Architecting the Future of Weather Satellites

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ABSTRACT: Between 2014 and 2018, the NOAA Office of Systems Architecture and Advanced Planning (OSAAP) conducted the NOAA Satellite Observing System Architecture (NSOSA) study to plan the long-term future of the NOAA constellation of operational environmental satellites. This constellation of satellites (which may include space capabilities acquired in lieu of U.S. government satellites) will follow the current GOES-R and JPSS satellite programs, beginning about 2030. This was an opportunity to design a modern architecture with no preconceived notions regarding instruments, platforms, orbits, etc., but driven by user needs, new technology, and exploiting emerging space business models. In this paper we describe how the study was structured, review major results, show how observation priorities and estimated costs drove next-generation choices, and discuss important challenges for implementing the next generation of U.S. civil environmental remote sensing satellites.

KEYWORDS: Remote sensing; Satellite observations; Sensitivity studies

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Since the 1970s, NOAA has flown satellites focused principally, but not exclusively, on providing data to the National Weather Service. The primary mission of these satellites is operational environmental monitoring in support of both terrestrial and space weather forecasting. Different from NASA satellites, for which the primary mission typically is research, they form part of an international system of systems (Davis 2007; Hall 2001; Rao et al. 1990; Lautenbacher 2006). NOAA's primary satellites have been the GOES series at geostationary orbit and the POES series, followed by the Joint Polar Satellite System (JPSS) series, in polar orbit. To give a sense of scale and time, the current GOES-R program has a life cycle cost estimate of US\$10.8 billion (NASA 2018) covering four satellites and associated ground systems. It will provide service from 2017 to approximately 2034 (NOAA 2018). The JPSS program has a similar life cycle cost and timeline. Given typical U.S. federal government acquisition timelines for major space systems, acquisition programs for replacement capabilities need to begin no later than the early 2020s.

In 2013, the Office of Systems Architecture and Advanced Planning (OSAAP) within NOAA/NESDIS was tasked to baseline the existing satellite architecture and to initiate a study of the satellites to come after the current generation. An original impetus for the study was from NOAA/NESDIS Independent Review Team (IRT) reports (IRT 2012). IRT and other analyses of satellite fly-out timelines showed near-term action was required, as new satellites could be needed in 2028–30.

The NOAA Satellite Observing System Architecture (NSOSA) study began with preliminary explorations in 2014 and became a formal study with multi-agency participation in 2015. Upon its completion in 2018, NSOSA work transitioned to implementation activities. The study is responsive to congressional direction, as outlined in the Weather Research and Forecasting Innovation Act of 2017 (Pub. L. No. 115-25, H.R. 353), to baseline the planned satellite architecture and provide planning guidance for the next generation.

The NSOSA study template (Di Pietro 2015), was extended with methods and tools commonly applied to large systems (Crawley et al. 2015; Sanchez et al. 2013; Maier 2009; Abbas 2018), though not applied until now to weather systems. The study was structured around a series of design cycles of variable length, following guidance in the literature (Crawley et al. 2015; Maier 2009; Di Pietro 2015; ISO 2011, 2018). Each cycle included design and costing of tens of alternative satellite constellations, the assessment of those constellations against a value model, and evaluation of the long-term costs of sustaining those constellations. The results from each cycle informed the subsequent cycle, with particular attention on identifying how to improve the cost–benefit of each approach.

Study scope and terms of reference. The terms of reference (TOR) defined the study goal:

Determine the most cost-effective space segment architectures for performing NOAA weather, space weather, and environmental remote sensing missions (excluding land mapping), beyond the Program of Record (POR) to 2050. Architecture alternatives should be compatible with an estimated annual capped NESDIS top line budget.

The POR was the currently funded NOAA baseline of satellite systems, plus agreed-upon national and international partner contributions used for sustained operational purposes. NOAA elements of the POR had termination dates representing their likely operational lifetimes, and hence their windows for replacement or substitution. Non-NOAA elements of the POR were assumed to have continuity throughout the analysis period. The analysis period extended to 2050 to model steady-state performance and sustainment costs, though no individual program would have extended that far. The satellite configuration in the year 2025 is referred to as the POR2025 (Table 1). The performance of the POR2025 is used frequently as a reference point in the study. POR2025 represents full operational capability from systems currently being acquired.

While NASA satellite data often are operationally useful and assimilated into operational numerical weather prediction models, that is not assumed in this study and so NASA satellites are not part of the POR. However, the technology developed for NASA satellites was considered available for incorporation into future systems.

The study was deliberately scoped to the architecture of the satellite portion of the NESDIS enterprise and excluded the ground segment. Differing timelines for decisions and implementations between space and ground segments, and between space and ground architecture studies, made this acceptable. Provisions for accounting for cross dependence between the space and ground architecture studies were incorporated into the study plan.

Strategic issues. In addition, NOAA/NESDIS leadership identified strategic issues:

- Is the current satellite architecture (a combination of U.S. government–owned, dedicated GEO and LEO satellites plus international partnerships) the most cost-effective means to provide essential operational functions? If not, what would a more cost-effective constellation look like? Would it be physically different or involve different business arrangements?
- Are there capabilities not in the POR that would likely provide better cost-effectiveness than capabilities in the POR? Are there low-cost-effectiveness capabilities in the POR?

Table 1. Program of Record (POR) definition.

POR component	POR2025	Study assumed long-term availability
GOES-R series	Two in operation, one on-orbit spare, Western Hemisphere GEO locations	Availability degrades unacceptably by 2033, continuation part of study scope
Meteosat Third Generation	One imaging and one sounding, GEO location over Europe	Availability to end of analysis period assumed (2050) through additional units
Himawari	One in GEO location over western Pacific	Availability to end of analysis period assumed (2050) through additional units
GEO-KOMPSAT	One in GEO location over western Pacific	Availability to end of analysis period assumed (2050) through additional units
JPSS series	One in LEO sun–synchronous 1330 LTAN orbit, one available as backup	Availability degrades unacceptably by 2038, continuation part of study scope
EPS-SG	One of each type (A and B version) in LEO sun–synchronous 0930 LTAN orbit	Availability to end of analysis period assumed (2050) through additional units
COSMIC-2 GNSS-RO capability	COSMIC-2 equivalent, LEO	No availability past 2028, continuation part of study scope, possible commercial capability assumed available by 2028
Ocean altimetry (<i>Jason-3</i> and equivalent)	<i>Jason-3</i> in repeat track LEO	Availability to end of analysis period assumed (2050) through additional units
In situ and coronagraph space weather observations from Earth–sun L1 point	Space Weather Follow-On (SWFO)	No availability past 2028, continuation part of study scope
Synthetic aperture radar	RADARSAT Constellation Mission, LEO	Availability to end of analysis period assumed (2050) through additional units

- How do we reconcile the need to minimize the probability of service gaps with the desire to efficiently use satellite resources and rapidly bring new capabilities into operations?
- How do we effectively exploit new commercial space capabilities without introducing unacceptable risks into the availability of critical data?
- How do we design a system that is accepting of new observing technology while still delivering consistent information content to a broad user base?

