Exploring the Trade-offs of Aggregated versus Disaggregated Architectures for Environmental Monitoring in Low-Earth Orbit

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Traditionally, government space agencies have developed aggregated systems that co-host multiple capabilities on shared spacecraft buses. However, in response to cost growth and schedule delays on past programs, leaders in the government space community have expressed an interest in *disaggregation,* or distributing their capabilities across multiple spacecraft. Since their aggregated National Polar-orbiting Operational Satellite System (NPOESS) program was cancelled in 2010, both the National Oceanic and Atmospheric Administration (NOAA) and the Department of Defense (DoD) have investigated opportunities to reduce program costs through disaggregation. This paper expands their initial investigation and explores the cost impacts of aggregation and disaggregation across a large trade space of candidate architectures for environmental monitoring in low-Earth orbit. We find that on average, aggregated architectures are less costly than fully disaggregated ones but also find opportunities for cost savings by developing semi-aggregated systems, or systems with one or two satellites per orbital plane. Finally, we investigate several trades that are currently under consideration by NOAA and the DoD and make recommendations for future environmental monitoring systems in low-Earth orbit.

IN 1994, President Bill Clinton directed the Department of Defense (DoD) and the National Oceanic and Atmospheric Administration (NOAA) to combine their existing environmental satellite systems and to collaboratively develop the joint National Polar-orbiting Operational Environmental Satellite System (NPOESS). By executing the agencies' missions jointly, the NPOESS program enabled NOAA and the DoD to share the development, production, operations, and launch costs of the new system and to save the government $1.3 billion .[1]

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Despite this initial cost-savings potential, the NPOESS program struggled to develop state-of-the-art technology under strict cost and schedule constraints; as a result, in 2010, President Barak Obama cancelled the program during its development phase and directed the collaborating agencies to execute their missions separately. Just prior to its cancellation, the NPOESS program had exceeded its 2002 projected lifecycle cost baseline by approximately $7.4 billion.[2]

In the years following the program's cancellation, both NOAA and the DoD have struggled to define their newly independent systems. NOAA's Joint Polar Satellite System (JPSS) continues to face management challenges, cost over-runs, and schedule delays[3] and the DoD's future weather satellite capabilities remain undefined after their post-NPOESS Defense Weather Satellite System (DWSS) was cancelled in 2012. Today, as older satellites retire faster than the NPOESS follow-on programs can replenish them, our nation finds itself at risk for a data-gap that could have drastic impacts on weather forecasts in the future.[4]

Concurrently, since future budgets will likely remain constrained, government leaders have expressed an interest in disaggregation, or "the dispersion of space-based missions, functions, or sensors across multiple systems." [5] A disaggregated approach to environmental satellite architectures is essentially the opposite of the aggregated and costly NPOESS system architecture of the past. Disaggregated architectures have multiple potential benefits—including increased resiliency, responsiveness, and flexibility—and are also potentially less complex and costly than aggregated systems like NPOESS.[5-9] Given its cost-savings potential and the uncertainty of NOAA and the DoD's post-NPOESS plans, future environmental monitoring satellites are top candidates for future disaggregation.

These current events and the government's interest in disaggregation motivate our paper, which presents a tool that explores a large trade space of options for the space segment of environmental monitoring programs. In this tool, we represent the space segment's design-space as a series of discrete but coupled decisions, enumerate options for each decision, and evaluate those options using parametric models of the system and metrics for benefit and cost. Using the trade space generated by our model, we then explore the cost impacts of aggregation, evaluate current trades under consideration by NOAA and the DoD, and make recommendations for future systems. Finally, we conclude by noting opportunities for future work.

I. Overview of Trade Space Exploration Tool

Typically, when government agencies have analyzed the cost impacts of aggregated versus disaggregated architectures, they have done so by comparing point designs for a handful of candidate systems (e.g. Ref. 10). To expand upon these previous analyses, we developed a trade space exploration tool that enabled us to comprehensively and quantitatively evaluate the cost impacts of aggregation. To do this, the tool generated and evaluated a broad trade space of potential system options for both NOAA and the DoD. Because the tool explored a large space rather than comparing the characteristics of a few detailed point designs, it necessarily traded model depth for breadth. As a result, the tool evaluated each option at the level of the system's *architecture*; as shown by multiple authors, this level of modeling fidelity is most useful at the very early stages of system definition, during pre-Phase A of both NASA and the DoD's acquisition timelines.[11-13] In this section, we review the trade space exploration tool and its specific application to environmental monitoring satellites in low-Earth orbit.

A. Architectural Decisions

Simmons demonstrated that a system's architecture can be represented as a set of decisions and decision options[14] and Table 1 lists the decisions that were used to define our systems' architectures. First, each architecture is defined by the number and type of orbital planes that its satellites occupy; the orbital parameters that we included are consistent with previous NOAA and DoD programs. Second, the maximum number of spacecraft per orbital plane is fixed to control the size of the trade space. Finally, each architecture is allowed three bus options. Each bus can be uniquely designed to support the instruments assigned to it. Alternatively, bus designs can be common across a train of spacecraft (i.e. flying in the same orbital plane) or across the entire constellation of spacecraft (i.e. spacecraft flying in multiple planes).

The instrument options, with the exception of the visible / near-infrared (VIS-NIR) imager-radiometer and the conical microwave imager sounder, correspond to instruments that are currently flying on NPOESS's predecessor, Suomi National Polar-orbiting Partnership (NPP) and or were slated to fly on NPOESS. In addition to these instruments, three VIS-NIR imager-radiometer options are included; the first is the 22-channel VIIRS (Visible Infrared Imaging Radiometer Suite) that was developed during the NPOESS program and is currently flying on NPP. The others, VIIRSLite-NoOcean and VIIRSLite-Ocean, represent less-capable candidate imager-radiometers that were considered during the NPOESS program. These instruments have less horizontal spatial resolution than

Table 1. Architectural Decisions and Assumptions

Varied Architectural Decisions	
Variable Decision	**Decision Options**
Number of Orbtial Planes	1 - 3 orbital planes
Orbit RAAN	Terminator, mid-morning, or afternoon orbits
Number of Satellites / Plane	1 - 4 satellites / plane
Payload Selection	Any combination of • VIS-NIR imager radiometers (VIIRS, VIIRSLite-noocean, VIIRSLite-ocean) • conical microwave imager-sounders (CMIS, SSMIS-U, Windsat) • cross-track microwave / IR sounders (ATMS, CrIS) • earth radiation budget sensors (ERBS cross-track scanning, ERBS-biaxial scanning) • ozone monitors (OMPS-Limb, OMPS-Nadir) • solar irradiance monitors (TSIS) • aerosol polarimetry sensors (APS)
Spacecraft Architecture	Any partition of instruments into spacecraft
Spacecraft Bus Commonality Type	Dedicated bus, common buses within train, common buses across constellation
Fixed Architectural Decisions	
Fixed Decisions	**Assumed Decision Option**
Mission Lifetime	10 years
System Lifetime	5 years (account for spacecraft replenishment)
Orbital Parameters	Sun-synchronous, 800 km orbits
Mission Types	Weather & climate (space weather, search & rescue, data collection missions excluded)

VIIRS and have eight and 14 channels respectively; both instruments are assumed to have the low-light imaging capability that is required by the DoD, but only VIIRSLite-Ocean is able to take ocean color measurements. Three options for conical microwave imager-sounders are also included in the model. CMIS (Conical Microwave Imager-Sounder) and Windsat were both developed during the NPOESS program and SSMIS-U refers to an upgraded SSMIS (Special Sensor Microwave Imager/Sounder) that the NPOESS program considered as an option to replace CMIS.[15] Each sounder option differs in the amount and quality of the data products that it is able to collect. Additional details about the instrument specifications and capabilities are given in Ref. 15.

