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Optimizing Earth Observing Constellations of Satellite Sensors Using ASPEN: A Proof-of-Concept Study for Global NWP and Nowcasting Applications

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ABSTRACT

The Advanced Systems Performance Evaluation tool for NOAA (ASPEN) is applied to the problem of optimizing the design of a constellation of sensors by calculating the scientific benefit, cost, and cost effectiveness of all possible combinations of sensors within a specified catalog of sensors. In this proof-of-concept study, sensors are derived from the NOAA Satellite Observing Systems Architecture (NSOSA) study and the Geostationary Extended Observations satellite system (GeoXO) program, and the targeted applications are restricted to two examples, global NWP and a suite of 6 nowcasting applications. The example calculations use the current version of ASPEN, the current version of the ASPEN data bases, and a simplified method of estimating costs.

Achieving optimization adopts the approach of visualizing the results as cost-benefit “efficient frontier” scatterplots and identifying the most efficient constellations—the constellations that maximize benefit for a given cost. The optimal constellation depends strongly on the budget, the sensor costs, the applications considered and their observational requirements and priorities, and the design ensemble of possible constellations. For illustration a simple decision rule is applied to select the optimal constellation for a given budget. In practice such guidance must be carefully considered in the context of neighboring constellations in the efficient frontier scatterplot.

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1. Introduction

For new satellite Earth observing sensors the formulation, design, acquisition, calibration and validation, and implementation into operational use can take years. Since such sensors are often used in combinations, national weather and space agencies have well established plans to deploy and exploit constellations of Earth-observing satellites [e.g., Simmons et al. 2016]. Different approaches have been taken to optimize the "Next-Gen" Earth-observing architecture. For example, detailed simulation experiments called Observing System Simulation Experiments (OSSE) [e.g., Boukabara et al. 2016b] as well as Forecast Sensitivity to Observation Impact (FSOI) methods are well developed for assessing data impacts on global NWP skill. But OSSEs are expensive and time consuming, FSOIs are applicable to current data, and both OSSEs and FSOIs are limited to weather forecast applications. As an alternative, several projects have collected and compared observing system capabilities and application requirements. These include the Space Platform Requirements Working Group (SPRWG) [Anthes et al. 2019], the NOAA Satellite Observing System Architecture Study (NSOSA) [Maier et al. 2021], the GeoXO Requirements Working Group (XORWG), and the NOAA Observing System Integrated Analysis (NOSIA) [Helms et al. 2016]. In addition the Consolidated Observing User Requirements List (COURL) [Murray et al. 2008] and the WMO Observing Systems Capability Analysis and Review (OSCAR) database [WMO, 2019] collect diverse sets of requirements. These types of studies and databases can apply to a wide range of applications and can support the optimization of the return-on-investment for new capabilities. However, these approaches have limitations that must be carefully considered to ensure that they are not applied beyond their range of validity. This concern also applies to the Advanced Systems Performance Evaluation tool for NOAA (ASPEN) [Boukabara and Hoffman 2022], which is used in this study.

ASPEN has been designed to be an extensible, repeatable, and explainable system that could answer a wide range of questions. ASPEN is designed to measure the *degree to which one or more observing systems can satisfy the needs of one or more environmental applications*. (In this discussion observing system and application are generic terms. An observing systems is a producer of information and an application is a consumer of information.) ASPEN is in essense a performance/gap analysis tool. ASPEN measures how much an observing system fulfills the (prioritized) requirements ranges of the applications. The higher this degree of satisfaction, the more the observing system is considered beneficial. ASPEN introduces two novel concepts for capabilities/requirements assessments. First, ASPEN provides an interface to compare the performance of different observing systems to the requirements of applications. This interface is generally applicable and observing system neutral because it characterizes the Earth System in terms of geophysical observables and their attributes. Second ASPEN requirements are matched to priorities. This is a way to capture and apply the knowledge that satisfying certain requirements is more valuable than satisfying others.

ASPEN is similar in some ways to NOSIA and NSOSA. The NOSIA database, maintained by the NESDIS Technology, Planning, and Integration for Observation (TPIO) division, documents the relationship between observing systems, mission requirements, and their mission service impacts [Helms et al. 2016]. The primary sources of data for NOSIA are inputs from about 500 NOAA Subject Matter Experts (SMEs) knowledgeable on observing system impacts upon the products and services for which they are responsible, as well as input from NOAA Mission Service Area (MSA) portfolio managers who provided the structure and priority of functionally aligned services. The primary source of NOSIA observing system cost data is the NOAA Observing Systems Council (NOSC) System of Record (SoR) database. The NOSIA Value Tree traces the relationships captured in the database from NOAA Goals to MSAs to key products and services to data sources to observing systems. Graphical tools can be used to mine the data, extract, and integrate the data at a level familiar to the user, displaying the data in unambiguous depictions. In this way, NOSIA provides a repeatable integrated analysis capability to assess NOAA's observing system architecture.

The NSOSA study (2014-2018) was conducted by the NOAA Office of Systems Architecture and Advanced Planning (OSAAP) to support planning the long-term future of the NOAA follow-ons to GOES-R and JPSS [Maier et al. 2021]. Each NSOSA iteration included designing, costing, and assessing the benefit of tens of alternative satellite constellations in order to answer a number of questions related to the space-segment architecture. Key steps in the NSOSA process include the development of the value model, development of the instrument catalog, synthesis of constellation alternatives, and calculation of the constellation benefits.The NSOSA value model developed by SPRWG evaluates the generalized observation capabilities, using the principles of multi-attribute utility theory (MAUT). Details are given by Anthes et al. [2019]. Elements of the NSOSA instrument catalog that are used in the present study are described in Section 3.2 and Appendix A. The NSOSA team examined about 150 distinct constellation configurations of the millions possible. After an initial very diverse sample, the study focused on edge cases, cases with extreme performance, low costs, or high benefit-to-cost ratios. As in ASPEN, performance scores for each metric range from zero for minimally useful constellations to one for maximally useful constellations. The overall benefit is then a weighted summation of the performance scores.

In this study we use ASPEN to estimate optimal and near-optimal constellations among the possible combinations of a limited set of GEO and LEO sensors. For simplicity we only consider NOAA assets. Including a full GEO Ring in place of just the GeoXO sensors or considering additional polar orbiters beyond the JPSS sensors would require either ignoring or specifying the impact of differences in performances between the NOAA and international partner sensors. The optimal and near-optimal constellations that are determined might then be used to support decisions about the Next-Gen Earth architecture. For that, we generated all possible permutations within a given design ensemble considering the following sensors: For the GEO sensors we follow the GeoXO plans in terms of sensors considered: a VIS IR GEO Imager similar to the GeoXO Imager (GXI), a Lightning Mapper (LM) similar to the GeoXO Lightning Mapper (LMX), and an Ocean Color Sensor (OCS) similar to the GeoXO Ocean Color Instrument (OCX) on the GOES East and West platforms and an IR GEO Sounder similar to the GeoXO Sounder (GXS) and an Atmospheric Composition Sensor (ACS) similar to the GeoXO Ocean Color Instrument (OCX) on the GOES Central platform. For the LEO sensors we consider a MW LEO Sounder similar to the Advanced Technology Microwave Sounder (ATMS), a VIS IR LEO Sounder similar to the Cross-track Infrared Sounder (CrIS), a VIS IR LEO Imager similar to the Visible Infrared Imaging Radiometer Suite (VIIRS), and an Ozone Mapper Profile Suite (OMPS) similar to the current instrument.