Study technical approach. An architecture can be thought of as the set of decisions with the largest impact on value, cost, and risk (Crawley et al. 2015; NRC 2008) for the systems of interest. The intent is the decisions will flow into concept design phase work on the component systems (satellite programs, in the NSOSA case) (NRC 2008; Di Pietro 2015). In the NSOSA study, the architectural questions were as follows:

- The current constellation supports a concept of operations (CONOPS) that includes both providing data to numerical weather prediction (NWP) models and to human forecasters for their operations. Should that overall CONOPS be maintained or should it undergo substantial change?
- What performance level (above or below POR2025) should we aim for on functions currently provided by NOAA systems?
- What environmental remote sensing functions not provided by current NOAA systems should we add, and at what performance level?
- To what orbit (e.g., geostationary, polar sun-synchronous, or some other) should each function be allocated?
- What acquisition approach (U.S. government–owned satellites, partnerships, hosted payloads, or commercial data/service buy) should be used for each function? What demonstration process, if any, should be used when acquiring new capabilities?
- What is the time-sequenced road map by which new capabilities are developed and acquired, and how does that integrate with the programmed fly-out of POR capabilities?

The NSOSA study addressed these questions by carrying out design cycles composed of seven process steps (Fig. 1):

- 1) value model development,
- 2) instrument catalog development,
- 3) constellation alternative synthesis,
- 4) design and cost alternatives,
- 5) score alternatives,
- 6) integration,
- 7) review/assess/revise.

The NSOSA study went through five full cycles of the process in Fig. 1, developing and assessing constellation designs in each cycle. The results of each cycle were used to influence the following cycle and concentrate attention on approaches with demonstrated superior performance, or to explore alternatives that had been left unexamined. Details of the methods and tools for each step are described in the appendix.

Key results and analysis

Efficient frontier analysis. A standard approach to visualize trades in a complex design space is to use an efficient frontier plot (e.g., chapter 15 of Crawley et al. 2015). In an efficient frontier plot, each point represents a design alternative. The horizontal axis position is the cost

and the vertical position is a value. The value, or score, comes from a value model. Figs. 2–4 are examples of efficient frontier plots. Each figure shows all of the constellation alternatives studied as a numbered dot. All figures use average annual cost (AAC) as the cost metric. AAC is the average cost per year, from the present day to 2050, to maintain the constellation at the computed level of performance. AAC represents the long-term cost of sustaining a given level capability, not just the incremental cost of the next acquisition program.

The AAC used is a relative cost, the actual AAC in constant dollars divided by the AAC of a reference constellation (constellation 13), also in constant dollars. The reference constellation is similar to the POR. It includes NOAA costs only. The differences between the current POR and the reference constellation are that all NSOSA constellations must have normalized availability to 2050 (effecting long-term production and launch rates), sustained radio occultation (RO) capabilities, and a sustained presence at the Earth–sun Lagrange One (L1) point. The POR has individual RO and L1 missions, but not a sustained capability, and does not have production or launch past the current programs.

The value metric plotted (the y axis) varies from figure to figure, but the constellations plotted remain the same. In Fig. 2 the value is a composite over all Environmental Data Record (EDR) Value Model (EVM) objectives (see appendix; Anthes et al. 2019), including strategic as well as observational objectives. In Fig. 3 the y-axis value is only over the space weather observation objectives. In Fig. 4 the y-axis value is only over the terrestrial weather observation objectives. The choice of value model subset is used to illustrate different aspects of the results. In some figures the axes ranges have been truncated to better illustrate specific features.

The “efficient frontier” is the upper-left edge of the point cloud in each of these figures, technically the convex hull of the point cloud. The curve of the efficient frontier is the highest value achievable for a given cost. Beginning with Fig. 2, there are two key observations. First, constellation 141 (C141) has the highest value score. Second, value does not increase at costs above that of C141 in Fig. 2, but value does keep increasing with increasing cost in Fig. 4. The reason is that in Fig. 2 the value metric includes strategic

Fig. 1. NSOSA analysis: seven process steps used in each design cycle.

Fig. 2. NSOSA base efficient frontier chart evaluated with *all EVM objectives*. Each numbered point is a constellation alternative. The two horizontal lines are the value model scores for the POR2025 and the POR as it was in the year 2013. This figure shows the full set of constellation alternative results.

objectives, which include “adherence to a level budget profile.” High-cost constellations are penalized even as they have functional performance scores that increase. Compare this to Fig. 4 where the value plotted contains only the terrestrial weather observation objectives. Value continues to increase with greater cost since higher cost buys continuously increasing observation capabilities, and the penalty for cost above the level budget profile comes only from strategic objectives. Note also in Figs. 2 and 4 that C141 is very cost efficient, as value drops rapidly as cost decreases below the C141 AAC.

This does not mean constellation 141 in all of its details should be selected as the future choice. First, there is a close cluster of alternatives with cost and performance close to that of C141. Value and cost estimates are uncertain, and no practical value model captures all relevant stakeholder concerns. Other close performers might represent a preferred basket of risks and benefits when all factors are considered. Second, there is no assurance of a specific future budget, and NOAA cannot select a complete future constellation alternative at this point. A robust choice should perform on, or close to, the efficient frontier for a range of AAC. C141 is an example of the “hybrid architecture” that was ultimately favored and is described in the “Recommended architecture and conclusions” section.

As an elaboration, and to provide examples, we have highlighted three constellations in Fig. 4 (all three appear in all of Figs. 2–4, but they are most visible in Fig. 4). The three constellations are C141 (a hybrid case on the efficient frontier), C51 (a heavily augmented legacy continuation case showing what could be achieved with sufficient budget), and C66 (a less augmented legacy case with cost similar to C141 but much lower value score). The elements of the three constellations are shown in Table 3. For each element, one type of satellite produced in blocks and flown at a rate to achieve a desired availability, we list the instruments assigned. The terms “low-end,” “nominal,” and “high-end” refer to the instrument’s performance level. Being specific, note that for GEO platform 1 the first instrument listed for C141 and C51 is “high-end imager–sounder.” This instrument is the instrument listed in the last column of Table 2. The first instrument listed for C66, “nominal imager,” corresponds to the middle column of Table 2. The first instrument listed for GEO platform 2 on C141 in Table 3, “low-end imager,” corresponds to the first column instrument in Table 2. Thus, C141 uses a mixture of imaging instrument capabilities in GEO; C51 and C66 have uniform capability. Throughout the remainder of Table 3 an instrument prefaced by “low-end” corresponds to the lower-performance instrument in the instrument catalog targeted at the study threshold (ST) performance level, “high-end” corresponds to the maximum effective target instrument in the instrument catalog, and “nominal” to the expected performance level instrument. The default is “nominal,” so with no preface it means the nominal performance case was selected.

