THE NOAA SATELLITE OBSERVING SYSTEM ARCHITECTURE STUDY

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ABSTRACT

NOAA is conducting a study, the NOAA Satellite Observing System Architecture (NSOSA) study, to plan for the future operational environmental satellite systems that will follow GOES-R and JPSS, beginning about 2030. This is an opportunity to design a modern architecture with no pre-conceived notions regarding instruments, platforms, orbits, etc., but driven by user needs. The NSOSA study team has developed and is currently evaluating over 50 architecture alternatives, to include partner and commercial contributions that are likely to become available. The measurement objectives include both functional needs and strategic characteristics (e.g., resiliency, flexibility, responsiveness, sustainability). The study is being informed by the Space Platform Requirements Working Group (SPRWG), commissioned by NESDIS. The SPRWG has been charged with assessing new or existing user needs and is providing relative mission impacts from different candidate observing systems. The SPRWG results are serving as input to the process for new foundational (Level 0 and Level 1) requirements for the next generation of NOAA satellites that follow the GOES-R, JPSS, DSCOVR, Jason-3, and COSMIC-2 missions.

1. INTRODUCTION

Over the next few years the United States will begin operating a new generation of weather, space weather, and environmental remote sensing satellites. These include the JPSS low Earth orbit (LEO) satellites, and the GOES-R series of geostationary (GEO) satellites, as well as DSCOVR, Jason-3, and the COSMIC-2 constellation. GOES-16, the first satellite of the GOES-R series was successfully launched in November 2016 and is undergoing checkout and calibration. JPSS-1 is expected to launch later in 2017. This Program of Record (POR) will supply essential weather and environmental satellite services into the late 2020s or somewhat beyond, depending on the particular service. Given the newness of these capabilities it might seem premature that NOAA is already pursuing serious planning for the generation after these systems. But examination of the most likely lifetimes of the current generation of systems and typical development timelines for major satellite programs shows that it is far from too early. Opportunities exist to effect next generation systems within two years. If change is needed, it will be necessary to make major decisions on a similar timeframe.

The Office of Systems Architecture and Advanced Planning within NOAA/NESDIS began the NSOSA study in 2015 to determine a small set of the most cost effective space segment architectures for performing NOAA weather, space weather, and environmental remote sensing missions (excluding land mapping), beyond the POR to 2050. This architecture problem can be best thought of as identifying, and making, the early (pre-concept) decisions about future satellite systems with the largest impact on value, cost, and risk [1], [2]. One of the deliverables of the study are technology and integrated roadmaps that will inform NOAA leadership as to when some of those decisions need to be made. Candidate architectures have been developed that are designed to enable early basic decisions about allocation of functions to orbits and instrument capability.

From previous studies of weather satellite constellations, we know that value and cost are primarily determined by choice of instruments, distribution of instruments over orbits, and replenishment policies. Development risk is determined primarily by instrument technology maturity. Operational risk, primarily the risk of capability gaps or asset wastage, is determined mostly by constellation management policy. The consequence is that our definition of a next generation architecture must encompass instrument capabilities and enabling technologies, allocation to orbital platforms, and launch and replenishment policy.

NESDIS has also identified other key problem-space areas that are being addressed in the study.

- How do we design an architecture that is accepting of new commercial opportunities and observing technology while still delivering consistent information content to a broad customer base?
- How do we reconcile the need to minimize the probability of service gaps with the need to efficiently use all expensive satellite resources and rapidly bring new capabilities into operations rather than have them sitting in spare positions?
- How will the optimal balance between data gathered for exploitation by human forecasters and data assimilated into numerical models change over the next 30+ years?
- How do we balance mutually exclusive collection needs from a disparate stakeholder base, such as space weather from distant orbits like the L1 halo versus terrestrial weather from LEO?
- How do we balance the desire for flexibility to accommodate budget uncertainty against the desire to maximize efficient use of currently projected budgets?