The optimization is performed within the space of a design ensemble—an enumeration of all possible constellations under consideration. In the baseline “simple design ensemble” there are two copies of each LEO sensor, and it is assumed that every constellation includes a MW LEO Sounder and a VIS IR GEO Imager. A more “extended design ensemble” is also considered that

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allows for up to 3 different versions of each sensor and 1, 2, or 4 copies of the LEO sensors and that does not require-assume that every constellation includes a MW Sounder and a GEO Imager. Costs of all permutations (constellations) are computed using a simple cost model that adds the costs associated with the individual sensors in the constellation. Since these costs are based on the annualized per sensor allocation of the total system costs, they include the costs of launch, spacecraft, and ground system, but this method of combining costs is only approximate.

The ASPEN satisfaction metric (called the benefit) is computed for each permutation, to assess the degree of satisfaction of application requirements. The benefit/cost ratio (called the cost effectiveness) is also computed. In this study the benefits are calculated with respect to the Global NWP application and 6 different nowcasting applications. (We capitalize Global NWP and the names of the nowcasting applications when referring to the ASPEN versions of these applications.) To select the most efficient constellations of all possible ones, we plot each as a point in terms of ASPEN benefit vs. costs. Those on the upper bounding line (called the efficient frontier, Maier, 2021) are the most beneficial for the cost. It is important to realize that this ranking is dependent on the application used. It will change if other observing systems or applications are used/added (as should be done).

Please note that ASPEN is in a state of development. We believe ASPEN holds great promise as a support tool for optimizing constellations of observing systems following the methodology employed in this study. However, this study is only a demonstration of what is possible employing the current prototype version of ASPEN. In this study we address the problem of optimizing NOAA's combination of the planned GeoXO constellation and the current polar orbiters for the global NWP and nowcasting applications. This problem statement results in several artifacts and results in a number of caveats concerning the results presented. As discussed in detail in the Conclusions, we apply the ASPEN methodology to a limited set of observing systems and applications, using the current version of ASPEN, the current ASPEN data bases, and a simplified method of estimating costs.

The plan of this paper is as follows. The ASPEN methodology is briefly described in Section 2.1 and the method of combining sensor performances into constellation performances is described in Section 2.2. The data used are described in Section 3, including the application requirements and priorities for Global NWP and for the six nowcasting applications in Section

3.1 and the performances of the sensors that will make up the constellations in Section 3.2. The possible constellations are defined in terms of two design ensembles described in Section 4. Four sets of proof-of-concept constellation optimization studies are described and compared in Section 5. A summary and concluding remarks are given in Section 6.

2. ASPEN Methodology

2.1. ASPEN concepts

The basic ASPEN concepts and methods are described in detail by Boukabara and Hoffman (2022). In ASPEN observing system performances are compared to application requirements in terms of Earth system variables and their attributes. In the context of ASPEN, observing systems are any providers of geophysical information and applications are any consumers of geophysical information. Examples of observing systems are satellite sensors, ground-based radars, commercial providers of data, and confederations of mobile phones of citizen scientists. Examples of applications include NWP and nowcasting, as well as various "users", such as broadcast meteorologists, and emergency managers. Both observing systems and applications could be composites, e.g., constellations of including multiple sensors, such as GeoXO or JPSS and mission service areas (MSAs), such as Severe Weather or Coastal Hazards.

The ASPEN calculation of the benefit of an observing system for an application begins by scoring observing system performances by the application requirements ranges. These scores normalize and truncate the performances to the range 0 to 1 indicating completely useless to maximumly useful information, respectively. This scored performance is determined for all combinations of variables, attributes (e.g. horizontal and vertical resolution, coverage, and precision), applications, and observing systems. In ASPEN the observing system performances, the application requirements ranges, and the application priorities are stored as variables by attributes tables. The benefit is then the sum of the performance scores weighted by the application priorities. The cost effectiveness is the benefit divided by the cost of the observing system.

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ASPEN was developed using NSOSA concepts and databases, and like NSOSA is highly rigorous and transparent. NSOSA, being based on MAUT, focuses on a small number of key objectives, while ASPEN aims to account for a wide range of Earth system variables and their attributes and to be more capable of assessing all potential solutions and accounting for all applications. The assumption made in ASPEN is that satisfying application requirements close to the maximum level, will lead to maximizing systems skills and performances. Similarly, satisfying application requirements at the minimum level will lead to minimum levels of performance and skills of those systems. A major criterion for ASPEN's trustworthiness is the trustworthiness of its inputs: (1) observing systems detailed performances and costs, and (2) application observational requirements ranges and priorities. We are now expanding ASPEN to be more descriptive of the Earth system environment and more encompassing of the diverse application requirements. This includes expanding the list of variables from the 91 defined in the prototype version that is used in this study to more than 400, as well as defining additional attributes needed to better describe observing systems performances and application requirements.

In this proof-of-concept study, beyond demonstrating the analyses made possible by ASPEN, we will illustrate ASPEN's ability to trace benefits associated with any observing system, to inputs including application requirements and priorities. This capability is based on analyzing the benefit contributions given by multiplying the scored performance by the application priority for all variables, attributes, applications, and sensors. As a result, the ASPEN analyses are traceable, reproducible, transparent, and efficient to use by allowing "what if" scenario assessments. In other words, ASPEN analyses are defensible with stakeholders.

2.2. Constellation calculations

Boukabara and Hoffman (2022) did not discuss combining sensors into a constellation. It is possible to create a sensor performances table for each constellation. However, this is not without complications since a given application might use information from a constellation in a different way than another application. In this study, we apply a maximum benefit by variable (MBV) approach to calculate the combined benefit of a constellation of sensors for an application. That is, for each pair of an application and a constellation, the sensor providing the maximum benefit for each variable is used to provide the information for that variable.

In the MBV approach, information for a single variable from multiple sensors is not combined. This makes the MBV approach most appropriate for applications like the nowcasting applications. In such applications the forecaster is presented with images (maps) of several variables, and it makes sense to present the forecaster with data from the best source for each variable. Even though information from multiple sensors is not combined in this idealization, in reality multiple sources of information about a single variable might be used to fill in temporal gaps or as a source of verification. The MBV approach only provides a lower bound for benefit for applications like global NWP which use a Bayesian approach to optimally combine different sources of information. For these types of applications, ASPEN should use alternative methods of determining the benefit of a constellation of sensors for an application. One approach, which could make use of data sets prepared for OSSEs, is to sample several days worth of simulated observations of the different sensors and estimate the performance for the combined set of sensors in each constellation.