Given the very high capabilities in C51 it is obvious why its score (on Group A objectives) is highest, though its costs are also highest. The composite score of C51 versus C141 in Fig. 2

Fig. 3. Efficient frontier plot evaluated against *only space weather-related objectives*. The alternatives in the blue circle all have off-Earth–sun-axis observation capabilities, the alternatives in the red circle do not. The positive effect of one capability (off-axis sensing) is clearly evident.

shows no overall net benefit because of decrements on strategic objectives associated with violating annual cost ceilings. Everything included in C51 carries real value, but affordability is an essential constraint. The value differences between C66 and C141 illustrates the impact of key assumptions on data value and the role of data from international partnerships. C141 does not maintain continuity of some observations in the POR, such as imaging from the 1330 local time ascending node (LTAN) sun-synchronous orbit, while C66 does. C141 takes only small value decrements for these differences because the higher performance of future partner systems, such as the European Polar Satellite–Second Generation (EPS-SG) largely makes up for those deficits. The budget headroom freed by those choices allows investment in other capabilities, like selectively enhanced GEO imaging and proliferated microwave (MW) and IR measurements that are not matched in C66, which is more focused on legacy continuity. Within the framework of the NSOSA value model these choices are clearly cost effective, illustrating the key importance of identifying such value choices.

Fig. 4. Efficient frontier plot scored for *terrestrial weather-related observational objectives only*, for all alternatives studied. Radical alternatives are shown in the red circles. Large constellations are not close to the efficient frontier, even with unrealistic assumptions about large-scale hosting (circled alternative 47 in the large cluster).

Order-of-buy analysis. The efficient frontier chart identifies the most cost-efficient alternatives; however, each constellation alternative in Fig. 2 is a tiny subset of the alternatives that could be generated. Each alternative in Fig. 2 could be varied by changing flight rates (and thus assurance levels and cost), by adding, subtracting, upgrading, or downgrading any instrument, and by making other small variations. Local variations in design are properly the responsibility of the acquisition programs that will implement the selected architecture in the future. The study searched for design choices with consistent large cost–benefit impact. High and low cost–benefit variations are used to generate superior constellation alternatives and identify architecture alternatives that best accommodate them. This process generates an “order-of-buy list,” a quantitative version of the value-focused thinking approach (Keeney 1996).

Consider Fig. 3, where the value model is restricted to the 19 space weather objectives. While there is an efficient frontier in Fig. 3, the striking feature is the two separated groups. The group of alternatives in the blue circle has observation capabilities off the Earth–sun axis (e.g., at the Earth–sun L5 point). The group in the red circle does not. The cost–benefit

Table 2. GEO Vis/IR GEO weather imager reference concepts.

	Low-end performance case, targeted at ST	Nominal performance case, targeted at EXP	High-end performance case, targeted at ME
Resolution (km)	2–4 (IR), 1 (Vis), 0.5 (Pan)	2 (IR), 1 (Vis), 0.5 (Pan)	1 (IR), 0.3 (Vis), 0.3 (Pan), 0.75 (day–night band, DNB)
Full-disk update rate (min)	15	10	5
Mesoscale update rate (s)	10	30	15
Mesoscale regions	1	2	5
Wavelength range (μm)	0.47–11	0.47–13.35	0.40–13.7
Radiometric accuracy (K)	0.1	0.1	0.05
Number of bands	16	16	157 including DNB
Mass (kg)	170	275	477
Power (W)	350	450	630
Data rate (Mbps)	30	30	4,700
Relative cost	0.7	1	1.5
Sourcing	GEO Multispectral Mapper (GEMM) proposal	ABI and upgrade studies	NSOSA studies and industry input

impact of the off-axis capabilities is strikingly positive and is justified at almost any cost level. Off-Earth–sun-axis solar observation capabilities have very positive cost–benefit ratio and appear high on the order-of-buy list.

Given a matched pair of alternatives, one in the red circle in Fig. 3, the other in the blue circle, differing only in the off-axis observation capabilities in one member, we can compute a quantitative “delta value score” versus “delta cost” for that matched pair due to the off-axis observation capability. Dividing the two deltas is the change in value that can be bought for a fixed increment of cost. The NSOSA study did this analysis for a wide range of capabilities. Rarely were the results as simple and as applicable across a wide budget range as they are in Fig. 3, but they drove several more general conclusions:

- *Partial disaggregation and availability:* Increased flight rate and redundancy score highly in the EVM for the subset of capabilities with very demanding availability objectives (global sounding and real-time regional imaging). Alternatives that can selectively buy high availability for this subset of capabilities are cost efficient. Partially disaggregated LEO constellations can exploit this by separating sounding from other capabilities in disaggregated satellites and using different flight rates.
- *Value of legacy capabilities:* Some legacy capabilities are less cost effective than certain new capabilities. For example, lightning mapping and geostationary infrared sounding were lower on the order-of-buy list than global 3D winds and enhancements to ocean surface vector winds.
- *Satellite proliferation:* With the exception of Global Navigation Satellite System Radio Occultation (GNSS-RO), there were no capabilities where it was found to be cost effective to proliferate over a large constellation (>10 satellites) of small satellites. Most of the value of global update rates in the EVM is reached by the time a constellation has five well-placed LEO satellites, making larger constellation not cost effective.
- *Number of orbits:* Increasing the number of orbits that provide global capabilities, and thus improving the update rate, is cost effective, though typically only for increases in the one to three orbit range. For example, increasing microwave soundings and ocean surface vector winds above the POR baseline of two and one orbits, respectively, to between three and five orbits each is relatively high on the order-of-buy list.

- *High-altitude, high-inclination orbits:* Constellations near the efficient frontier at high budget levels all have a high-inclination orbit component providing real-time weather imaging of Alaska and the Arctic and other global real-time observations. The study found

Table 3. Example composition of three constellations.