Finally, Table 1 also lists the decisions that are fixed in our analysis; these include lifetime, orbital parameters, and mission type. These decisions were fixed to limit the scope of our analysis but are consistent with past environmental monitoring systems. It is also important to note that we assume a fixed ground architecture; because there is currently little quantitative understanding of disaggregation's cost impacts on ground systems, [6] we focus our analysis on the space segment, where cost-estimating relationships for small and large satellites are widely available.

B. Trade Space Explorer & Architecture Evaluator

The trade space of potential architectures includes all possible combinations of decision options where each architecture is defined by selecting one option for each of the decisions in listed in Table 1. To explore this trade space, the model follows the process depicted in Fig. 1 and uses two major components—a trade space explorer and an architecture evaluator. The trade space explorer begins by generating a semi-random population of architectures to be evaluated. The architecture evaluator then executes three evaluation steps. First, the evaluator performs a preliminary design of every spacecraft in the architecture. To execute the spacecraft design process, the tool translates the architecture from the set of selected decision options to the physical components that those options represent: spacecraft buses and a set of payload instruments. Physical information about each of the instruments—its mass, power, and data-rate—are used as the primary input to the iterative spacecraft design process, which develops a mass budget for each bus.

Next, the tool uses the preliminary spacecraft design to evaluate the architecture's benefit and cost. Once all of a population's architectures are evaluated, the results are passed back to the trade space explorer, which selects the highest performing architectures and uses them to seed the next population of architectures. New generations are created using a genetic algorithm, which applies mutation and cross-over operators to the highest performing architectures in each population. As shown in Fig. 1, once the new population is generated, the process repeats for a specified number of iterations.

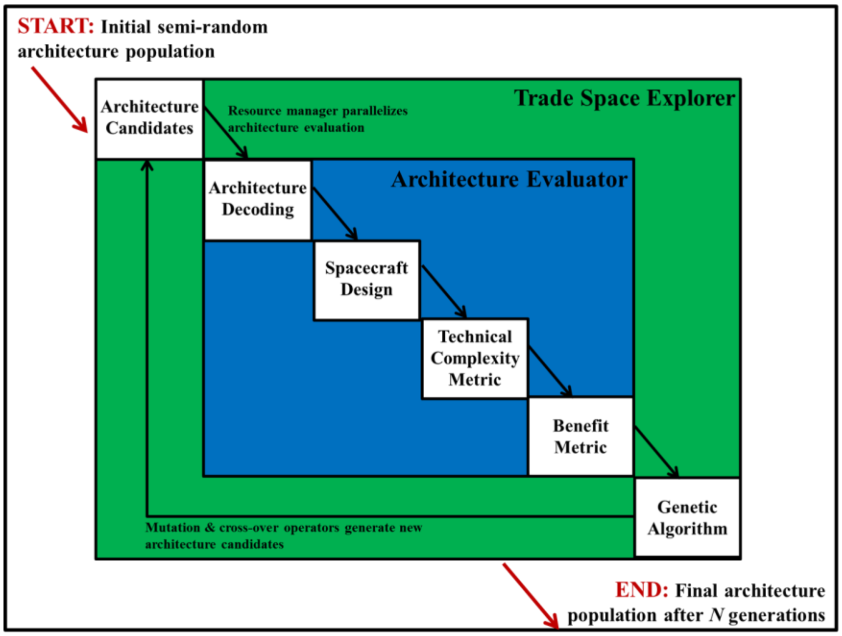

Figure 1. Exploration & Evaluation Process

For this particular analysis, we used an initial semi-random population of approximately 2,500 architectures and allowed that population to evolve for 500 generations. Our trade space exploration process was executed using a Java-based source code that was originally developed to explore a trade space of communication satellite architectures.[13] Our architectures were evaluated using a rule-based expert system[16] and a methodology developed by Selva.[17]

II. Metrics

Two basic metrics—cost and benefit—were used to evaluate the architectures. Both metrics were constructed to capture the key trade-offs associated with aggregation and disaggregation. As shown in Fig. 2, aggregating multiple instruments into the same spacecraft or within the same orbital plane allows different types of data to be cross-registered. When different data types are combined, new data products can be formed or existing products' quality can be enhanced.[17] Alternatively, by disaggregating spacecraft and distributing instruments across multiple orbital planes, systems can increase the temporal resolution of their data products.

As also shown in Fig. 2, in terms of cost, the trade-offs of aggregation and disaggregation are less clear. Traditionally, the government has employed aggregated architectures because they require fewer launches and fewer components. However, recent studies have suggested that despite having fewer components, aggregated architectures are more complex, and therefore more costly, than disaggregated ones.[7,18-20] These findings suggest that as architectures become increasingly aggregated, the cost-saving benefits of aggregation are out-weighed by the growing cost of complexity. Furthermore, although disaggregated architectures require more components, by doing so, they may be able to capitalize on the cost-saving benefits of mass-production.[5] Finally, as the government begins to use new, less costly launch vehicles, the cost to launch a disaggregated constellation may decrease and become comparable to the cost of launching only a few aggregated satellites. The metrics that we used to evaluate architectures were designed to capture each of these trade-offs.

A. Cost Metric

The cost metric calculates the space segment development, production, and launch costs but excludes ground system and operations costs. Importantly, the cost metric *does* capture many of the costs associated with aggregation and disaggregation, including the cost of complexity, the cost-saving benefits of large-scale production, and the cost of multiple launch vehicle options. Because our analysis occurs pre-Phase A, when systems' costs are notoriously uncertain, our cost metric is not an absolute measure of cost. Instead, we calculate cost using traditional cost-estimating relationships but normalize our estimates with respect to a baseline system. This allows our analysis to focus on alternative architectures' *relative* costs. The cost metric is calculated using the following process:

- Instrument mass and power is adjusted for TRL according to the recommendations given in Ref. 21.
- Payload non-recurring costs are estimated using the NASA Instrument Cost Model given in Ref. 22.
- Bus non-recurring costs are estimated using either the Unmanned Space Vehicle Cost Model Version 8 (USCOMv8) or the Small Satellite Cost Model (SSCM); both sets of parametric equations are taken from Ref. 22. The cost metric uses the SSCM when a spacecraft's dry mass is less than 500 kg,[22] otherwise, USCOM is applied.