For efficiency when considering several constellations, the first step in the MBV calculation is to calculate the benefit to each application for each variable due to each sensor. These can then be used to directly calculate the MBV constellation benefits by summing the maximum variable benefits for each constellation. The MBV approach is also used to determine the combined benefit due to the different modes of a sensor like the VIS IR GEO Imager for each application. This approach is used in determining the benefit of such a sensor to an application and is a preliminary step in constellation calculations to determine the benefit to each application for each variable due to such a sensor.

3. Data

3.1. Application requirements and priorities

In this study we consider either the single Global NWP application or the six nowcasting applications. This is for illustration only—many other applications should be included to capture the full benefit of proposed observating systems. The nowcasting applications are for dense fog, fire monitoring, floods, offshore winds and sea ice, thunderstorms, and winter precipitation. For the purpose of this study the nowcasting applications are assigned equal strategic priorities. These are the applications used because these ASPEN application requirements and priorities have undergone the most scrutiny (as detailed in the next paragraph) and they are the closest we have to ASPEN application tables that are truly vetted and fully peer reviewed. As we will see, the results make sense, as expected, but only from the Global NWP and nowcasting perspectives. To apply ASPEN comprehensively requires that in the future we account for other applications to encompass the whole NOAA mission.

The application requirements and priorities were developed by members of the NOAA NESDIS Systems performance Assessment Team (SAT) and reviewed by the entire SAT. The SAT is a technical team with diverse expertise in remote sensing, data assimilation, impact assessment, sensors engineering, calibration, meteorology, oceanography, land/hydrology, and other areas. In addition to the SAT membership, the SAT meetings purposefully included representatives from academia, private sector, NASA, and additional members of other NOAA offices.

For Global NWP, the SAT study (Boukabara et al. 2022) was led by Dr. Rick Anthes and included representatives from NOAA, NASA, DoD, and academia. For the nowcasting applications, the SAT study was led by Dr. Jordan Gerth who conducted surveys of the front-line operational forecasting staff (technical reports in preparation 2023). We converted the results of these studies to the needed ASPEN tables. These recommendations were discussed briefly by the entire SAT, and finalized by the CORE-SAT, but they were not reviewed and the final recommendations by the CORE-SAT were not discussed or reviewed by an independent group of experts.

The geophysical variables and their application priorities used in this study are given for each application in Fig. 1a. Future updates are anticipated. Individual applications require between 12 and 14 geophysical variables, but considering all 7 applications, a wide variety of variables are required (38 of the 60 non-space weather variables included in the prototype version of ASPEN). Of these 38 variables nearly half (16) are required by just one of the 7 applications while wind, relative humidity and imagery are required by at least 6 of the 7 applications. A few variables were identified during the SAT discussions as required but are ignored in this study (and are not listed in Fig. 1) since requirements and priorities were not established by the SAT. Examples of these variables include surface pressure for Global NWP, reflectivity for Thunderstorms, burn scars and topography for Floods, and smoke injection height for fire monitoring for Nowcasting.

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In addition, there are no requirements for vertical winds, although these are provided by the IR GEO Sounder and would potentially be useful for some of the nowcasting applications. Since the observing system capabilities used in this study do not include these variables, the effect of adding them to the applications would only reduce all the benefits calculated for a given application by a constant, which would not affect the interpretation of the results presented.

It should be noted that two deficiencies in the application requirements and priorities were discovered and corrected during the course of this study. First, while the nowcasting applications have requirements for relative humidity and the sensors performance are for relative humidity, the Global NWP requirements are given in terms of specific humidity. As a result, there would be no useful humidity information for Global NWP. This disconnect shows that future ASPEN development should be better coordinated. In the present case it is only necessary to estimate the relative humidity precision requirements (all priorities and the requirements for other attributes are unchanged). Anthes and Rieckh (2018) present various estimates of the standard deviations for specific humidity and relative humidity. By comparing their Fig. B1 and Fig. B2 we estimate that the relative humidity standard deviations are approximately 1/3 larger than the corresponding specific humidity standard deviations. We have therefore translated the specific humidity requirement range of [15, 5] % to the relative humidity range of [20, 6.67] %. Second, the Dense Fog Nowcasting application specifies requirements for both specific humidity and relative humidity—we eliminated the specific humidity requirements.

3.2. Sensors performances

Sensor data for this study is based on information from the NSOSA study and from the GeoXO program for 9 sensor types. The sensors are briefly described in Appendix B. Sensors are specified in three classes to approximate the three levels of performance of the SPRWG study (Anthes et al. 2019). The threshold class (TC) corresponds to the SPRWG threshold level of minimal utility, the expected class (EC) corresponds to the SPRWG intermediate level expected to be feasible by 2030, and the maximal class (MC) corresponds to the SPRWG maximum effective level beyond which additional capabilities would not be cost effective. The sensors considered and their costs (detailed below) are listed in Table 1.

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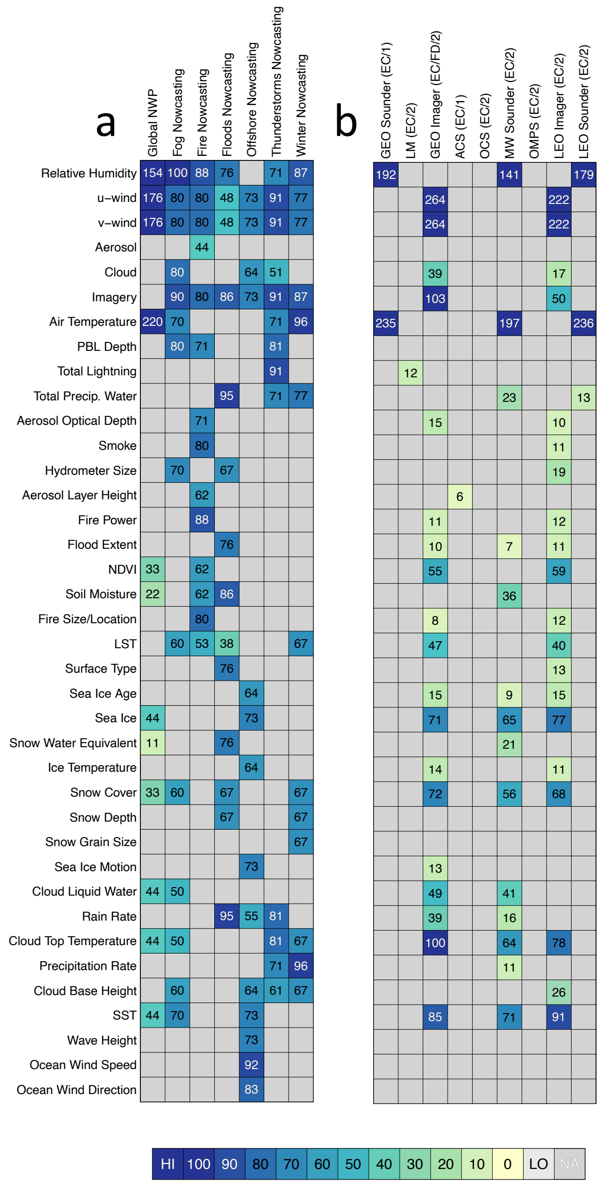