		C141	C51	C66
Architecture type		Hybrid	Legacy Augmented	Legacy Augmented
GEO platform 1	Type	U.S. government (govt.) satellite	U.S. govt. satellite	U.S. govt. satellite
	Number	1 + residual	2 + residual	2 + residual
	Instruments	High-end imager–sounder	High-end imager–sounder	Nominal imager
		Lightning mapper	High-end lightning mapper	Lightning mapper
		In situ space weather (SWx)	In situ SWx	In situ SWx
				Coronagraph
				X-ray imager
				UV imager
				In situ SWx
GEO platform 2	Type	Hosted imagers	U.S. govt. satellite	Hosted payload
	Number	2 + residual	1 + residual	1 + residual
	Instruments	Low-end imager	High-end IR sounder	Instrument of opportunity
			Nominal MW sounder	
			In situ SWx	
GEO platform 3	Type	U.S. govt. satellite, bus sharing	U.S. govt. satellite, bus sharing	
	Number	2 + residual	2 + residual	
	Instruments	Coronagraph	Coronagraph	
		X-ray imager	X-ray imager	
		UV imager	UV imager	
		Photospheric imager	Photospheric imager	
		Heliospheric imager	Heliospheric imager	
		In situ SWx	In situ SWx	
	Special Features	Shared production for L5	Shared production for L5	
LEO platform 1	Type	U.S. govt. satellite	U.S. govt. satellite	U.S. govt. satellite
	Number	3 + residual	3 + residual	3 + residual
	Instruments	Day–night imager	Low-end IR sounder	Low-end IR sounder
		Nominal IR sounder	Nominal MW sounder	Nominal MW sounder
		Nominal MW sounder	Low-end passive MW ocean surface wind vector (OSVW)	Low-end passive MW OSVW
		Nominal MW imager (with passive OSVW)	GNSS-radio occultation (RO)	GNSS-RO
		GNSS-RO	SWx in situ	SWx in situ
		Selected SWx capabilities		
	Special Features	Dynamic placement in 1330 or 0530 LTAN sun synchronous or non–sun synchronous	Dynamic placement in 1330 and 0530 LTAN sun synchronous or non–sun synchronous	Dynamic placement in 1330 and 0530 LTAN sun synchronous or non–sun synchronous
LEO platform 2	Type	U.S. govt. satellite	U.S. govt. satellite	U.S. govt. satellite
	Number	1 + residual	1 + residual	1 + residual
	Instruments	Wind lidar	Wind lidar	Wind lidar
		GNSS-RO	GNSS-RO	GNSS-RO
		In situ SWx	In situ SWx	In situ SWx
		Instruments of opportunity	Instruments of opportunity	Instruments of opportunity

Table 3. (Continued).

		C141	C51	C66
Architecture type		Hybrid	Legacy Augmented	Legacy Augmented
LEO platform 3	Type		U.S. govt. satellite	U.S. govt. satellite
	Number		1 + residual (1330 LTAN orbit)	1 + residual (1330 LTAN orbit)
	Instruments		High-end EO/IR imager– sounder	Nominal imager
			GNSS-RO	Nominal IR sounder
			In situ SWx	ATMS-class MW sounder
			Instruments of opportunity	Ozone sensor
				GNSS-RO
				Instrument of opportunity
				In situ SWx
	Special features			Maneuver reserve fuel
LEO platform 4	Type		U.S. govt. satellite	
	Number		1 + residual (1330 LTAN orbit)	
	Instruments		High-end MW sounder	
			High-end MW imager	
			High-end precipitation radar	
Tundra platform 1	Type		U.S. govt. satellite	
	Number		2 + residual	
	Instruments		Low-end imager	
			In situ SWx	
			Auroral imager	
Solar platform 1	Type	U.S. govt. satellite	U.S. govt. satellite	U.S. govt. satellite
	Number	1 + residual (L1)	4 + residual (L1 and diamond)	1 + residual (L1)
	Instruments	In situ SWx	In situ SWx	In situ SWx
Solar platform 2	Type	U.S. govt. satellite	U.S. govt. satellite	
	Number	1 + residual (L5)	1 + residual (L5)	
	Instruments	Coronagraph	Coronagraph	
		X-ray imager	X-ray imager	
		UV imager	UV imager	
		Photospheric imager	Photospheric imager	
		Heliospheric imager	Heliospheric imager	
		In situ SWx	In situ SWx	
	Special features	Shared production with GEO SWx	Shared production with GEO SWx	

Tundra orbits (24 h, 90° or 63° inclined orbits) were the favored choice, although a number of high-inclination orbits have been studied for environmental remote sensing missions (Trishchenko et al. 2016).

Radical alternative assessment. A key concern of NOAA decision-makers was the cost effectiveness of radical alternatives, where such alternatives are defined as large changes to the assignment of functions to orbits relative to the legacy choices. A typical radical alternative is to eliminate GEO weather satellites and use only a large fleet of small LEO satellites. The fleet would have to be large enough to provide real-time weather imagery at least minimally consistent with ST-level performance defined in the EVM for regional real-time weather imaging

(and several other real-time functions). This effectively requires coverage of CONUS with an update rate faster than 5 min, and preferably faster than 1 min, a very demanding requirement that requires a large constellation. Fusing the observations from large constellations also poses significant complexities in calibration of multiple instruments, handling moving points of view, varying atmospheric propagation paths, and communication networking.

Figure 4 highlights the position of radical alternatives relative to legacy continuation, augmentation, and hybrid approaches. As discussed in greater depth in Maier (2018), the radical alternatives are not competitive with legacy continuation or augmented legacy continuation constellations. The noncompetitiveness is not just a consequence of the configurations chosen, it reflects fundamental characteristics of the value model and the structure of international agreements on environmental data. Some key findings are as follows:

- *Large uniform LEO or MEO constellations:* A large, uniform constellation, whether in LEO or MEO, sized to meet minimum NOAA needs for regional real-time observations will greatly overproduce global observations relative to NOAA needs. NOAA's global real-time needs are largely satisfied at low cost through international data sharing agreements.
- *Large constellation costs:* Large constellations have lower unit costs due to larger production volumes, but higher total costs because the numbers of payloads and satellites rises faster than unit costs come down in larger-scale production. For these radical alternative cases, more than one satellite was assumed manifested per launch vehicle. Environmental remote sensing instruments in LEO are somewhat less expensive than those designed for GEO, but not enough to offset the increased numbers. Demanding spectral coverage and radiometric accuracy requirements drive costs regardless of whether instruments are in GEO or LEO. This is in contrast to communication constellations where the cost of payloads drops much more quickly as the communication distance falls from GEO to LEO distances.
- *Microwave measurements:* MW measurements essential for environmental remote sensing are difficult and expensive to do from higher orbits (whether MEO or GEO). The all-MEO concepts either require very complex microwave sensors or need a LEO add-on to provide microwave sensors at better economies of scale.
- *GNSS-RO:* GNSS-RO measurements map efficiently to large constellations of LEO satellites and are effective supplements to IR and MW soundings, but are not substitutes for them. GNSS-RO does not eliminate the need for other observations.

It is important to understand what changes to assumptions might change the conclusions. In this case, the key assumptions are 1) NOAA is willing to rely on close international partners to fulfill requirements for global real-time weather imaging, and 2) NOAA and its international partners will not fully converge their programs into a single global constellation. Both assumptions are stable under current and projected political environments. NOAA and its international partners coordinate their programs, sometimes share instruments, and work toward a common vision, but this is short of convergence to a single global constellation.