The study is deliberately scoped to the architecture of the satellite portion of the NESDIS enterprise and excludes the ground segment. The differing timelines for decisions and implementations between space and ground segments make it acceptable to separate the studies. While separate, the cross-dependence of the satellite architecture on architectural decisions in the ground segment and in the larger weather enterprise are understood and provisions for accounting for them are in the study plan.

2. ARCHITECTURE STUDY APPROACH

The NSOSA study is organized into four major tracks built around three major investigative cycles. All tracks contribute to all cycles, and all results are consolidated into incremental products in each cycle. The four tracks are Instrument Catalog development, Environmental Data Record (EDR) Value Model development, Mission Value Model development, and Integration. Each of the cycles is referred to as a "design cycle" and each design cycle does complete, end-to-end designs of multiple alternative architectures. The work of the four tracks is supported and connected to the stakeholder community through a number of outreach efforts. The most important of these is the Space Platform Requirements Working Group (SPRWG). In addition the study will engage with a broad range of stakeholders through established forums and an advisory group.

2.1. Instrument Catalog Development

Past studies and experience have shown that the cost and performance of the instruments is the principal value and cost key to the weather and environmental satellite architecture. The role in value is obvious, the whole point of flying the satellites is to fly the instruments and collect the data they produce. The capabilities of the instruments translates directly into the capabilities of the enterprise. The cost of instruments typically drives the cost of a satellite. For typical weather satellites in current orbits, neither the cost of launch nor the cost of the satellite bus plays as large a role as the cost of instrumentation.

Because instruments play such a large role in the architecture, we have set up one major track of the study to investigate future instrument options. This task is:

- Cataloging existing and developmental instruments relevant to the NSOSA mission areas.
- Soliciting instrument concepts for the 2030 era from industry, academia, and from government laboratories.
- Selectively commissioning design studies for categories of instruments where the first two task elements yield insufficient results.

The instrument catalog development team, made up of scientists and engineers at NASA's Jet Propulsion Laboratory (JPL) and the NASA Goddard Space Flight Center (GSFC), has cataloged existing and developmental instruments relevant to the NSOSA study. They solicited instrument concepts for the 2030 epoch from industry, academia, and government laboratories and, when necessary, selectively conducted design studies for categories of instruments where needed (e.g. real time regional imagery, three-dimensional wind profiles, etc.). The team identified likely capability-size-cost relationships for "generic" instruments relevant to missions that can be flown starting circa 2030 rather than to select a particular instrument concept for the next generation of weather satellites. Choosing a specific instrument is a task for later, after completion of the NSOSA study, when we initiate pre-program formulation activities. Where those capability-cost-size relationships become key to favorable architectures, the study team uses this information to develop technology roadmaps that will identify recommended investments in sensor technology and concept development over the next few years.

2.2. EDR Value Model Development

2.2.1 EDR Model Overview

The heart of problem-space analysis in an architecture study is development of a value model. The NSOSA study team has developed two distinct value models, for reasons to be described. The NSOSA study needed a value model that is much more than collection of projected requirements or user needs that can, or can't, be satisfied by a constellation alternative. The ground rules of the study required that we be able to assess alternatives over a tradeable range that includes, but is not limited to, the projected long-term budget constraint.

The value model developed for this study encompasses a number of possibly contradictory constraints.

- The model needed to be of sufficient fidelity such that we can trust its results in making important strategic investment decisions. The fidelity needed to be incrementally tested and demonstrated through the design cycles.
- The model needs to be of controlled complexity such that NOAA decision makers can understand the underlying rationale for relative value results and such that the model can be evaluated for 10's of alternative architectures. The model needed to be amenable to significant automation in scoring and assessment.
- The model had to be flexible enough to allow for the assessment of architecture alternatives that were similar to and substantially different from today's architecture.