Figure 1. Application priorities (a) for variables by application (summed over attributes) and contribution to the mission benefit (b) by sensor (summed over attributes and applications). Values in (a) are in percent times 10 and in (b) are scaled so that a value of 0.035 is plotted as 100. Gray cells in (a) indicate that the application has no requirement for that variable. Gray cells in (b) indicate that the sensor provides no benefit (i.e., no useful information) for that variable. Variables not required by any of the applications are not listed.

We estimated sensor performances in geophysical space for each of the 20 sensors in Table 1 that has a cost assigned. There are 27 possible sensors given the 9 sensor types and the three sensor classes, but for the LM no information was available for the TC and for the ACS and the OCS information was available only for the EC. In addition, each VIS IR GEO Imager has three modes of operation—Full Disk (FD), CONUS, and Mesoscale (Meso)—and each mode of operation requires a separate ASPEN sensor performance table. We started with engineering specifications from the NSOSA instrument catalog (Zuffada and Beatty 2016, and Monica Coakley, personnel communications, 2020-2021). The engineering specifications provided information on where and how often observations are made. The engineering specifications were converted to estimates of precision and vertical resolution in geophysical space based on analogies to existing instruments and forward model and retrieval algorithm simulations.

Table 1. Sensors, legacy equivalents and assumed costs ($M) for the three sensor classes: the threshold class (TC), the expected class (EC) and the maximal class (MC). The number of sensor options for each sensor type are also given for the simple design ensemble (SDE) and extended design ensemble (EDE), which are discussed in Section 4. Bolded portions of the sensor name column are acronyms or short names used as labels in figures.

Sensor Type	Legacy	TC (M)	EC (M)	MC (M)	SDE	EDE
IR **GEO Sounder**	GEO-CrIS	79	157	314	2	4
Lightning Mapper (**LM**)	GLM		92	184	2	3
VIS IR **GEO Imager**	ABI	157	314	628	1	4
Atmospheric Composition Sensor (**ACS**)	ACX		101		2	2
Ocean Color Sensor (**OCS**)	OCX		92		2	2
MW LEO Sounder	ATMS	56	111	222	1	10
Ozone Mapper Profile Sensor (**OMPS**)	OMPS		120		2	4
VIS IR **LEO Imager**	VIIRS	161	322	644	2	10
VIS IR **LEO Sounder**	CrIS	100	199	398	2	10

Different geophysical variables are observed by different sensors as listed in Fig. 1b for the EC sensors. Figure 1b was determined by calculating the overall benefit to both the Global NWP and nowcasting applications, giving Global NWP a strategic weight equal to all six nowcasting applications. Note that variables not required by any of these 7 applications are not listed in Fig. 1. In Fig. 1b, we see that the EC imagers provide useful information—information useful in terms of the requirement ranges for the 7 applications considered here—for many variables: 20 for the VIS IR LEO Imager and 19 for the VIS IR GEO Imager. The MW LEO Sounder provides useful information on 14 variables. Other sensors—the LM, the ACS, and the VIS/IR Sounders—observe only a handful of variables, and two sensors—the OCS and OMPS—provide

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no useful information (for the current requirements). Of the 38 variables in Fig. 1b, 16 are either not observed or observed by only a single EC sensor. Others are observed by 2 or 3 EC sensors.

The sensor performances are all given for a single sensor. A modified sensor performances table is generated whenever a sensor orbital configuration specifies multiple sensors, *n*. The modifications are simplistic. For a sensor in the same LEO orbit (but with different equatorial crossing times) the temporal refresh time is divided by *n*. For a sensor in GEO orbit the domain is assumed to be defined as viewed from GOES Central if n=1 and from GOES East and West if n=2.

3.3. Sensor costs

The cost model used in ASPEN should be tailored for the task under consideration. Currently the cost model simply sums the annualized per sensor allocation of the total system costs in a constellation. As such these costs include development costs, launch costs, spacecraft costs, and ground system costs, but do not include exploitation costs (i.e., the costs of modifying applications and educating users to properly use the new observations). A further complication is that ground system and exploitation costs might depend on application. Whatever cost model is used, it is key that the same basis for estimating costs is applied consistently to all observing systems (or data or products) that are being compared side-by-side.

For this study total program costs estimated from public sources and reasonable assumptions are allocated per year and per sensor. We begin by assigning the sensor costs estimates of Table 4 of Boukabara and Hoffman (2022) for the current GEO and LEO instruments to the corresponding EC instruments. Boukabara and Hoffman (2022) determine the sensor costs from the total JPSS and GOES-R program costs by (1) accounting for the number of satellites in each program, (2) assuming each satellite is active for 5 years and (3) dividing the annualized satellite cost proportionally to the sensor contract costs. Cost estimates for GeoXO sensors are given by Adkins (2022) for two assumed discount rates and a distribution of sensors in which the GXI, LMX, and OCX are hosted on the East and West platforms and the GXS and ACX are on the Central platform. Cost estimates for the two discount rates are similar but considering both and adjusting the East and West platform sensor costs from two sensors to a single sensor we set the OCS cost to 1.0 times the already assigned LM cost, the ACS cost to 1.1 times the already

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assigned LM cost, and the IR GEO Sounder cost to 0.5 times the already assigned VIS IR GEO Imager cost.

To extend these costs to the TC and MC instruments we multiply by 0.5 and 2.0 respectively. These multiplication factors are roughly consistent with the average ratio of Study Threshold to Expected and Maximum Effective to Expected costs seen in the estimated costs of the NSOSA instrument catalog (Zuffada and Beatty 2016).

4. Design ensembles of constellations

Before optimizing a constellation, we must specify the design ensemble, an enumeration of all possible constellations under consideration. In this study we consider two design ensembles—a simple design ensemble (SDE) made up of only EC sensors in fixed orbital configurations and an enhanced design ensemble (EDE) that allows choices from all classes of sensors and several LEO orbital configurations. A cost must be assigned to each constellation under consideration. In the present study the constellation cost is simply the sum of the costs of all the sensors in the constellation.