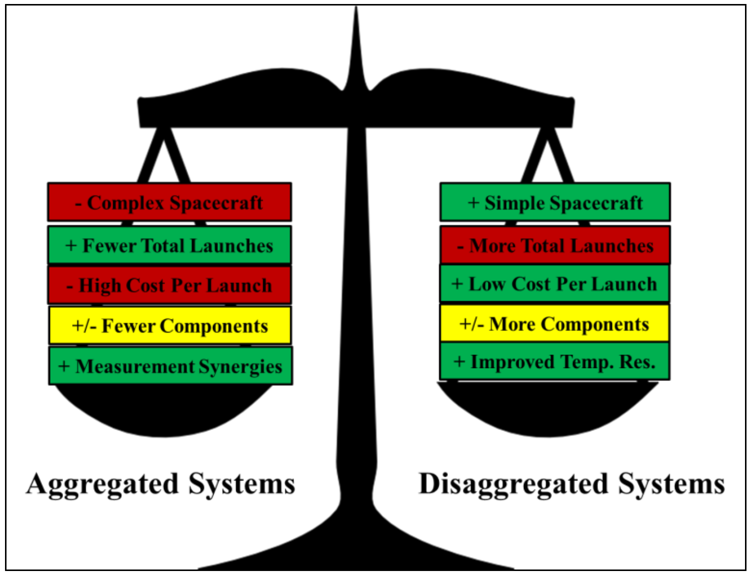

Figure 2. Trade-offs of Aggregation versus Disaggregation

- Payload and bus non-recurring costs are corrected to account for the cost of complexity.
- Recurring costs for both the spacecraft and the instruments are calculated using the corresponding NASA Instrument, USCOM, or SSCM cost models and discounted using a 90% learning curve as recommended by Ref. 23.
- Launch costs are calculated by assigning each spacecraft to the lowest cost launch vehicle with the necessary performance and volume accommodations. Because our analysis focuses on systems that are developed by U.S. government agencies, only domestic launch vehicles are used; however, we included both traditional launch vehicles (i.e. Atlas and Delta) and new, less traditional systems, including the Taurus-XL, the Minotaur-IV, and Space-X.
- Finally, each system's cost is normalized by the cost of NPOESS, which serves as our reference system in this analysis.

To account for the cost of complexity, we add cost penalties to systems that contain sources of design or architectural complexity. Design complexity refers to the complexity of the individual components whereas architectural complexity refers to complexity that is induced by interactions and relationships *between* components. Table 2 lists the complexity sources and penalties that are included in our cost metric. These include instrument TRL (discussed above) and bus design complexity which can be induced by high mass or high data-rate payloads, or by instruments with high pointing requirements. Commonality is also a source of bus design complexity, since adapting a common bus to fly in multiple orbits or to host different instruments is not without costs. Architectural complexity captures interactions and relationships between instruments that may add to the cost of the system. These include mechanical, optical, and electromagnetic interferences as well as instrument reliability and programmatic relationships. Each of source of complexity that is included in our metric was observed to impact cost on past environmental monitoring programs.[15,24]

Complexity is included in the cost estimate by identifying the complexity sources that affect each component. For every source, a cost penalty (shown in Table 2) is added to the component's non-recurring cost. This process was motivated by JPL's Cost-Risk Sub-factors[25-26] and has been used in previous studies of disaggregation; [28] for additional details about our cost metric methodology please refer to Refs. 15, 27. Finally, for reference, by accounting for complexity, our cost metric estimates NPOESS and JPSS costs' to be 20% and 12% greater than the estimates produced by mass-based parametrics alone.

B. Benefit Metric

In order to inform cost-benefit trades, each architecture is also evaluated for benefit, which is assessed with respect to the NPOESS program's Integrated Operational Requirements Document II (IORD-II).[29] Benefit is defined as a function of *which* environmental data records (EDRs) the architecture collects, *how many* EDRs the architecture collects, and *how well* the architecture collects those EDRs. To quantitatively assess benefit, the model employs the VASSAR (Value Assessment of System Architectures Using Rules) methodology.[30] A schematic depicting this

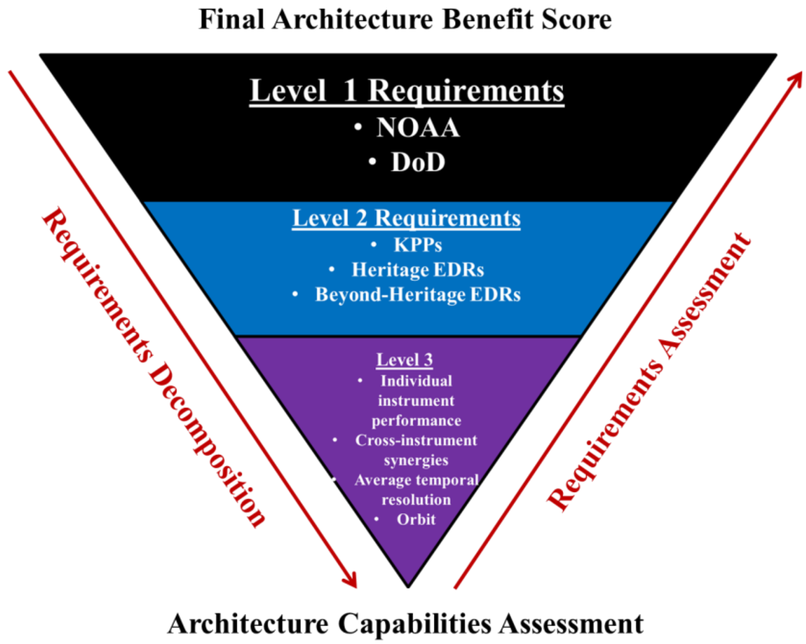

Figure 3. Benefit Metric Illustrated

methodology is given in Fig. 3, which shows that the process begins with a set of decomposed stakeholder requirements that are input into the tool. Next, the tool matches each architectures' capabilities to the set of decomposed requirements and aggregates requirement satisfaction to obtain a final benefit score.

Stakeholder requirements decomposition occurs at two levels for both NOAA and the DoD. Each agency's Level 1 requirements are further decomposed into three sets of Level 2 requirements: key performance parameters (KPPs), heritage EDRs, and beyond-heritage EDRs. KPPs for NOAA and the DoD were taken directly from the IORD-II and were assigned to each agency according to the instruments that it prioritized. Specifically, the IORD-II KPPs that are generated by ATMS and CrIS are assigned to NOAA while those that are generated by VIIRS and a conical microwave sounder are assigned to the DoD; this division of KPPs is consistent with each agency's current prioritization of instruments and requirements.

The EDRs in the heritage EDR category are those that were collected by each agency's heritage, pre-NPOESS program. Finally, the beyond heritage category contains the EDRs that were attributed to each agency in the IORD-II but were not produced by the agency's heritage system. The Appendix contains a list the individual EDRs that contribute to each agency's Level 2 requirements satisfaction scores. Level 2 scores are then combined in a weighted average to produce each agency's Level 1 score. The KPPs, heritage EDRs, and beyond-heritage EDRs are assigned weights of 50%, 35% and 15% respectively.