Based on these constraints, the NSOSA team developed two, interrelated value models. The first, the EDR Value Model (EVM) is based on technical measures applied at a generic sensor level. The EDRs that are the subject of most of the objectives in the EVM are generics or representative of classes of existing specific EDRs. This model defines a set of objectives spanning EDR delivery, user communication services (e.g., data rebroadcast, sensor data collection), and strategic priorities. Each has a measurement scale with determined lower and upper bounds. Alternatives with performance within the bounds are in the "tradeable range" and are comparatively rated. The study team works closely with the SPRWG in building this model. The second, based on a pre-existing set of mission satisfaction metrics, is known as the Mission Value Model (MVM). The two models are used in different phases and to cross-check each other.

2.2.2 SPRWG and Its Role

A fact-of-life in this study is that there is no shortage of user-needs, both legacy and emerging. We have a large body of legacy requirements that span from the sensor level through EDRs to missions, all of which correspond to established user needs. In addition, all stakeholders can easily think of a wide range of improvements they would like to see in data quality and variety, and can often clearly articulate the mission benefits that might accrue if the data or service could be so improved. In addition to established user needs, there are well recognized needs that are not currently being filled. Finally, the continuing progress in key mission areas, such as numerical weather forecasting, leads to increased demands for particular data types, improved resolution, and faster data delivery. Our problem was much less to identify user needs than it has been to 1) organize and prioritize them, and 2) understand the impact of specific observing system capabilities to a range of user needs and to the broader user community overall. One element that was missing at the onset of the study was a clear understanding of what changes in the mission space are essentially certain by the 2030s along with what changes are possible but far from certain, and how either type of change will drive, or be driven by, the data available from satellites.

The SPRWG has been set up to manage the interface between stakeholders (widely represented on the SPRWG) and the architecture study team. The SPRWG determined the details of the tradeable range in the EVM where they projected out the mission concepts of operations out to 2030. They assessed where changes to how missions are conducted (e.g. NWP, human forecasting, etc.) will be reflected in data quality attributes. For each objective and each attribute of those objectives, the SPRWG determined three levels of capability: Study Threshold, Expected, and Maximum Effective. The Study Threshold level is the minimum capability of an objective or attribute that will allow a mission to continue (even in a degraded state); below that level, the mission will fail. The Expected level is what the SPRWG determined to be the most likely capability in the 2030 time frame based on user needs and technology evolution. The Maximum Effective level is where the SPRWG determined that there was no cost-benefit of making further improvements. Finally, the SPRWG developed the set of scoring weights and priorities of objectives within objective classes (terrestrial/ocean measurements, space weather measurements, and strategic objectives). NOAA leadership determined the final ranking and the interleaving of the objectives from the different classes into one single list.

2.3. Mission Value Model Development

Ideally, we would have a value model that would allow assessment of alternative architectures directly in terms of 2030 era mission metrics and that could be used in all phases of the study process, as it is important to maintain a clear linkage between the technical performance of future alternative architectures and the missions of national and international importance that they support.

The approach being taken is that we are building in parallel to the EVM a 2030 era mission value model based on the established NOSIA-II [3] effort within NOAA. This model takes as input the technical performance values determined in the EVM assessment. Hence the two models are linked and can be used to cross-check each other for consistency. Of particular importance, the NOSIA-II model has a full vetted mission model that maps out approximately 20 Mission Service Areas, within all of the NOAA services, served by hundreds of discrete data products. This provides an essential overall map allowing identification of the most important sensor data records that play the driving role in multiple mission areas. The NOSIA-II model also allows assessment of the relative efficiency of meeting a mission need from a space or ground asset, and so helps identify the most appropriate areas for space observation.

During the early stages of the study the team used a preliminary version of the MVM based on the legacy NOSIA-II model. Subsequently, the team has solicited users and researchers for likely evolution by 2030 of the elements of the NOSIA-II model to update its target time from the present to 2030. The EVM is used as the primary screening tool in the design cycles with the preliminary MVM used to cross-check results. The MVM results illuminated areas of disconnect between the two models that are being repaired or ameliorated in the final design cycle. The MVM will allow full assessment of alternative architectures against the mission set before study completion.