In the SDE, all LEO sensors included in a constellation are included in a 2-orbit configuration. The VIS IR GEO Imager, the LM, and the OCS included in a constellation are always on both the East and West platforms. The IR GEO Sounder and ACS included in a constellation are always on the Central platform. This configuration of GEO sensors follows GeoXO plans (Adkins 2022). In the SDE we also specify that every constellation includes the MW LEO Sounder and VIS IR GEO Imager sensors. The other 7 EC sensors are each either included or not, giving a total of 2^7=128 individual constellations.

In the EDE all sensors listed in Table 1 might be chosen for a constellation but only a single choice, i.e., a single class and a single orbital configuration is allowed for any sensor type. The GEO orbital configurations are the same as in the SDE, but the LEO orbital configurations allow for 1, 2, or 4 sensors in each case. For example, the sensor options for the VIS IR GEO Imager are Null, EC/2, TC/2, and MC/2. Here Null indicates the constellation does not include a VIS IR GEO Imager. Besides Null, the sensor options are composed of the sensor class (EC, TC, or MC), followed by the number of sensors in the orbital configuration (always 2 for East and West GEO platforms in the VIS IR GEO Imager case). For the MW LEO Sounder there are a total of

10 sensor options—Null plus three orbital configurations times three classes. The right-hand columns of Table 1 give the number of sensor options for the SDE and EDE. The product of number of sensor options for the EDE is 768000, but we must reduce this by 1 to eliminate the constellation containing no sensors to give the total number of EDE constellations.

To keep track of the constellations in an ensemble we need to be able to determine the sensors in the constellation from the constellation number and vice versa. For the SDE where the choices are binary the constellation number displayed as a binary number reveals the sensors included by the locations of the 1's in this binary number. A generalization of this approach used for the general case makes use of the sensor options, always including Null as the first sensor option. Any constellation is defined by one sensor option choice for each sensor type, or equivalently by the indices of these choices. The indices are combined into a unique constellation number. In the case of the SDE the constellation number is a binary number because the indices are all either 0 or 1.

5. Constellation optimization prototype results

We calculated the cost and benefit for all constellations in the design ensembles of Section 4, which make use of the sensors described in Section 3.2 for the Global NWP application and the nowcasting applications described in Section 3.1. This gives four cases: Global NWP for the SDE and EDE and nowcasting for the SDE and EDE. Visualization of these results as cost vs. benefit scatterplots defines an efficient frontier, a small list of the most efficient constellations for the cost. Constellations on and close to the efficient frontier are candidates for the optimal constellation. A simple decision rule applied below determines the most beneficial constellation of all constellations within a given budget constraint. In practice such guidance must be carefully considered in the context of neighboring constellations in the efficient frontier scatterplot.

5.1. Global NWP simple design ensemble

Figure 2 shows the benefit contribution to the application (b^A) provided by each sensor in the SDE for each variable that Global NWP requires. For example, air temperature information is provided by the IR GEO Sounder (b^A=0.143), the MW LEO Sounder (b^A=0.127), and the VIS IR LEO Sounder (b^A=0.153). Several sensors included in this study provide little or no useful

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information for the Global NWP or nowcasting applications. The four sensors that provide no useful information for Global NWP (indicated by columns of all zeros in Fig. 2) are the LM, the ACS, the OCS, and the OMPS. First, we note that OCS is not expected to contribute to Global NWP or nowcasting, but is included here as part of GeoXO. This results in superfluous constellations—for any constellation without OCS there is another (what we term “superfluous”) constellation that adds OCS but does not provide any additional benefit to Global NWP or nowcasting. Second, in addition to the OCS, three other sensors provide no useful information to Global NWP in this study and only limited useful information to the nowcasting applications. This is a result of limitations in the requirements specified in the prototype version of ASPEN being used. Ozone information is assimilated by Global NWP models, but the current ASPEN Global NWP (and nowcasting) requirements do not include ozone. Thus, in the current study OMPS and OCS do not provide any benefit to Global NWP or nowcasting. Also, for Global NWP the current ASPEN requirements do not include any variables observed by the LM or the ACS. But ACS observes ozone and lightning observations have been shown to provide useful information for NWP in some forecast systems. Also, for the nowcasting applications, useful information from the LM and the ACS is restricted to Total Lightning from the LM for the Thunderstorms Nowcasting application and to Aerosol Layer Height for the Fire Monitoring Nowcasting application.

With more complete requirements specifications for lightning and ozone variables, sensors like the LM, the OCS, and the OMPS would provide benefit to Global NWP, but that benefit would be small compared to the benefit due to temperature, wind, and humidity observations which have high application priorities for Global NWP.

Figure 3 decomposes the benefits for temperature cited above into contributions for each attribute. The IR GEO Sounder has the best performance in terms of data latency, horizontal resolution, and temporal refresh, but located at the GOES East and West locations only covers a fraction of the globe. Compared to the VIS IR LEO Sounder, the MW LEO Sounder appears to be less capable in terms of latency, horizontal resolution, and precision. However, exclusions due to cloud cover, which would decrease the capabilities of the IR sounders, are not included in this version of ASPEN.

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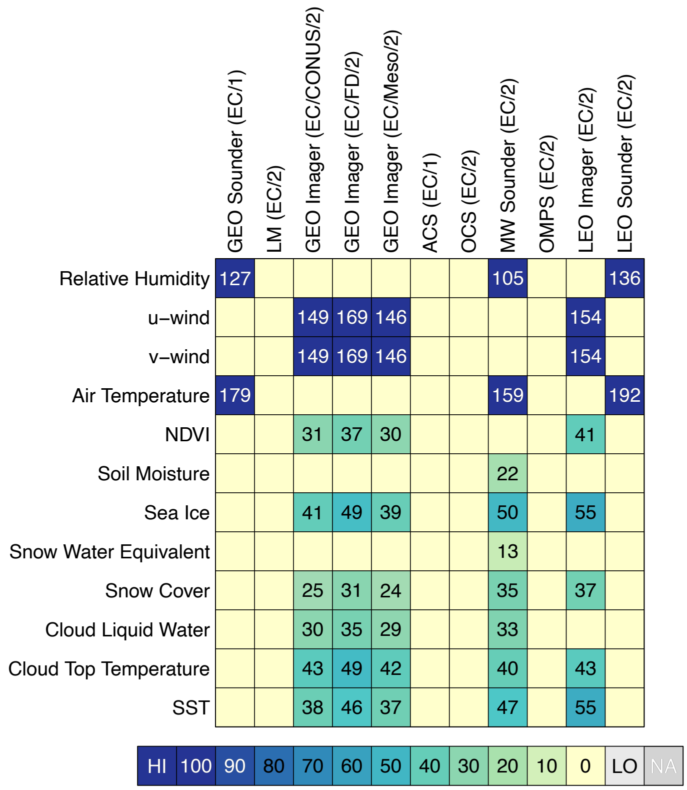

Figure 2. The benefit contribution to Global NWP for each required variable for each sensor in the SDE. Benefit contributions are summed over the attributes. The benefit contributions have been scaled for the purpose of the plot so that a value plotted of 100 is equivalent to an actual value of 0.80. Note that each mode of the VIS IR GEO Imager is treated separately in this plot.