Several performance attributes are associated with each Level 2 requirement. If an architecture contains all of the specified attributes, it is awarded a full requirement satisfaction score; however, if some of the attributes are absent, the architecture is awarded a partial requirement satisfaction score, according to which attributes it contains. The four performance attributes that are specified for nearly every requirement are individual instrument performance, cross-instrument synergistic performance, average temporal resolution, and preferred right-ascension of ascending node (RAAN). The individual instrument performance attribute is used to distinguish between the performance of individual instruments of the same type; as a result, these attributes primarily distinguish between architectures that contain different VIS-NIR imager-radiometers and microwave imager-sounders. Cross-instrument synergistic performance attributes identify cases where EDR performance is improved when data is collected by more than one *type* of instrument; for example, cross-instrument synergies can improve measurement accuracy or can create new measurement capabilities, like the ability to collect data in both cloudy and clear conditions. The Appendix summarizes the cross-instrument synergies that are included in the model, which only awards requirement satisfaction when synergistic instruments fly in the same orbital plane. Additionally, the model also specifies average temporal resolution for each measurement using the values defined in the IORD-II and finally, it specifies the RAAN from which each agency prefers its data to be collected. The DoD's weather missions requires data from an early-morning orbit (5:30 crossing time), while NOAA's weather and climate missions must be executed from

Table 2. Complexity Penalites Included in Cost Estimate

Complexity Type	Condition	Penalty	Penalty Applied To
Instrument Design Complexity	1 (i.e. TRL = 7)	3%	Instrument mass & power
Instrument Design Complexity	2 (i.e. TRL = 6)	5%	Instrument mass & power
Instrument Design Complexity	3 (i.e. TRL = 5)	25% & 10%	Instrument mass & power
Instrument Design Complexity	4 (i.e. TRL = 4)	30% & 20%	Instrument mass & power
Instrument Design Complexity	5 (i.e. TRL = 3)	50% & 25%	Instrument mass & power
Bus Design Complexity - Commonality	Common bus capability needs to be increased to host additional instruments	5%	Bus non-recurring cost estimate
Bus Design Complexity - Commonality	Common bus capability needs to be adapted to fly in multiple orbital planes	5%	Bus non-recurring cost estimate
Bus Design Complexity - High Data - Rate	Data-Rate > 7Mbps	2%	Bus non-recurring cost estimate
Bus Design Complexity - High Mass	Satellite Dry Mass > 3000kg	5%	Bus non-recurring cost estimate
Bus Design Complexity - Pointing Requirements	Bus hosts instruments with high pointing requirements	5%	Bus non-recurring cost estimate
Architectural - Mechanical Interaction	Jitter inducing instrument hosted with sensitive instruments	5%	Disturbed instrument & bus non-recurring cost estimates
Architectural - Optical interaction	Instruments with conflicting FOV hosted on same bus	5%	Non-recurring cost estimate of instrument requiring accomodation
Architectural - Programmatic	Multiple instruments managed by same program	5%	Instrument non-recurring cost estimate
Architectural - Reliability	Multiple "critical" instruments hosted on same bus	5%	instruments are VIS-NIR sensor, conical microwave imager-sounder, CrIS, ATMS

orbits with afternoon (13:30) crossing times; both agencies can use the mid-morning orbit to increase temporal resolution.

Each architecture's ability to satisfy the Level 2 requirements is a function of the instruments assigned to it and the allocation of those instruments to orbital planes. Additional information about the process that the tool uses to evaluate architectural benefit and the VASSAR methodology can be found in Ref. 11, 12, 17, 30.

III. Analysis

The specific goals of this analysis are three-fold:

- To evaluate the cost of aggregation versus disaggregation across a broad trade space of Pareto optimal architectures and with varying levels of cost and benefit.
- To evaluate the cost of disaggregation trades currently under consideration by NOAA and the DoD with respect to this broad trade space of options.
- And to note characteristics that are shared across architectures in the trade space and that suggest best practices that can be applied for future environmental monitoring satellite programs.

To complete this analysis, two separate trade spaces—one for NOAA and one for the DoD—are explored. Before exploring Fig 4's trade spaces in greater detail, a few general characteristics are important to note. First, several reference systems are plotted to anchor the reader to our cost and benefit scales. For both NOAA and the DoD, the NPOESS architecture maximizes benefit and consequently, is one of the costliest architectures in the trade space; however, for both agencies, the NPOESS architecture is either close to or on the Pareto front.

While the systems that succeeded NPOESS have significantly less benefit and cost, many lie quite far from the cost-benefit Pareto front. For example, architectures based off of the JPSS & NPP satellites, JPSS & DWSS satellites, or all three satellites (JPSS, NPP, & DWSS) are significantly dominated because we assume that the separate programs do not use common spacecraft buses or coordinate their instruments' development. However, when JPSS is considered as a stand-alone program (i.e. without reference to DWSS or NPP), we see that it lies close to the Pareto front. Finally, the current programs of record, JPSS and NPP, do not meet many of the DoD's requirements; these systems' benefit scores are low because they do not provide data from the DoD's preferred early morning orbit, nor do they provide microwave imaging and sounding data from a conically scanning instrument.

In the following sections, we explore the trade space in greater detail by focusing on the fuzzy Pareto front. To select the fuzzy Pareto front, we identified architectures on the true Pareto front and removed them from the trade space. We then identified Pareto optimal architectures in the subsequent trade space and removed them as well. We repeated this process until five successive Pareto fronts were removed and assigned to the "fuzzy" Pareto frontier that is discussed below.

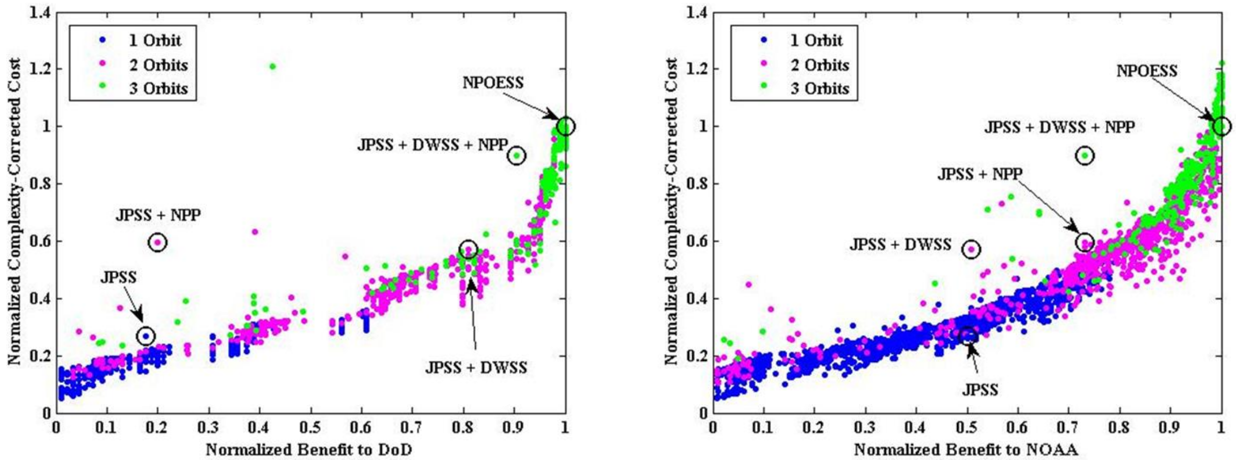

Figure 4. Full Trade Spaces With Reference Architectures

A. The Cost Impacts of Aggregation Versus Disaggregation

To assess the cost of aggregation versus disaggregation, we classify each architecture according to the average number of satellites that it contains per plane; architectures with an average of one satellite per plane, one to two satellites per plane, and more than two satellites per plane are classified as aggregated, semi-aggregated, and disaggregated, respectively. Next, we select a fuzzy Pareto front in two ways: (1) by evaluating architectures according to traditional cost-estimating relationships that have not been corrected for complexity, and (2) by