Cost distribution analysis. Costs of environmental remote sensing satellites generally are dominated by the cost of the payloads (the instruments) rather than the costs of the satellite buses or the launch vehicles. Figure 5 shows typical distributions for representative cases based on models used in the study. The three graphs show the cost fractions across payloads, satellite bus, flight software, and launch. All three are for a production block of four satellites, and all indirect (e.g., systems engineering, system test, program management) costs have been ascribed to the segment in proportion to the direct cost. The first is for a GEO satellite of complexity comparable to a GOES. The second is for a small, relatively simple LEO satellite, one with ~150 kg of payload. For example, a future satellite that carried only lower-mass

advanced sounders and no imager or a new imager but no sounders. This case applies to the partially disaggregated constellation components discussed in the “Recommended architecture and conclusions” section, not the large all-LEO constellations discussed in the “Radical alternative assessment” section above. The last is for a typically larger, comprehensive LEO environmental remote sensing satellite (similar to JPSS). All three are based on satellites modeled in the Concept Design Center–System Architecture Team (CDC-SAT, described in the appendix) for this study, not specific current satellites.

Payloads account for 40%–60% of space segment costs in these cases. In the small-satellite case the launch costs are probably unrealistically high as they assume a single launch vehicle is devoted to the satellite (except, as noted above, for the radical alter-

native all-LEO cases where many satellites were carried per launch), which results in a large amount of wasted launch mass. Such launches would most likely be shared between multiple satellite missions, but the degree of such sharing is not possible to predict in advance.

The consequence of high payload cost fractions is minimizing the number of launches or satellite buses is not very important to cost control, but matching payload capability and numbers to the need is very important. For example, in the discussion previously on why proliferated LEO and MEO constellations performed poorly, a central issue is that they gain value from proliferating sensors, but the sensors are expensive. A constellation with a large number of imagers cannot use lower-quality imaging than a constellation with fewer imagers, and the same largely applies with sounders and other instruments.

Major constellation architecture alternatives considered. The architecture of a satellite constellation is largely defined by a set of decisions about allocation of functions to orbits, target performance points, and the business model by which the satellites are acquired. For example, legacy continuation constellations follow the current configuration patterns: All satellites are U.S. government traditional programs, all regional real-time functions are housed on GEO satellites, all global non-real-time functions are on LEO polar satellites, some space weather functions are housed on a satellite at the L1 libration point. These constellations can be augmented by independent satellites at other orbits, such as the Earth–sun L5 point or a high-inclination Tundra orbit.

Many constellations can have the same architecture but make different decisions in the details of instrument choice, production block size, launch policy, and so forth. During the NSOSA study we considered six major architectures, and a larger number of variations on the six themes:

- 1) *Legacy continuation*: These constellations retain the current structure of two active U.S. government–owned GEO satellites, a comprehensive LEO satellite in the 1330 LTAN sun-synchronous orbit, and an L1 satellite. At higher cost points additional elements in additional orbits are added and the performance of the instruments in the GEO/LEO legacy are upgraded. “Legacy” indicates the efficient frontier of satellites in this architecture in Fig. 6.

Fig. 5. Example cost distributions for different satellite types using NSOSA cost models of representative categories of future environmental remote sensing satellites. The cost of a typical satellite production block is dominated by payload costs (development and production) rather than launch or satellite bus costs.

- 2) *All MEO*: A radical alternative centered on a large constellation of identical MEO satellites providing continuous global coverage
- 3) *All LEO*: A radical alternative built around a very large constellation of identical LEO satellites.
- 4) *Business model alternatives*: These maintain the functional allocation of legacy continuation but use commercial hosted payload services wherever plausible, with very generous assumptions about future availability and quality of those services. Higher-performance members of this family are built on strict cost–benefit order, and business model risks of hosted payload services are ignored. These are referred to as the “Business Alternatives” in Fig. 6.
- 5) *Legacy continuation with augmentations*: These are targeted at meeting the “expected” performance level in the EVM over as wide a range of observations as possible (not strictly cost–benefit ordered) by adding augmenting systems to the legacy continuation base. The efficient frontier for this architecture is marked as “Legacy-Aug” in Fig. 6.
- 6) *Hybrid constellations*: These use combinations of ideas. Specifically, these use hosted payload services for some payloads in GEO (but not in other orbits), use partial disaggregation in LEO (two to four classes of smaller satellites instead of JPSS), and add augmenting observations in fairly strict cost–benefit order. These are marked as “Hybrid” in Fig. 6.

Figure 6 summarizes the relative performance of major architecture alternatives. Figure 6 is a reduced version of Fig. 2 with a narrower x-axis range and a limited set of constellation alternatives for visual clarity. Figure 6 contains architecture alternatives 1, 4, 5, and 6 above marked with their own efficient frontier curves (alternatives 2 and 3 are excluded as they were not competitive). Legacy constellations have numbers in the 60s, Business Model Alternatives in the 70s, Hybrids in the 80s, and Legacy-Augmented in the 90s. Constellation 84 is in the 80 series, and so forth. The other constellations fall into variation cases. The Business Model Alternative architecture performs best since it uses very efficient, but probably unrealistic, business choices and accepts the risks

Fig. 6. Efficient frontiers for groups of alternatives comparing architectures. The alternatives shown were from the third cycle when the team began concentrating on Hybrid vs Legacy Continuation architectures. The curves show Business Alternative (70s) and Hybrid (80s) are best-value architectures that systematically outperform Legacy and Legacy-Augmented (60s and 90s). The differences are small at high budget levels but large at lower budget levels. The Business Alternative case incurs unquantified risks with little additional benefit over the Hybrid case. The uncertainty bars can be used to roughly judge the significance of differences in value or cost measures.

inherent in those choices. The Legacy and Legacy-Augmented series do worse since they are constrained to inefficient legacy choices. The Legacy-Augmented series is further constrained since it strives for meeting historically expressed needs regardless of where they appear on the order-of-buy list discussed in the “Order-of-buy analysis” section. Importantly, the Hybrid series is able to nearly meet the cost efficiency of the Business Model Alternative series, while having far fewer business risks. The Legacy–Hybrid gap shows significant cost benefits are available by making changes to the Legacy-based allocation of functions to physical elements as shown by the double-headed blue arrows on Fig. 6.

Variance and significance analysis. Based on Fig. 6, the Business Alternative constellations are superior. But, the value gap between them and the Hybrid series appears small, and the gap with the Legacy series converges as the relative cost rises. The Business Alternative constellation contains very significant implementation risks. The apparent size of the value gap implies the Hybrid case, with lower risks, may be preferred over Business Alternatives, and at high budget levels there may be no justification to move away from Legacy Continuation. Understanding if this is true requires some measure of significance in value and cost differences.

A useful measure of significance is comparison to uncertainties. Where gaps exceed known uncertainties, they are “significant.” Conversely, where the uncertainties are larger than the gap, the gaps are not significant. One complication is the existence of strong correlations among some sources of uncertainty. The results shown here are robust to those correlations, but the analysis involved is beyond the scope of this discussion (Maier and Wendoloski 2020).

