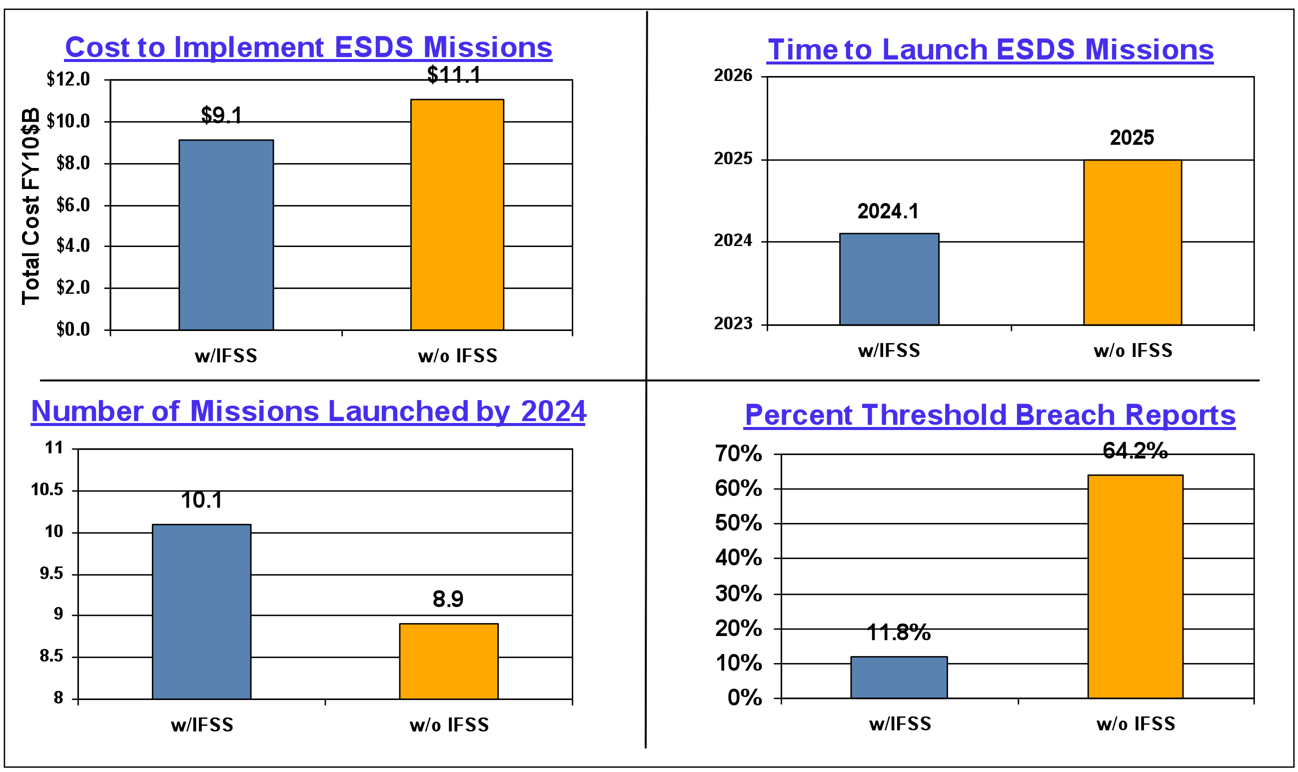

Figure 12 - Comparison of Sand Chart Tool Portfolio Analysis with and without IFSS

There are several considerations when determining when to apply an IFSS development approach. It is recognized that an IFSS approach may not be suitable for all mission types as it may not apply to instruments that are fully integral to a spacecraft or otherwise impose significant design restrictions on the spacecraft. For those instruments that are compatible, the availability of standard spacecraft busses from the Rapid Spacecraft Development Office (RSDO) facilitates the IFSS approach by providing a spacecraft bus of known capability in an acquisition time on the order of 20 to 36 months [6]. This approach could apply to both missions directed by NASA Headquarters as well as competitively procured missions as both could benefit from the potential reduction in cost risk that could be realized by an IFSS approach.

Based on the historical instrument delivery and delay data and the analysis results, the typical "IFSS Offset" for instrument development is on the order of two years. This provides instruments with a two year head start prior to a three to four year mission development phase. For most instrument development efforts, this is after the instrument Critical Design Review (CDR) but prior to instrument integration and test. At this point, the instrument should be fairly mature and most instrument problems should be identified but, even if not, ample time remains to recover prior to delivery to the spacecraft for system environmental test. During the time of early instrument development, it is also assumed that mission systems engineers and spacecraft contractors would be involved, albeit at low level of effort, to ensure mission requirements and spacecraft accommodations are considered.

5. Conclusion

The need for an instrument first, spacecraft second (IFSS) mission development approach was addressed. Based on historical data, over two-thirds of NASA missions experience significant difficulty in developing science instruments. These instrument development difficulties are due in part to the immaturity of the instruments at the start of Phase B as can be seen in historical missions where the mass and cost growth of instrument developments is twice the growth experienced by the spacecraft. The corresponding instrument delivery delays result in mission cost growth at a ratio on the order of two to one due to the "marching army" cost experienced by the other mission elements awaiting instrument delivery. By adopting an IFSS development approach, the marching army cost penalty can be addressed by allowing more time for the instrument to develop prior to initiating full mission development which can provide the potential for decreasing total mission cost growth.

To look at the viability of the IFSS development approach, a methodology was developed to assess the potential cost savings in implementing the new paradigm. Representative designs and project cost for the eleven Earth Science Decadal Survey Tier 2 and Tier 3 representative missions were assessed to determine if cost savings could be achieved. In addition, the savings for the total portfolio of Tier 2 and 3 missions was assessed. The results of the study show, using historical spacecraft and instrument development durations, that savings on the order of $2B can be achieved by implementing an IFSS approach. In addition, these missions can be launched a year earlier while decreasing the instances of threshold breaches from 2-in-3 to 1-in-8. Based on the results of the analysis, serious consideration should be given to developing missions using an IFSS approach.

The potential for savings warrants a pilot project implementation of an IFSS pathfinder mission to assess if the hypothesized savings and reduction in schedule growth can be realized.

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Biographies

Robert Bitten *is a Principal Engineer at The Aerospace Corporation and has conducted independent cost estimates for NASA proposal evaluations and independent assessments for a variety of different NASA missions and organizations. He is a winner of the President's Award, The Aerospace Corporation's highest honor, for his effort in assessing the cost effectiveness of different alternatives in the in the Hubble Space Telescope Remote Servicing Module (HST RSM) Analysis of*

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***Claude Freaner** has worked in the cost estimating field in industry and at NASA Headquarters for the last 30 years. As part of his duties, Claude is responsible for independent cost assessment of proposed and ongoing missions within NASA's Science Mission Directorate. Claude recently received the 2006 NASA Cost Estimating Leadership Award which is given "to provide recognition to an individual who has brought leadership and inspiration to the space cost community in activities such as championing a cause, leading and mentoring others in the space cost community, acting as a strong cost advocate, and garnering the respect of his cost peers." Claude has a Bachelor of Science in Mathematics from the University of Idaho, a Masters in Business Administration (MBA) in Management Science from San Diego State, several certifications in Cost Analysis and Program Management and is a Certified Parametric Practitioner.*