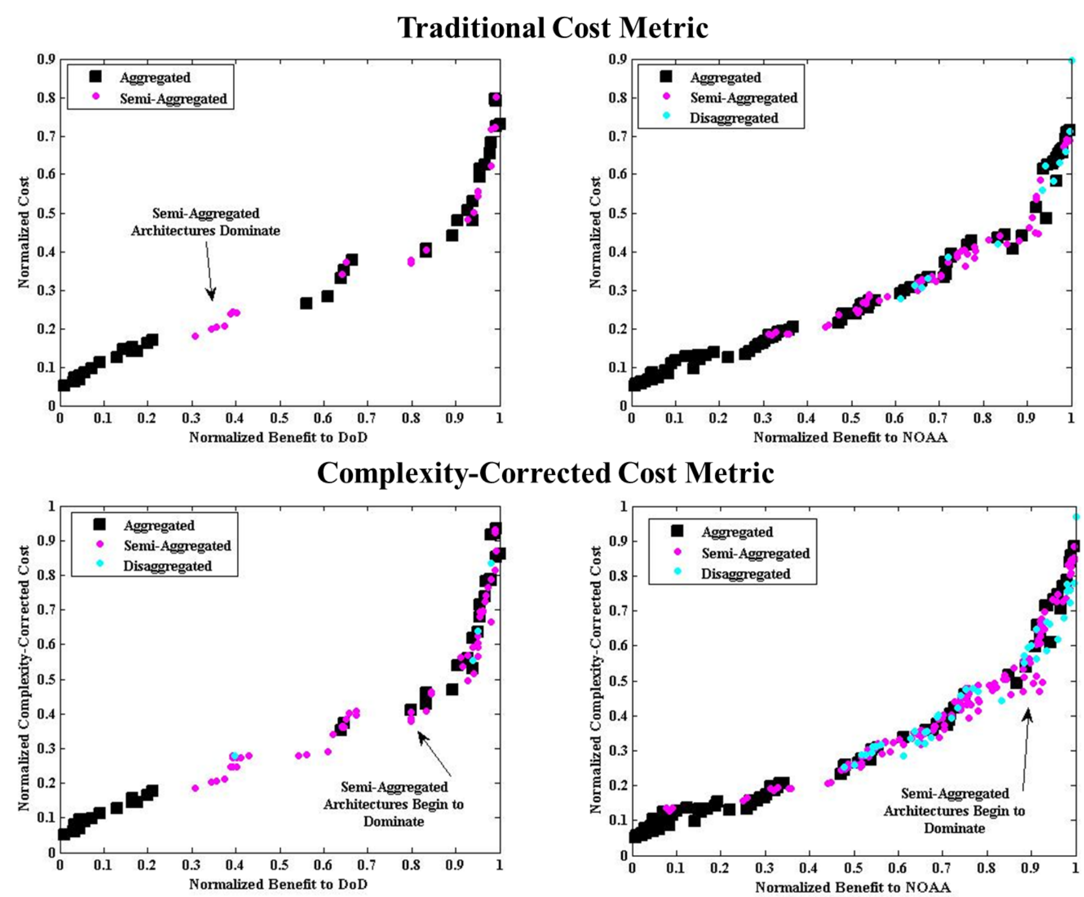

Figure 5. Fuzzy Pareto Fronts with Both Cost Metrics

evaluating them using our complexity-corrected cost metric. As shown in Fig. 5, when the cost metric does not account for complexity, the fuzzy Pareto fronts are largely dominated by aggregated architectures; however, when complexity costs are included in the metric, a larger number of semi-aggregated and disaggregated architectures begin to appear on the fuzzy Pareto front.

Fig. 6 provides additional description of the composition of both Pareto fronts. For both NOAA and the DoD, when cost estimates do not account for complexity, aggregated architectures constitute the majority of the Pareto front. However, once complexity is factored into the cost equation, the proportion of semi-aggregated architectures grows while the proportion of aggregated architectures shrinks; in contrast, even when complexity is included in the cost estimate, the proportion of disaggregated architectures on the Pareto front does not change significantly. The poor performance of the fully disaggregated architectures is important to note since these architectures constitute the majority of the full trade space. Specifically, the full trade space contains approximately 5e11 architectures, 99%, 9e-6% and 0.07% of which are disaggregated, aggregated, and semi-aggregated, respectively. Thus, we conclude that:

- Even when cost estimates account for complexity, aggregated architectures containing one satellite per plane perform significantly better than disaggregated architectures that contain greater than two satellites per plane.
- However, when we account for complexity, we observe that semi-aggregated architectures provide a possible alternative to fully aggregated ones. Semi-aggregated architectures reduce spacecraft complexity by breaking up complex satellites into two simpler satellites that fly in a train.

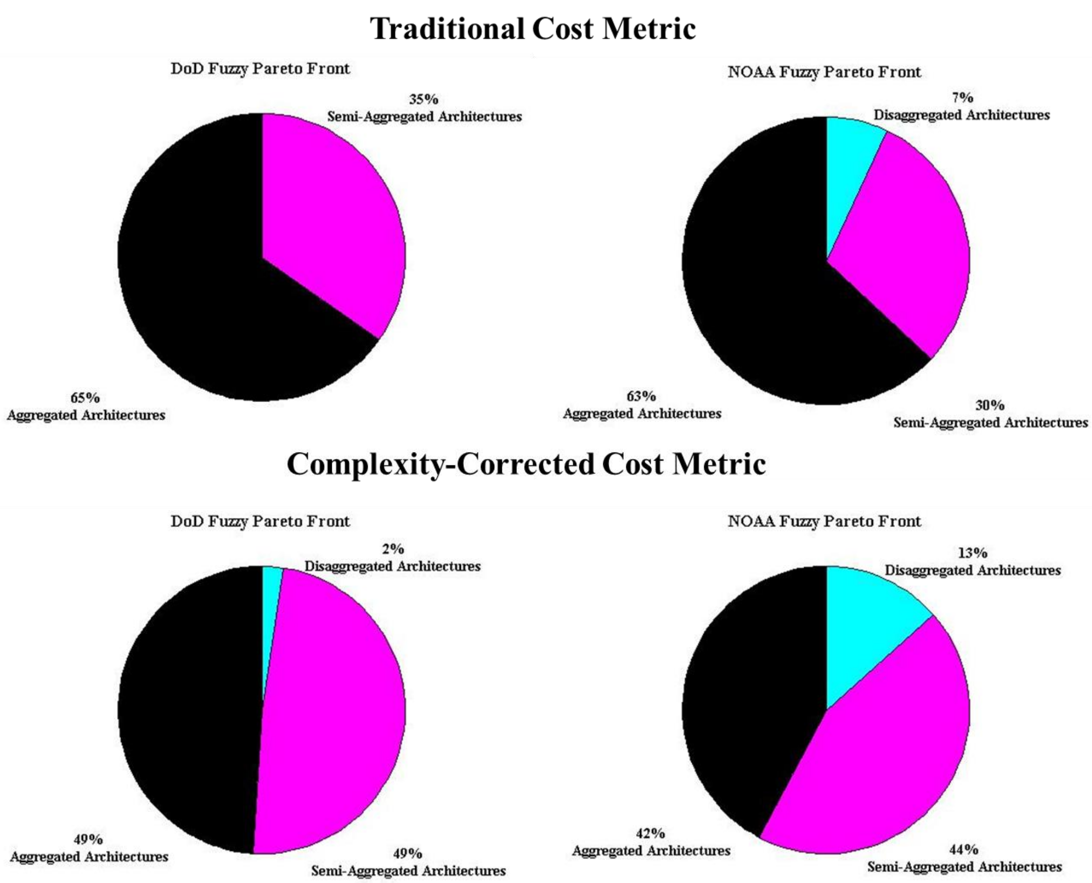

Figure 6. Fuzzy Pareto Front Descriptive Statistics

As shown in Fig. 5, there are several regions of both NOAA and the DoD's Pareto front where semi-aggregated architectures dominate aggregated ones. General characteristics of these semi-aggregated architectures include:

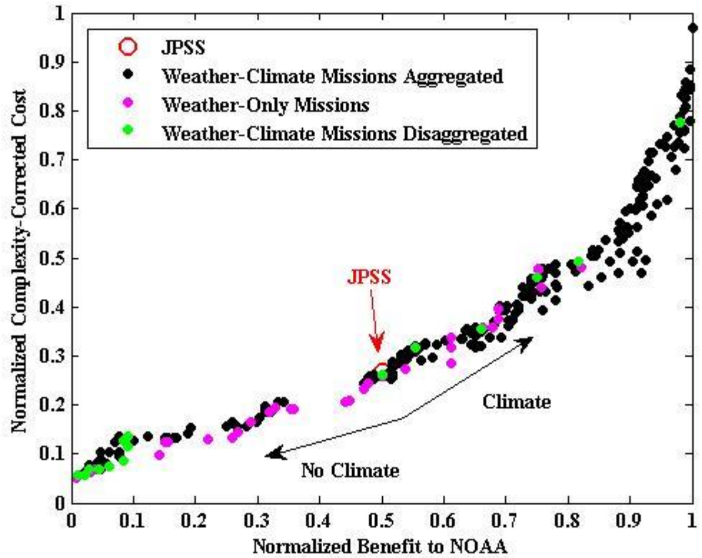

Figure 7. NOAA's Climate-Weather Trades

- For NOAA, the dominant semi-aggregated architectures each contain one plane with VIIRS, a conical microwave imager-sounder, and CrIS and two planes with ATMS. Different sets of climate-centric sensors (i.e. TSIS, ERBS, OMPS, and APS) are co-hosted alongside these four primary instruments.
- For NOAA, all but one of the dominant semi-aggregated architectures separates VIIRS and the microwave imager-sounder and assigns them to separate spacecraft in the same orbital plane. Although VIIRS and the microwave sounder are separated from each other, they are sometimes hosted on the same satellite as the instruments listed above.
- For the DoD, regardless of the cost metric used, semi-aggregated architectures dominate at medium benefit levels (i.e. between 0.3 and 0.6). In these architectures, a VIS/NIR sensor and a conical microwave imager-sounder are assigned to separate spacecraft in the terminator orbit. For higher benefit architectures, either the VIS/NIR or the microwave sensor is also flown alone in a second orbital plane.
- Finally, when complexity is included in the cost metric, semi-aggregated architectures begin to dominate at higher levels of the DoD's Pareto front as well. These architectures assign VIIRS and CMIS to separate spacecraft in the terminator orbit and fly VIIRS in a second orbital plane.

In the next section, we continue exploring characteristics of cost-effective semi-aggregated and disaggregated architectures by analyzing current disaggregation trades with respect to the fuzzy Pareto front of architectures. For the remainder of this analysis, we will use the complexity-corrected cost metric, since it allowed us to identify alternative semi-aggregated and disaggregated architectures here.

B. Current Disaggregation Trades

NOAA and the DoD are currently considering the following disaggregation trades:

- Disaggregating climate-centric sensors from weather-centric sensors and hosting both on separate spacecraft for future NOAA systems.[3, 31]
- Establishing a free-flyer ATMS-CrIS spacecraft by disaggregating these critical instruments from the larger JPSS spacecraft.[31]
- And disaggregating the VIS/NIR and microwave-imager sounder instruments and hosting both on separate spacecraft on future DoD systems.[32]

Fig. 7 illustrates the first disaggregation trade: assigning climate-centric and weather-centric sensors to separate spacecraft. To construct this plot, we classified ERBS, OMPS-Limb, TSIS, and APS as climate-centric sensors and VIIRS, ATMS, CrIS, and OMPS-Nadir as weather-centric sensors; as will be discussed below, we refrained from assigning the microwave imager-sounders to either category. Fig. 7 shows that the current JPSS program is located at a transition point in the trade space: at benefit levels below JPSS, the architectures contain *only* weather-centric sensors. However, as benefit increases above JPSS, architectures increasingly contain climate-centric sensors that are hosted on the same spacecraft as weather-centric ones. Thus, if NOAA hopes to increase JPSS's benefit in the future, it should consider architectures that aggregate climate-centric and weather-centric sensors onto the same spacecraft. If future systems are planned to generate JPSS-levels of benefit, then there is no compelling *technical* reason to disaggregate climate and weather sensors.

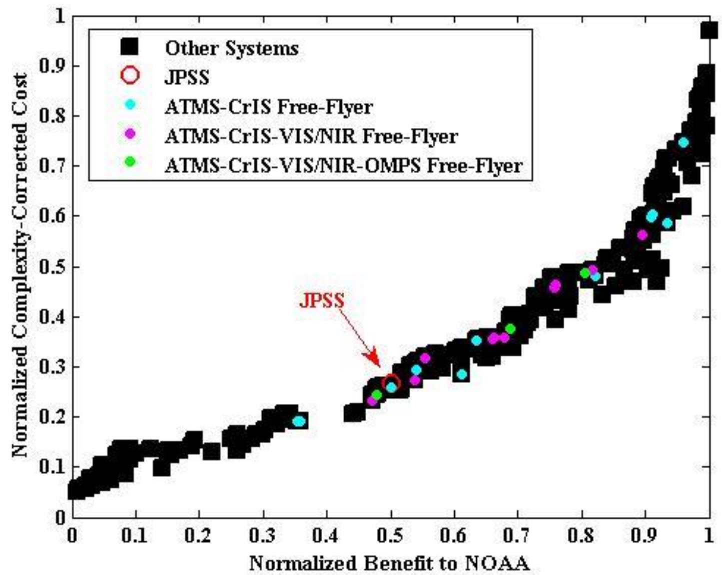

Figure 8. NOAA's Free-Flyer Trades

While there may be little technical reason to disaggregate climate and weather sensors, there is an operational one: by limiting the scope of the JPSS project, NOAA can reduce its cost and schedule risks.[31] The desire to reduce these risks, particularly in light of a possible gap in weather satellite data, motivated an independent review team to recommend developing a ATMS-CrIS free-flyer spacecraft.[31] By developing a smaller free-flyer spacecraft, NOAA could accelerate its development timeline and reduce the risk of a data gap.[31] To investigate the lifecycle cost impact of this (and related) trades, we identified all architectures that used ATMS-CrIS free-flyers and also those that used ATMS-CrIS-OMPS-VIS/NIR or ATMS-CrIS-VIS/NIR free-flyers. The results, shown in Fig. 8, indicate that as a whole, none of the proposed disaggregation strategies dominates other architectures in the trade space. However, the tool did allow us to identify architectures with free-flyers that had similar cost and benefit to JPSS; these architectures are listed in Table 3. Of these possible free-flyers, a few characteristics are important to note:

- Architectures with a CrIS-ATMS free-flyer also had a VIS/NIR free-flyer or both a VIS/NIR and a microwave imager-sounder free-flyer. By disaggregating the sensors in this way, the architectures were able to use similarly-sized common buses and to capitalize on the cost-saving benefits of a block buy.
- Architectures with a CrIS-ATMS-VIS/NIR free-flyer either flew two copies of the same spacecraft in different orbital planes or had a single orbital plane but an additional spacecraft that hosted a microwave imager-sounder and several climate-centric instruments.