2.4. Integration (and Design) Task

The central element of the study is the generation and assessment of architecture alternatives. For the purposes of this study an architecture is a definition of a set of functions, a set of physical assets (instruments and their allocation to platforms assigned to specific orbits) assigned to those functions, a concept of operations that shows how the physical assets are employed in time sequence to meet a defined mission, and a set of rules (including policies, standards, protocols and constraints) by which the platforms populate and sustain the resulting constellation.

We analyzed over 50 different satellite architectures ranging from the continuation of the current combination of instruments and orbits to radical alternatives that utilize emerging satellite technology and commercial capability. Each architecture's capability was assessed against the EVM and, in some stages, the MVM. Overall satellite and constellations costs were developed by analyzing the individual satellite configurations included in the constellation and the construction, storage, and expected launch cadence determined by the objectives of each constellation. This required both the integration of the previously described tasks as well as constellation design and constellation policy development. In addition, there were a number of important study tasks (e.g., industry Request for Information evaluation, formal architecture description writing, etc.) that are logically assigned to the same team. We refer to this team as the "Integration Team" which was made up of scientists and engineers from NASA's Jet Propulsion Laboratory (JPL), the Johns Hopkins University Applied Physics Laboratory, the Massachusetts Institute of Technology Lincoln Labs, and the Aerospace Corporation.

While there are many subtasks within the integration task, the Integration Team executed several particularly complex and important tasks.

1. Constellation design where we synthesized and examined the various alternative orbital configurations. The constellations were grouped into four broad categories: Legacy Continuation, Augmentations to Legacy Continuation, Enhanced Legacy Variants, and significant departures

from legacy that included All-Medium Earth Orbit where we used an approach modeled on GPS, and All-LEO where we looked at the potential of large swarms of small satellites. We also have considered substantial instrument hosting and commercial data purchases.

2. Constellation policy design, with particular attention to more complex policies using launch-on-need and event-driven orbit adaptation.
3. Constellation level cost analysis, including the impacts of different production levels and use of block design and acquisition.
4. The actual design of satellites given instruments and constellations. This is critical to costing, but must be done in a very rapid and lightweight fashion. The NSOSA team utilized the Aerospace Corporation's Concept Design Center capability for this [4], [5].
5. The assembly of technology and integrated roadmaps where a funding and execution timeline are developed to clearly indicate to NOAA leadership the cost and schedule required to improve and mature certain instrument technologies and to lay out an overarching plan for establishing a program or programs of satellite development and delivery to orbit.

2.5. Design Cycles

The overall process is organized as a series of design cycles. The organization of an architecture study as a series of relatively short end-to-end design cycles has a long history. Rapid turn design cycles are used in civil architecture and urban planning as well as large software projects and major US DoD architecture efforts [6, 7]. There are many advantages to this organization. Probably the most important is that it allows for information that can only be learned in the later phases of integrating a complex design to be fed back into a subsequent cycle. We have experienced this directly when certain architectural decisions in earlier cycles needed to be adjusted in later phases of the study. For example, it was found that the scoring weights applied to certain objectives needed to be adjusted to better match the intentions of NOAA leadership. Furthermore, it is through these design cycles that we have been able to evaluate the impact of different architectures on the ground system requirements and capabilities. In some constellations there were no impacts to the ground system whereas others required substantial changes to ground system hardware, software, and CONOPS.

3. CONCLUSIONS

The NSOSA study is still underway so any elaborating on any conclusions of future satellite architectures would be premature. Based on the preliminary results of initial design cycles, we have found it very challenging to balance all mission and programmatic objectives. This study, and previous work, suggests that there are two key elements to providing improved system performance within budget caps. First is the ability to apply technology developments to create new instrument concepts within a reasonable cost and development schedule. Second is to develop more responsive constellation management approaches to simultaneously improve fault tolerance and efficient use of space assets. We are examining constellation alternatives without pre-conceived notions of instrument approaches, assignment to orbits, or approaches to constellation management.

4. REFERENCES

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