Value uncertainty in the EVM model used in the NSOSA study has two major sources:

- *Performance scoring uncertainty:* The performance of a given constellation and instruments against the EVM requires some judgment and estimation. Hence, the scores have some uncertainties.
- *EVM judgment uncertainty:* The judgments that went into the EVM, with regard to both performance levels and prioritization, were based on a particular group consensus and had error bounds. A different group might have concluded somewhat differently, particularly with regard to prioritization. Anthes et al. (2019) describe the process by which the priorities were determined.

The NSOSA study modeled both uncertainty sources. First, during the performance scoring process the analysts tracked uncertainty, in the sense of plausible upper and lower bounds on their scores, as they assessed instrument concepts and constellation alternatives against the EVM. We used the bounds in a Monte Carlo analysis of the overall value to estimate value variances (Maier and Wendoloski 2020). Second, during the prioritization consensus building we tracked the level of expressed disagreement. There was general agreement on the overall rank order, in that no stakeholder argued an improvement near the bottom of the rank order really should be near the top. But there were frequent disagreements over local ordering. That is, while one stakeholder might have three objectives in rank order 7, 8, and 9, another might argue the same three were ordered 9, 6, and 10. This allowed construction of a Monte Carlo model of value where each objective in the EVM was allowed to randomly vary in priority up to a few steps in the rank ladder with the variation during the Monte Carlo runs expressed as uncertainty bars. The root sum square of the two variance sources together are the vertical uncertainty bars in Figs. 6 and 7.

Cost uncertainty has two major sources, one is inside the NSOSA model and the other is outside.

- **Cost variance:** The cost models used in the NSOSA study provide a cost variance curve for each component based on the empirical cost database used to estimate cost in the CDC-SAT. This allows computation of the variance on an approximate Gaussian distribution for the cost of each satellite (both nonrecurring and recurring portions). It also allows variances at the satellite level to be composed into an overall cost variance (Young 1992), which is shown as the horizontal uncertainty bars in Fig. 7.

- **Program drift:** A second, and very important, source of cost uncertainty not modeled is program drift. Drift occurs when a program is constructed to build a particular concept of the system, but the political and acquisition processes result in building something quite different from what was originally conceived and budgeted. Drift can lead to very large cost differences. A probabilistic model and error bars are not appropriate visualizations of this uncertainty.

As seen in Fig. 6, the performance gaps between Hybrid constellations and others with similar costs are typically smaller than the value uncertainties. This indicates the performance differences are not significant and selection of the Hybrid case is warranted because of the lower unmodeled risks. Conversely, the value gaps between Legacy and Hybrid series constellations are typically larger than the uncertainties, indicating those gaps are significant. Finally, the value difference between the POR2013 and the POR2025 (indicative of the value gained by NOAA investments in the GOES-R and JPSS series of satellites relative to the previous generation of *GOES-13/-14/-15* and *POES*) is comparable in size to the differences over the full range of constellations. Therefore, the range of performance improvements possible with reasonable future technology is comparable to that achieved by the last generation of improvements.

Based on the results seen in Figs. 6 we pursued more in-depth study of combinations of Legacy Continuation and Hybrid concepts. The results for the selected set chosen for in-depth study are shown in Fig. 7. The combinations were based on the following:

- Partial disaggregation of LEO satellites, with different combinations of smaller satellites with mixtures of traditional instruments (such as vertical sounders) and currently unflown instruments (such as passive ocean surface vector winds or special purpose imagers). This is the “Disagg” indicated in the legend in Fig. 7.

Fig. 7. Selected high-interest constellation alternatives with uncertainty bars. All of the constellations selected for this analysis had partially disaggregated LEO elements (indicated by the “Disagg” in the legend) and variable combinations of Legacy, Hybrid, and GEO–Tundra shared bus (GT) approaches for high orbits.

- Varying GEO and high-inclination-orbit elements, including U.S. government–owned dedicated satellites, partial use of commercial payload hosting, and satellite buses with shared deployment between GEO and Tundra orbits. This is the Legacy, Hybrid, and GT in the Fig. 7 legend.
- Varying aggregated and disaggregated space weather solutions, including aggregation of space weather instruments onto multipurpose satellites, separation onto dedicated satellites, and exploration of shared buses for off-Earth–sun-axis operation.

The results illustrated in Fig. 7 indicate the overall goal of understanding architecture choices was reached. The remaining differences within the GEO and LEO components overlapped sufficiently that more detailed studies are required for final decisions, but the overall allocation to orbits is well understood.

Recommended architecture and conclusions

Based on the NSOSA results, NOAA has begun preformulation activities for future LEO, GEO, and space weather systems. In some areas of the constellation there is clear direction. In other areas substantial trade space has been left open, although we think particular outcomes are likely. Examination of the constellations on or near the efficient frontier showed features that were systematically favored and are thus recommended as baseline choices:

- Retention of a GEO/LEO split over radical alternatives.
 - All favorable constellations allocate regional rapid update observations to GEO satellites and global observations to LEO satellites.
 - Transition to a proliferated exclusively LEO or MEO constellation is not justified, given current and projected understanding of needs and technology changes.
 - Partial disaggregation of LEO systems into smaller satellites. Future LEO systems should be smaller, fly more frequently in more diverse orbits, and have a greater variety of instruments.
 - One of those satellite configurations should 1) contain infrared, microwave, and radio occultation sounders; 2) be flown in several orbits (as many as four for enhanced global update rate); and 3) have launches decoupled from any LEO imager.
 - The LEO smallsat family also should include lightweight ocean surface vector wind sensors and enhanced day–night-band imaging capability and should be flown in additional orbits beyond a single sun-synchronous orbit.
 - Instrument performance in the smallsat family should be similar to, but not necessarily identical to that of current systems such as JPSS. A variety of instruments with size and cost profiles compatible with smaller LEO satellites are feasible and should be investigated and prioritized in future acquisition studies.
 - The LEO constellation also should include selective capabilities requiring a larger, dedicated satellite. The leading candidate for inclusion is an operational Doppler wind lidar, though this depends on favorable results from current demonstration missions and technology developments (Endemann 2017; Källén 2018; Hovis et al. 2017).
- Continuous occupancy of at least the Earth–sun L5 point with a comprehensive set of solar observation instruments and the L1 point with in situ measurements. Exactly how this should be accomplished (e.g., standalone, shared configuration, or international partnership) should be determined in preformulation trades.
- Solar observation on the Earth–sun axis can be performed from GEO while collocated with other GEO instruments, on a standalone space weather observation satellite, or from alternative orbits. Collocation on GEO satellites is generally favored on a cost–benefit and

risk basis, but the choice is not firm and may change depending on the overall strategy for GEO observations (see next section).

- GNSS-RO receivers should be included on all government-owned LEO environmental monitoring satellites to guarantee a government-owned source for observations above the EVM ST level. Observations beyond that threshold capability should be open to commercial supply.