The architecture with a CrIS-ATMS-VIS/NIR free-flyer and a second spacecraft with a microwave imager-sounder and climate-centric instruments provides a potential compromise between the two trades considered above. Specifically, by limiting the scope of future projects to include only CrIS, ATMS, and VIIRS, NOAA could gain some of the operational benefits of a free-flyer mission. By establishing a second project that includes a microwave imager-sounder and climate-centric instruments, NOAA could continue collecting climate data without interfering with its operational weather mission. It may also be possible to transfer full responsibility for funding and managing the second project to NASA, which could explore additional opportunities for cost savings by seeking an international partner to contribute the microwave imager-sounder.

Fig. 9 illustrates the logic behind this recommendation. As benefit increases beyond JPSS, NOAA's systems contain both a VIS-NIR sensor and a microwave-imager sounder. However, at medium-high benefit levels (i.e. $0.4 <$ benefit < 0.8), most Pareto optimal architectures disaggregate these instruments and it is only at the highest benefit levels (i.e. benefit > 0.8) where architectures co-host the instruments on the same spacecraft. Thus, it seems

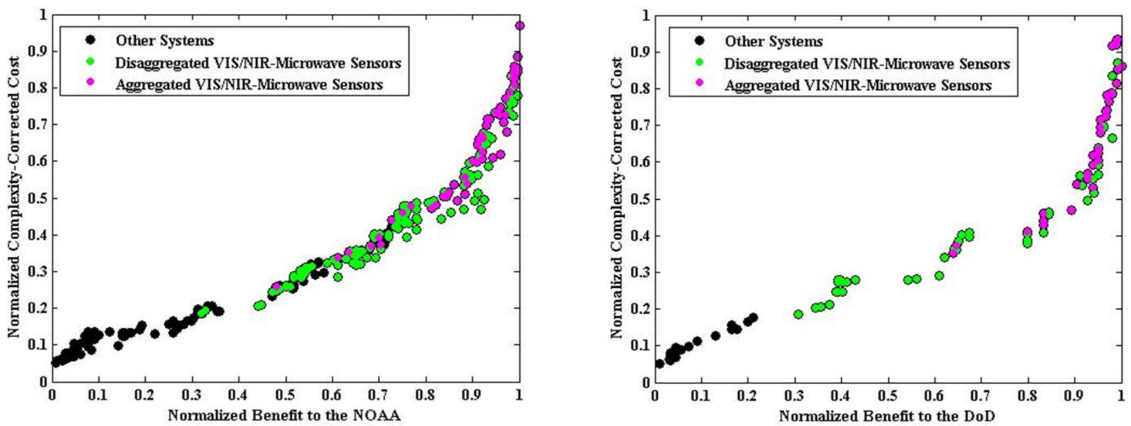

Figure 9. VIS/NIR-Microwave Imager Sounder Disaggregation Trades

advisable to “anchor” two spacecraft around these sensors and to separate the climate-centric and the weather-centric sensors accordingly.

Fig. 9 also illustrates a similar finding for the DoD: that at medium-high benefit levels, disaggregating the VIS-NIR and microwave imager-sounders is optimal, while at high benefit levels aggregating them onto the same spacecraft is. Unlike NOAA’s architectures, at medium-high benefit levels, the DoD’s architectures contain the VIS-NIR and microwave imager-sounders *only* and it is not until the very highest benefit levels that the DoD’s architectures begin to include other instruments and to aggregate them onto the same spacecraft as VIIRS and CMIS.

C. Strategies for Reducing Cost through Disaggregation

Finally, now that we have analyzed specific trades under consideration by NOAA and the DoD, we review several of our assumptions in the context of these results. Key assumptions that affect the cost of aggregated versus disaggregated architectures include:

- The system’s capabilities
- The cost savings enabled by commonality
- Launch costs
- And the cost of complexity

The discussion above suggests an important relationship between aggregation, disaggregation, and a system’s capabilities. For example, medium-high benefit DoD architectures disaggregated the VIS/NIR and microwave imager-sounders whereas higher benefit architectures aggregated them onto the same spacecraft. Thus, the cost of aggregation versus disaggregation seems closely related to the capabilities that a program decides to field and the requirements that it meets. In this analysis, we only considered capabilities that were derived from the NPOESS program; therefore, the options for the VIS/NIR sensor and microwave-imager sounder were all high performing and resource-intensive (i.e. they had large mass and power requirements). If NOAA or the DoD reduces the size and performance of these sensors in the future, then our conclusions may not hold.

Next, the fuzzy Pareto front for both agencies is composed entirely of architectures that use common spacecraft buses. Importantly, in order to achieve commonality’s potential savings, programs need to make both the up-front investment to develop a common bus and the commitment to procure copies of that bus within a short period of time; as noted by Burch,[7] the learning curve savings included in our cost metric are only applicable if systems are delivered six to twelve months apart. As a result, to capitalize on the savings potential of commonality, future programs may need more up-front funding to enable systems to be procured more efficiently. This statement is also true for the instruments in each architecture: to enable the learning curve cost savings that are assumed in our metric, future programs need to procure multiple copies of each instrument at the same time.

We also investigated whether the dominant semi-aggregated or disaggregated architectures in Fig. 4 would remain dominant if they had to launch on traditional launch vehicles. We found that even when these architectures were limited to launch only on traditional launch vehicles, they still performed well with respect to the aggregated architectures. The primary reason for this appears to be the cost and benefit of the microwave imager sounders that were included in the trade space. Specifically, these sensors are necessary to obtain a high benefit score but they appear to drive architectures’ cost and configuration. Future research could examine the specific impacts of these instruments by including less capable options with higher TRLs and by adjusting agency requirements accordingly.

Finally, as discussed previously, our results are contingent on the cost of complexity that was included in our cost metric. Our metric used rules-of-thumb to develop a complexity budget for each system and thus, could benefit from improved calibration in the future. However, we stress that during a pre-Phase A analysis of potential system architectures, any means for accounting for complexity is valuable, since it enables the system architect to gain insight into potential cost growth risks that could affect the system in the future.