In Fig. 4 the benefit for Global NWP is plotted vs. cost for all constellations in the SDE. Note that the baseline configuration of the two required sensors, the MW LEO Sounder and the VIS IR GEO Imager, provide a large benefit (0.71) that is hard to improve upon. All constellations are contained in the gray area, which is the area within the convex hull of all the points representing the constellations in the cost-benefit plane. By definition, all lines connecting points on the convex hull are contained in the convex hull area. The upper boundary of the convex hull (plotted in magenta) is the efficient frontier. A point along the efficient frontier has the maximum benefit for its cost, i.e., all other constellations having this cost or less have less benefit. Constellations along a horizontal line in this plot except for the leftmost one (i.e., least expensive one) have higher cost but the same benefit as the constellations along this line to the left. We refer to these constellations, plotted in dark gray, as superfluous. A superfluous constellation adds one or more sensors to a less expensive constellation but does not provide

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additional benefit. These additional sensors may provide some useful benefit on their own but are not chosen by the MBV method and do not add benefit in these superfluous constellations. That is for any of the applications under consideration some other sensor provides greater benefit for each variable. In the SDE for Global NWP the superfluous constellations are almost all due to the fact that the LM, OCS, ACS, and OMPS don't observe any of the Global NWP required variables. We could eliminate them from this analysis, leaving a design ensemble that includes the baseline sensors and either includes or not the IR GEO Sounder, VIS IR LEO Sounder and VIS IR LEO Imager for a total of $8=2^3$ constellations. Of these 8 interesting constellations it turns out that 2 are superfluous. This occurs because these 2 constellations contain both IR Sounders and the VIS IR LEO Sounder outperforms the IR GEO Sounder for air temperature and relative humidity, the variables providing benefit to Global NWP for these 2 sensors. Thus Fig. 4 highlights the remaining 6 constellations plus the most expensive constellation, the rightmost point on the efficient frontier, which is superfluous but is nonetheless included in the count of optimal constellations.

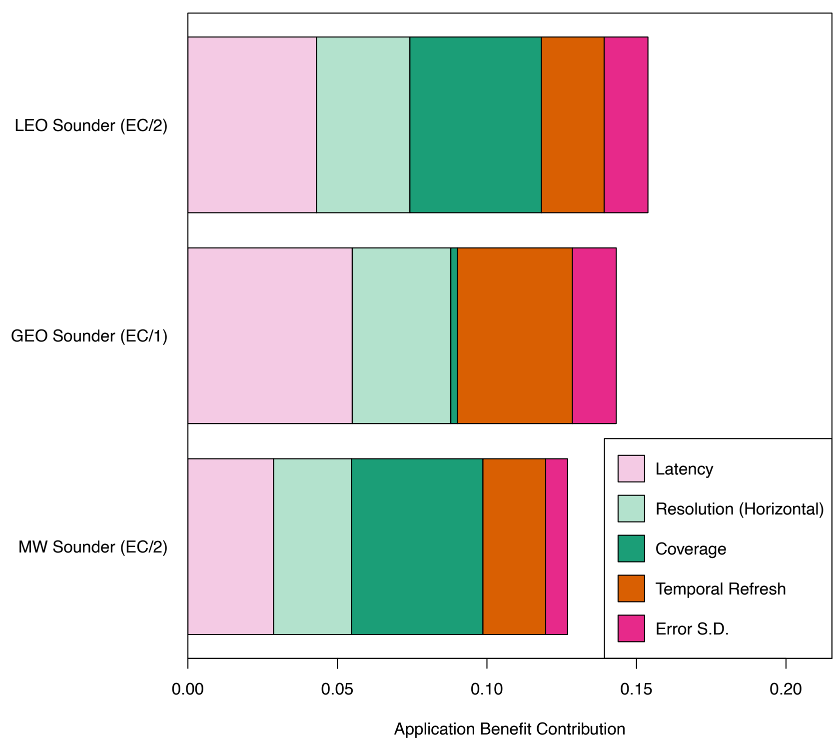

Figure 3. The benefit contribution by attribute to Global NWP for Air Temperature for the sensors in the SDE providing temperature information.

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The constellations on the efficient frontier are labeled sequentially with letters in the scatterplot and in the table in Fig. 4. This ordering is by cost, equivalently by position along the *x*-axis in the scatterplot of Fig. 4. (Additional letter labels are assigned sequentially by cost for other constellations discussed in the text. In the text, the letter X by itself will refer to constellation X in the figure being discussed.) Along the efficient frontier , both cost and benefit increase monotonically, with benefit asymptoting towards its maximum value. These trends are required along the efficient frontier. The definition of the convex hull guarantees that the slope of the efficient frontier line segments must decrease as cost increases. (If there were two consecutive efficient frontier line segments for which this did not hold, then a line connecting the distal points would pass through the area above the efficient frontier and outside of the convex hull.) Cost effectiveness decreases monotonically along the efficient frontier as well. This follows because the blue short-dashed lines of constant cost effectiveness plotted in Fig. 4 are steeper than the efficient frontier line segments. The most cost effective point along the efficient frontier must lie on a line of constant cost effectiveness that touches but does not intersect the efficient frontier. If the lines of constant cost effectiveness were less steep than point C might be the most cost effective.

The table reveals the following progression along the efficient frontier:

- A is the baseline constellation composed of the two required sensors, the MW LEO Sounder and the VIS IR GEO Imager;
- B adds the IR GEO Sounder;
- C replaces the IR GEO Sounder with the VIS IR LEO Sounder because the VIS IR LEO Sounder provides more benefit, but at higher cost;
- D adds the VIS IR LEO Imager;
- E adds back the IR GEO Sounder and adds the remaining sensors—OMPS, OCS, ACS, and LM—but these do not provide any benefit for Global NWP. (However, the IR GEO Sounder that is added back should improve the benefit over D. Why doesn't it?)