While GEO capabilities are an essential element of the future architecture, the approach presents a less clear picture. The NSOSA results prefer constellations where there is a mixture of government-owned satellites and commercially hosted payloads at GEO (these include constellations such as C141 that define the efficient frontier in Fig. 2 and are fully elaborated in Fig. 7). However, implementing those constellations is very sensitive to the long-term availability of specific commercial hosting capabilities, something that has not been verified with industry. The trade space for GEO includes

- a partially disaggregated mixture of larger and smaller satellite buses with commercial hosting services able to support the full spectrum of instrument capabilities;
- dedicated government-owned satellites, either monolithic or partially disaggregated, covering the full spectrum of observation capabilities; and
- a GEO/Tundra shared bus capable of being launched into either geostationary or a high-altitude inclined or polar Tundra orbit with both a fixed and variable set of instruments. This concept can be either entirely government-owned or mixed with selective commercial hosting. Ideally this would result in a fixed, constant launch rate with late finalization of instrument manifest and orbital placement based on the dynamically evolving state of the constellation.

The choice among these approaches turns on factors to be resolved through future program preformulation activities. Ongoing work (NOAA 2019) reflects these conclusions.

Decision robustness and adaptation. Since the conclusions above are based on the NSOSA study assumptions, it is important to understand how changes in these assumptions might alter the conclusions. As discussed previously, the preclusion of radical alternatives, like a very large LEO constellation to the exclusion of GEO elements, is robust except to all but the largest changes in assumptions including NOAA needs and instrument size versus capability.

Most adjustments to mission preferences are easily accommodated within the recommended constellation architecture through downstream acquisition decisions. For example, the relative importance of medium-range (3–14 days) forecasting, which depends on global NWP models, versus nowcasting can be reflected in the flight rate and instrument choices in the LEO and GEO elements. If medium-range forecasting has the highest priority, then the GEO element would fly less diverse and less capable instruments while the flight rate of the LEO satellites would be increased (to occupy additional orbits and improve the update rate) and the variety and performance of the instruments selected increased. Nowcasting could be emphasized over medium-range forecasting by the opposite choice, increase the performance and variety of instruments in the GEO element at the expense of flight rate and variety on the LEO side. Neither adjustment breaks the overall architectural choices, it only adjusts the decisions within the programs.

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Appendix: NSOSA study detailed approach

The NSOSA study used a seven-step, cyclic design process illustrated in Fig. 1.

- 1) Value model development
- 2) Instrument catalog development
- 3) Constellation alternative synthesis
- 4) Score alternatives
- 5) Design and cost alternatives
- 6) Integration
- 7) Review/assess/revise

The “Value model development” step created the EDR Value Model (EVM) through the Space Platform Requirements Working Group (SPRWG), a core team of 17 subject matter experts with reach back into stakeholder organizations (Anthes et al. 2019). For “Design and cost alternatives,” we exploited a specific available capability, the Aerospace Corporation’s Concept Design Center–Systems Architecture Team (CDC-SAT) for rapid satellite design (Aguilar and Dawdy 2000; Aguilar et al. 1998). Each design cycle completed end-to-end designs for multiple constellation alternatives that included instruments, satellites, and launch segments, and provided associated costs of the deployment and operations.

The NSOSA study went through five full cycles of the Fig. 1 analysis process. In each cycle we discarded some approaches that performed poorly, marked other approaches for greater emphasis in the following cycle, and suggested new approaches not yet tried. The “Key results and analysis” section showed results both from the full set of alternatives considered and from partial sets, the partial sets being either from early cycles when preliminary decisions were reached or late cycles when the approaches were narrowed based on previous results.

Instrument catalog development. Past studies and experience showed weather and environmental satellite architecture value and cost principally are driven by instrument cost and performance (see “Cost distribution analysis” section). For typical weather satellites, launch service and satellite bus costs each contribute less to mission cost than does the instrument. The “Cost distribution analysis” section provides examples.

The NSOSA study developed a catalog of instrument concepts projected to be available in the 2030s. The catalog’s purpose was to identify capability–size–cost relationships for instruments that could be flown on operational missions circa 2030. We developed limited point designs only to identify the capability–size–cost relationships and necessary technology investments. We built the catalog by

- cataloging existing and developmental instruments relevant to NSOSA mission areas;
- soliciting instrument concepts for the 2030 era from industry, academia, and government laboratories; and
- selectively commissioning design studies for categories of instruments if the first two task elements yielded insufficient results.

A goal of the catalog was to have instrument concepts that spanned the performance range for the capabilities in the EVM (Anthes et al. 2019). The lower bound of that range was

represented by the study threshold (ST) capability. The upper bound was the maximum effective (ME) capability. In most cases, the catalog contained instrument concepts covering the full performance range. In other cases, some of the performance range was cut off because the design trades found the low-end uneconomical or the high-end technically infeasible.

A complete discussion of the instrument catalog work is beyond the scope of this paper. We provide an example here of a catalog entry and the approach by which it was developed. Consider imagers for geostationary weather satellites, which primarily satisfy the objective in the value model of regional real-time weather imagery. These imagers also may contribute to global real-time weather imagery and possibly objectives related to non-real-time global imagery or ocean color.

Table 2 shows characteristics for the three GEO imaging instruments in the NSOSA catalog. Three instrument concepts are targeted, nominally to the ST, expected (EXP), and ME performance levels defined in the EVM, with the intent being the low-end instrument should be much less expensive than the high-end instrument. The EVM defined performance levels in terms of operational value, not technical difficulty, so there may or may not be a practical instrument design corresponding to all details of each performance level. The positioning of instruments across the EVM defined performance range depended on the analysis of each instrument category and the nature of cost and performance drivers. For example, the analysis of GEO imagers showed spatial resolution was a key cost driver. Diffraction-limited resolution and wavelength drive the size and mass of the optics, with resolution at the longest infrared wavelengths being the most stressing condition. Other performance values have an effect as well, but to a lesser extent. As a result, the low-end instrument in Table 2 just meets EVM ST specifications for resolution and wavelength range, but is allowed to exceed the ST levels for update rate. The high-end instrument meets the desired ME levels in resolution and wavelength range, but is much larger and significantly more expensive. The size drives additional cost into any satellite configuration that accommodates it. The underlying reason for the results shown in Table 2 is continuing advances in electronics and photonics make some aspects of imaging performance lower cost even with higher performance, while optical performance is more limited by fundamental physics and does not show the same cost reductions.