Table 3. Alternative Free-Flyer Spacecraft

Normalized Complexity Corrected Cost	Normalized Benefit	Terminator Orbit	Afternoon Orbit	Mid-Morning Orbit
ATMS - CrIS-VIS/NIR Free-Flyer				
0.49	0.82	none	SC1 = {VIIRSLite-noocean, CrIS, ATMS} SC2 = {CMIS, ERBS2, TSIS, APS}	SC1 = {ATMS}
0.46	0.76	SC1 = {ATMS}	SC1 = {VIIRS, CrIS, ATMS} SC2 = {Windsat, OMPS-Nadir, OMPS-Limb}	SC1 = {OMPS-Nadir}
0.46	0.76	none	SC1 = {VIIRS, CrIS, ATMS} SC2 = {CMIS, OMPS-Nadir, ERBS2, TSIS, APS}	none
0.36	0.68	none	SC1 = {VIIRS, CrIS, ATMS}	SC1 ={VIIRS, CrIS, ATMS}
0.36	0.66	SC1 = {VIIRS, CrIS, ATMS}	SC1 = {VIIRS, CrIS, ATMS}	none
0.36	0.66	none	SC1 = {VIIRS, CrIS, ATMS} SC2 = {SSMIS-U, TSIS, APS}	none
0.32	0.55	none	SC1 = {VIIRS, CrIS, ATMS} SC1 = {ERBS1, ERBS2, APS}	none
0.27	0.54	none	SC1 = {VIIRSLite-noocean, CrIS, ATMS}	SC1 = {ATMS}
0.23	0.47	none	SC1 = {VIIRS, CrIS, ATMS}	none
ATMS - CrIS Free-Flyer				
0.48	0.82	none	SC1 = {VIIRS, SSMIS-U} SC2 = {CrIS, ATMS}	SC1 = {VIIRS, OMPS-Nadir} SC2 = {ATMS}
0.35	0.63	none	SC1 = {VIIRS, SSMIS-U, ERBS2} SC2 = {ATMS, CrIS}	none
0.29	0.61	none	SC1 = {VIIRS} SC2 = {ATMS, CrIS} SC3 = {SSMIS-U}	none
0.29	0.54	none	SC1 = {VIIRSLite-ocean, APS} SC2 = {SSMIS-U} SC3 = {CrIS, ATMS}	none
0.26	0.50	none	SC1 = {VIIRSLite-ocean} SC2 = {SSMIS-U} SC3 = {CrIS, ATMS}	none
0.19	0.36	None	SC1 = {VIIRSLite-ocean} SC2 = {CrIS, ATMS}	
0.19	0.35		SC1 = {VIIRSLite-noocean} SC2 = {CrIS, ATMS}	
0.48	0.82		SC1 == {VIIRS, SSMIS-U} SC2 = {CrIS, ATMS}	SC1 = {VIIRS, OMPS-Nadir} SC2 = {ATMS}
ATMS - CrIS - VIS/NIR - OMPS Free-Flyer				
0.49	0.80	none	SC1 = {VIIRS, CrIS} SC 2 = {Windsat, ATMS, APS}	SC1 = {VIIRS, CrIS, OMPS-Nadir, ATMS}
0.25	0.48	none	SC1 = {VIIRS, CrIS, OMPS-Nadir, ATMS}	none

IV. Conclusion

The above analysis motivated several conclusions about the cost of aggregation versus disaggregation. First, we demonstrated that when complexity costs are included in a cost metric, aggregated architectures do not necessarily dominate the Pareto front. Although aggregated architectures *do* appear to consistently out-perform disaggregated architectures, semi-aggregated architectures occasionally have the potential to be less costly than aggregated ones. We also noted that for all architectures except the highest performers, disaggregating the VIS/NIR sensor from the microwave-imager sounder appeared to be an optimal trade. Finally, we used this finding to motivate a recommendation that NOAA consider architectures with a VIS/NIR, CrIS, and ATMS free-flyer and a separate spacecraft that is anchored around a microwave imager-sounder and that contains other climate-centric instruments.

There are many opportunities to refine our analysis and conclusions in the future. First, all of our conclusions are contingent on our initial assumptions and the evaluation metrics that were used. While our cost and benefit metrics were derived from detailed case studies of past programs, their accuracy could be improved through further calibration. Second, additional metrics that assess the risks inherent to both architectures could also be added; for example, disaggregated architectures may be more susceptible to launch failures (because the probability of experiencing no launch failures decreases with the number of launches) but more capable of responding to on-orbit failures (since smaller common spacecraft are more easily re-configured and used as spares). Third, the cost of aggregation and disaggregation may be contingent on the mission length, on each system's lifetime, and on the capabilities fielded by each system; future work should analyze cases other than what we considered here.

Finally, although this analysis did identify alternatives to NPOESS, JPSS, and DWSS's aggregated architectures that had the potential to reduce future lifecycle costs, we still observed that—even when we accounted for the cost of complexity—aggregated architectures still performed well with respect to the entire trade space. Thus, it seems incomplete to attribute past programs' cost growth to their systems' architectures *only*. Instead, in order to reduce the cost of future systems, we not only need to consider the technical costs derived from the system's architecture, but also the organizational costs that can be induced by the programs' management structure. A companion paper (e.g. Ref. 33) that is also presented at this conference explores these management issues in greater detail.

Appendix

This Appendix provides additional information on inputs to the benefit metric. Table 5 lists the EDRs that are assigned to each agency and categorizes them according to KPPs, Heritage EDRs, and Beyond-Heritage EDRs. Table 4 lists the cross-instrument synergies that are included in the calculation of the benefit metric.

Table 6. Cross-Instrument Synergies Contributing to Benefit Metric

Synergy Type	Synergistic Instruments	Synergy Description
Performance Enhancement	OMPS-Nadir & OMPS-Limb	OMPS-Limb increases vertical spatial resolution of ozone measurements
Performance Enhancement	VIS-NIR Imager Radiometer & APS	Aerosol data products are improved when combined with cloud data products produced by VIS-NIR imager-radiometers
Capability Enhancement	CrIS & ATMS	ATMS enhances CrIS by providing all-weather capability
Performance Enhancement	ERBS cross-track scanning & ERBS-biaxial scanning	Earth radiation budget measurements collected from cross-registered instruments with biaxial & cross-track scanning profiles increases measurement accuracy
Capability Enhancement	VIS-NIR Imager Radiometer & Microwave Imager-Sounder	Microwave imager enhances VIS-NIR imager by providing all-weather capability

Table 5. Requirements Classification Matrix

Environmental Data Record (EDR)	DoD Requirements			NOAA Requirements		
	KPPs	Heritage EDRs	Beyond Heritage EDRs	KPPs	Heritage EDRs	Beyond Heritage EDRs
Active Fires			X			X
Aerosol Optical Thickness			X			
Aerosol Particle Size					X	
Aerosol Refractive Index						X
Albedo		X			X	
Atmospheric Vertical Moisture Profile		X		X		
Atmospheric Vertical Temperature Profile		X		X		
Cloud Base Height			X			X
Cloud Cover / Layers		X			X	
Cloud Effective Particle Size		X			X	
Cloud Ice Water Path					X	
Cloud Liquid Water		X			X	
Cloud Mask			X			X
Cloud Optical Thickness					X	
Cloud Particle Distribution			X			X
Cloud Top Height		X			X	
Cloud Top Pressure					X	
Cloud Top Temperature		X			X	
Downward Longwave Radiation						X
Downward Shortwave Radiation						X
Global Sea Surface Wind Stress		X				X
Ice Surface Temperature		X			X	
Imagery	X			X		
Land Surface Temperature		X			X	
Net Heat Flux		X				
Net Solar Radiation at the Top of the Atmosphere						X
Ocean Color			X			X
Outgoing Longwave Radiation						X
Ozone Total Column / Profile			X		X	
Precipitable Water / Integrated Water Vapor		X			X	
Precipitation Type / Rate		X			X	
Pressure (Surface / Profile)		X				
Sea Ice Characterization		X			X	
Sea Surface Temperature	X				X	
Sea Surface Winds	X					X
Snow Cover / Depth		X			X	
Soil Moisture	X					X
Solar Irradiance						X
Surface Type		X				
Suspended Matter		X			X	
Total Water Content		X				
Vegetation Index			X		X	

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