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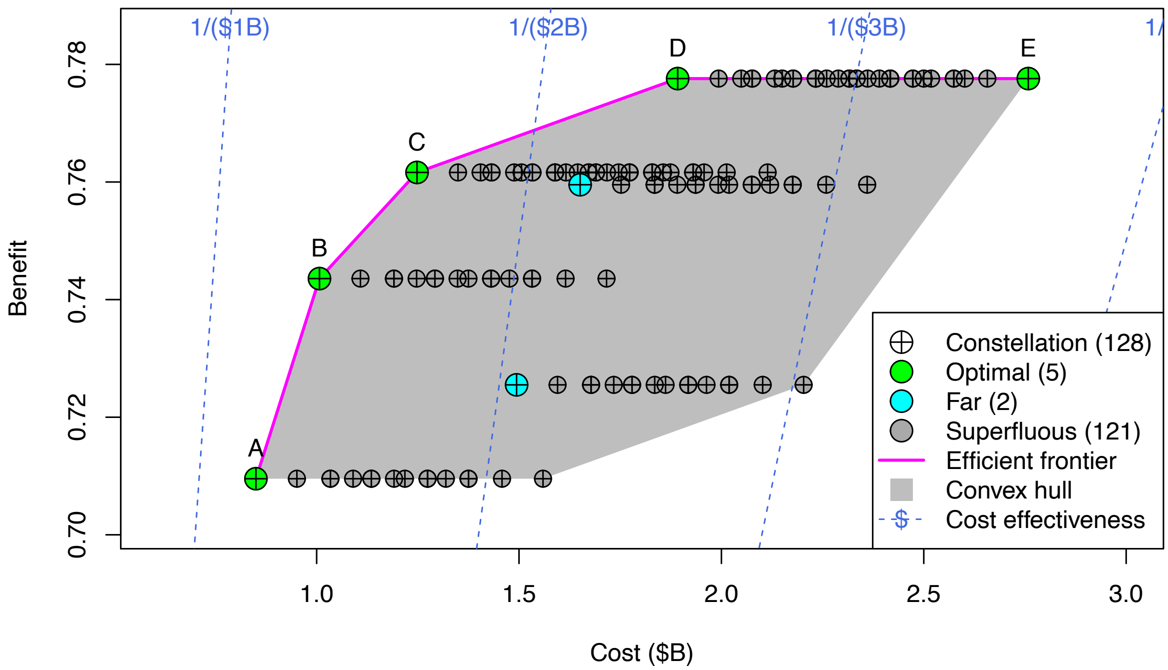

⊕	ID	Benefit	Cost	Cost Effectiveness	Distance to EF	GEO Sounder	LM	GEO Imager	ACS	OCS	MW Sounder	OMPS	LEO Imager	LEO Sounder
A	EF.128	0.710	0.850	0.835	0.0000			**EC/2**			**EC/2**			
B	EF.1	0.744	1.007	0.738	0.0000	**EC/1**		EC/2			EC/2			
C	EF.64	0.762	1.248	0.610	0.0000			EC/2			EC/2			**EC/2**
D	EF.96	0.778	1.892	0.411	0.0000			EC/2			EC/2		**EC/2**	EC/2
E	EF.127	0.778	2.758	0.282	0.0000	**EC/1**	**EC/2**	EC/2	**EC/1**	**EC/2**	EC/2	**EC/2**	EC/2	EC/2

Figure 4. Benefit vs. cost ($B) for constellations in the SDE for the Global NWP application. Plots of this type are organized as follows: In the scatterplot (top), the convex hull surrounding all constellations is shaded light gray, the efficient frontier is the magenta line, and individual constellations are plotted as circled-plus symbols. Colors under the circled-plus symbols indicate different categories with constellations defining the efficient frontier in green, constellations close to the efficient frontier (i.e., with a benefit within 0.01 of the benefit of the efficient frontier) in gold, constellations far from the efficient frontier in cyan, and superfluous constellations in dark gray. Selected constellations are annotated with letters, which are repeated in the first column of the table (bottom). The legend gives the number of constellations in each of these categories present. Lines of constant cost effectiveness are overplotted. The table (bottom) gives details for selected points ordered by increasing cost (i.e., along the x*-axis of the scatterplot). These constellations are identified (in column ID) by either EF for efficient frontier, CN for constellation near to the efficient frontier , or CF for constellations far from the efficient frontier , followed by the constellation number. The next four columns give numerical values from the scatterplot. The rightmost columns describe the sensors making up the constellations. All the cells indicating the presence of a sensor contain the sensor option in the form xC/n, where xC is the sensor class and n is number of copies of the sensor. Cells are shaded in different colors for different classes, green for EC sensors, gold for TC sensors and blue for MC sensors. The text in these cells is bold and underlined for sensors added to the constellation compared to the previous constellation. In this case, for example, EF.1 contains the IR GEO Sounder, VIS IR GEO Imager and MW LEO Sounder and relative to the previous constellation the IR GEO Sounder has been added.*

While Fig. 4 shows which sensor contribute to each constellation in the lower table, Fig. 5 shows which sensors provide information for which variables in each of these constellations. For example, compared to C, D adds the VIS IR LEO Imager (sensor 10) improving the performance for four surface variables—NDVI, Sea Ice Concentration, Snow Cover, and SST—but leaves the performance for the other variables unchanged. Since the VIS IR GEO Imager is by design included in all constellations in the SDE, the VIS IR LEO Imager can be added to but cannot replace the VIS IR GEO Imager. And the potential additional benefit of adding a VIS IR LEO Imager is limited (0.016, comparing D to C). This is because, as seen in Fig. 5, the VIS IR LEO Imager provides more benefit than the VIS IR GEO Imager only for these four surface variables, variables that do not have large priorities for Global NWP (Fig. 1a). Except for these four variables, and for Air Temperature and Relative Humidity, the other variables requirements are all best satisfied by the baseline constellation sensors—the VIS IR GEO Imager (FD mode, 4) and the MW LEO Sounder (8). For Air Temperature and Relative Humidity, each of the three sensors discussed earlier in relation to Fig. 3 are used depending on which are included in the constellations.

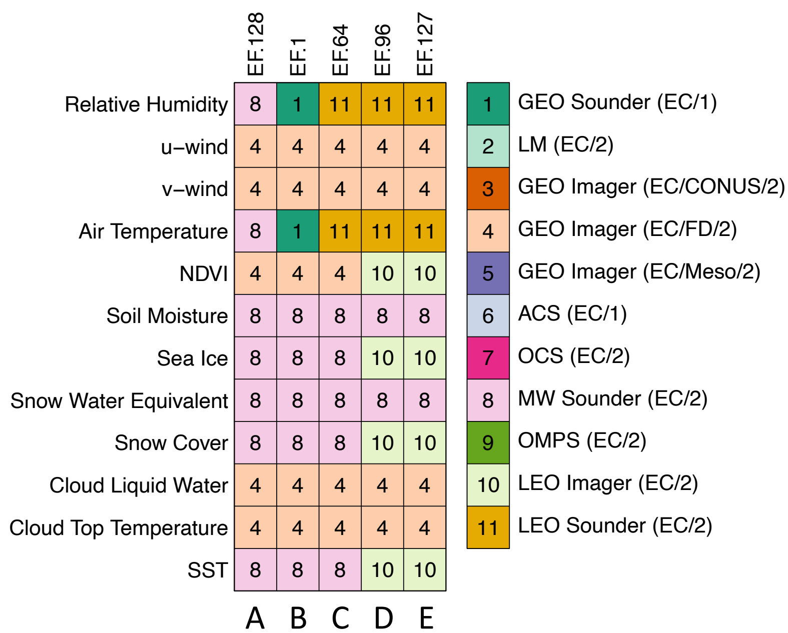

Figure 5. The sensor contribution table for the constellations listed in the table in Fig. 4 for the Global NWP application. Each cell in the plot identifies the sensor in the constellation that provided the information for each variable according to the MBV calculation (Section 2.2). E.g., snow cover is provided by the MW LEO Sounder in the first three constellations and by the VIS IR LEO Imager in the last two constellations.