LEO weather imaging systems do not face the same optics size drivers due to their lower imaging altitudes. The required optical apertures for LEO weather imaging resolutions are modest and do not drive the overall instrument size, mass, or cost. Swath width, geometric consistency, radiometric accuracy, and spectral resolution are the most important factors, and the cost of achieving these can be significantly reduced with advanced technologies in areas such as focal plane arrays, compact cryocoolers, and radiators. Incorporating these technologies into the GEO concepts also results in favorable impacts. However, the impact on total size, mass, and cost for the GEO payload instrument is much smaller than it is for the LEO instrument. The LEO imager and sounder instrument concepts reflect a wider range of possible technology-enabled advancements for reducing cost and for selectively improving performance. The demanding radiometric accuracy requirements for all weather imaging functions continue to be an important, cost-driving constraint.

LEO microwave sounder and imager concepts in the catalog make use of advances in hybrid deployable mesh reflector technologies, multifrequency feed horns, and compact microwave integrated circuits that enable superior performance in more compact formats. These size reductions usually result in notable cost reductions.

The NSOSA instrument catalog work identified a modest number of instruments where dramatic improvements in instrument size, mass, and cost are likely while maintaining or improving performance. Nearly all instruments benefit to a degree from new designs incorporating modern electronics. Notable improvements are especially recognized in the space weather instrument category.

EVM development. The heart of an architecture study is the value model, which in this study is the EVM. The EVM expresses, in quantitative form, the relative preferences of stakeholders for one set of capabilities versus another. Creativity in constructing alternatives is essential to realizing a high-value solution. However, unless the value model represents stakeholder preferences well, that creativity matters little and the trades expressed will be false. The NSOSA study created a value model at the level of generalized observation capabilities, using the principles of multi-attribute utility theory (MAUT) as documented by (Anthes et al. 2019). Details of the EVM are as follows:

- The EVM consists of 44 objectives: 19 are terrestrial weather-related observations (e.g., regional real-time weather imagery), 19 are space weather-related observations (e.g., on-Earth-sun-axis coronagraph imagery), and 6 are strategic objectives tied to NOAA priorities (e.g., assurance of core capabilities). The terrestrial weather observations are referred to as “Group A,” the space weather observations as “Group B,” and the strategic objectives as “Group D.” Communication related capabilities (Group C) were not traded.
- Each objective has a varying number of performance measures or attributes. Observation objective performance measures are tied to parameters like horizontal resolution and vertical resolution.
- Each performance measure has three performance levels: study threshold (ST), expected (EXP), and maximum effective (ME). Every alternative considered must meet every ST performance level unless that ST level is designated as “none,” meaning the observation is optional.
- Each objective has a swing weight representing the relative value of increasing the performance measures on that objective from the ST to ME levels.

A constellation alternative is scored by estimating its performance on all performance measures, interpolating a score from 0.0 to 1.0 on each objective (all ST being zero, all ME being 1.0, and using an interpolation curve based on the score assigned to the EXP performance level), and then a weighted summation of the objective level scores.

Constellation alternative synthesis. The study required generating and assessing constellation alternatives within architecture alternatives, which are defined as follows:

- A *constellation alternative* is a specific configuration of instruments on satellite buses, their assignment to orbits, and definition of long-term production and launch schedule for populating those orbits. Each constellation alternative has a number, e.g., constellation 141 or C141. The cost and performance of constellation alternatives are plotted on efficient frontier charts (see the “Efficient frontier analysis” section).
- A *constellation architecture* is a family of constellations defined by common approaches or rules. Each constellation architecture is given a brief name. For example, the Legacy Continuation architecture in the study is the set of constellations using an approach similar to the POR. In this architecture regional real-time functions (imaging, lightning mapping) are performed from U.S. government-owned GEO satellites deployed to two positions (the GOES-East and GOES-West locations). Global functions are performed from a comprehensive U.S. government-owned satellite in the 1330 LTAN sun-synchronous orbit. There is also a U.S. government-owned satellite at the Earth-sun Lagrange L1 point for in situ space weather measurements.

There are many constellation alternatives within the Legacy Continuation architecture. For example, the instrument capabilities on the GEO satellites can be upgraded or downgraded

from current performance, additional LEO systems in additional orbits can be added, and the performance of the instruments on the 1330 LTAN LEO satellite can be upgraded or downgraded.

With about 20 categories of instruments, three performance levels per category in the instrument catalog, and typically 10 or more ways to logically aggregate any given instrument configuration, there are millions of possible constellation configurations. With the partially automated tools available, the NSOSA team examined about 150 distinct configurations. This required careful trade space control to ensure results were both comprehensive and tractable. We used the following principles to generate constellations:

- Generate very diverse alternatives in the earliest cycles. Along with the Legacy Continuation architecture, we explored radical alternatives based on proliferated LEO or MEO satellites, augmentations of legacy constellations, and approaches exploiting different platform business models (Maier 2018).
- Explore the edges of the trade space. For example, designing to the bottom (ST) and top (ME) of each performance range.
- Exploit the results of each cycle to make improvements in the next cycle, e.g., determine elements with high benefit-to-cost values and determine strengths and weaknesses of each alternative.
- Determine cost drivers and minimize them while expanding other, less expensive features.

Satellite design, performance and cost analysis, and integration. The NSOSA team executed the steps in Fig. 1 during each design cycle, starting with developing the value model and instrument catalog and synthesizing a range of constellation alternatives. The team then designed and costed the identified constellation alternatives, scored these alternatives, and integrated the results.

- *Design and cost alternatives*¹: This task used instrument concepts from the instrument catalog and the orbit and instrument assignments from the synthesis process as input to satellite design. The task employed the CDC-SAT capability (Aguilar and Dawdy 2000; Aguilar et al. 1998). The CDC-SAT allows rapid design and costing efforts (many per day), while providing traceability to validated engineering and cost databases and tools. The design process included production and launch rates for defined levels of constellation reliability (Maier et al. 2018).
- *Score alternatives*: This task used the instrument performance (from the catalog), combined with analysis of constellation level performance (such as revisit rate or availability) to estimate the score for the constellation alternative on the EVM.
- *Integration, trades, and architecture analysis*: This task extended cost analysis beyond the satellite to the full constellation with production blocks and sequencing to provide consistent service out to 2050. It analyzed the cost effectiveness of individual constellation alternatives and the overall constellation architectures into which the constellation alternatives fit.

¹ All cost and design information in this study is of a planning and budgetary nature and provided for informational purposes only. It does not constitute a commitment on the part of the author's organizations.

Scoring tools were key enablers for these tasks. The CDC-SAT tied together a partially automated satellite bus design tool (known as the Concurrent Engineering Model, or CEM) with standard satellite cost models (Mahr and Richardson 2003; Nguyen and Kwok 2010), astrodynamics tools, and a launch vehicle library. NASA's Kennedy Space Center provided the launch vehicle library, including performance and costs, based on NASA approved and projected vehicles in the 2016 time frame. Input payload characteristics (size, mass, power, and cost) predicted by

instrument cost models (Habib-Agahi 2010; Habib-Agahi et al. 2011) came from the instrument catalog. The scoring tools were automated EVM-defined calculations and combined instrument catalog-defined performance levels with constellation level attributes such as revisit rate.

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