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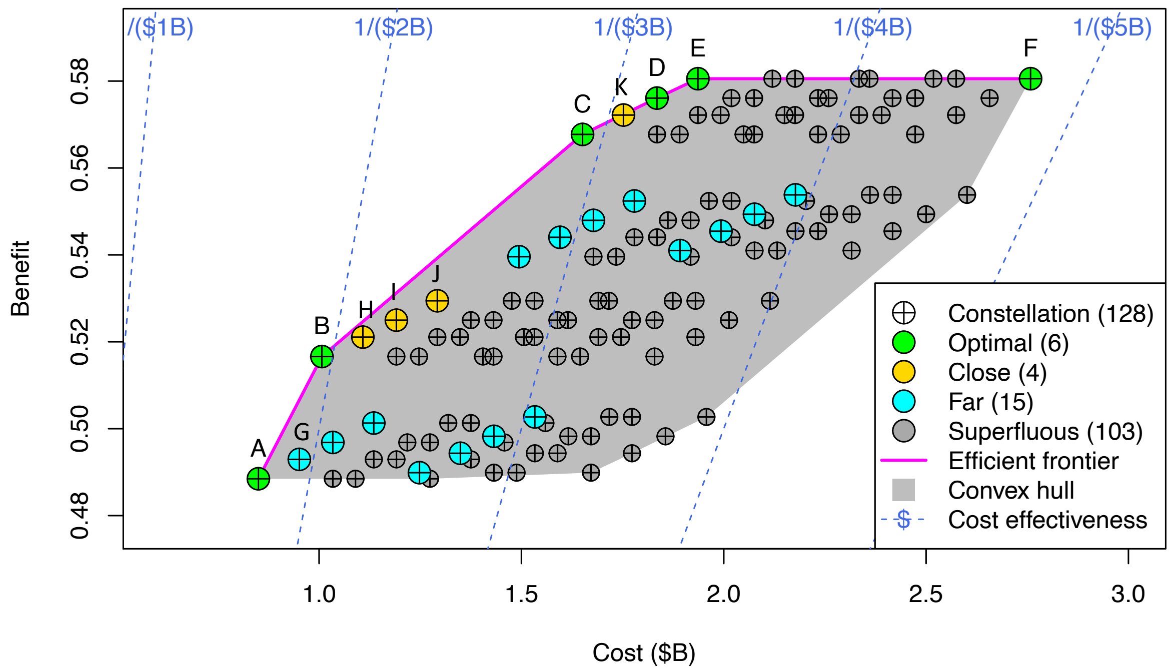
5.2. Nowcasting simple design ensemble

The general shape of the convex hull in Fig. 6 for the nowcasting applications is similar to that in Fig. 4 for the Global NWP application. However, the range of benefit for the nowcasting applications is 0.48 to 0.57, while it is 0.71 to 0.78 for the Global NWP applications. While some of the constellations defining the efficient frontier for the Global NWP case appear here as well (EF.128, EF.1, and EF.127) others are different.



⊕	ID	Benefit	Cost	Cost Effectiveness	Distance to EF	GEO Sounder	LM	GEO Imager	ACS	OCS	MW Sounder	OMPS	LEO Imager	LEO Sounder
A	EF.128	0.488	0.850	0.575	0.0000			**EC/2**			**EC/2**			
G	CF.4	0.493	0.951	0.518	0.0134			EC/2	**EC/1**		EC/2			
B	EF.1	0.517	1.007	0.513	0.0000	**EC/1**		EC/2			EC/2			
H	CN.5	0.521	1.108	0.470	0.0036	EC/1		EC/2	**EC/1**		EC/2			
I	CN.3	0.525	1.191	0.441	0.0062	EC/1	**EC/2**	EC/2			EC/2			
J	CN.7	0.529	1.292	0.410	0.0098	EC/1	EC/2	EC/2	**EC/1**		EC/2			
C	EF.33	0.568	1.651	0.344	0.0000	EC/1		EC/2			EC/2		**EC/2**	
K	CN.37	0.572	1.752	0.327	0.0001	EC/1		EC/2	**EC/1**		EC/2		EC/2	
D	EF.35	0.576	1.835	0.314	0.0000	EC/1	**EC/2**	EC/2			EC/2		EC/2	
E	EF.39	0.581	1.936	0.300	0.0000	EC/1	EC/2	EC/2	**EC/1**		EC/2		EC/2	
F	EF.127	0.581	2.758	0.210	0.0000	EC/1	EC/2	EC/2	EC/1	**EC/2**	EC/2	**EC/2**	EC/2	**EC/2**

Figure 6. Benefit vs. cost ($B) for constellations in the SDE for the nowcasting applications. As in Fig. 4.

The table in Fig. 6 reveals the following progression along the efficient frontier :

- A is the baseline constellation composed of the two required sensors, the MW LEO Sounder and the VIS IR GEO Imager;
- B adds the IR GEO Sounder;

- C adds the VIS IR LEO Imager;
- D adds the LM;
- E adds the ACS; and
- F adds the remaining sensors—OMPS, OCS, and VIS IR LEO Sounder—that do not provide any additional benefit for the nowcasting applications.

The series H, I, J are all fairly close to B and add the ACS, the LM, and both the ACS and the LM to B. Constellation K is very nearly midway between C and D and is different from C only in adding the ACS.

Figure 7 displays which nowcasting requirements are met by which sensors for which variables for two constellations along the efficient frontier (constellations B and E in Fig. 6). Constellations E (EF.39) is the constellation that provides the maximum overall benefit. In Fig. 7 we see that the baseline sensors (sensors 3 and 4 for the VIS IR GEO Imager and 8 for the MW LEO Sounder) provide the benefit for most variables. Notable exceptions are that the IR GEO Sounder (1) provides the benefit for Relative Humidity and Air Temperature and the VIS IR LEO Imager (10) provides information for Smoke, Hydrometeor Size, Fire Power, Flood Extent, Fire Size/Location, Surface Type, and Cloud Base Height for several of the nowcasting applications. In addition, the LM provides benefit for Total Lightning for the Thunderstorms Nowcasting application, and the ACS provides benefit for Aerosol Layer Height for the Fire Monitoring Nowcasting application. In Fig. 7a, there are no contributions from the VIS IR LEO Imager, the LM, and the ACS and most of the cells identified with these sensors are blank, except for the two fire variables observed by the VIS IR GEO Imager (3). It is not necessary but in Fig. 7 the same sensor provides the benefit across those applications requiring a particular variable. There is a single exception in that cloud and moisture imagery (CMI, labeled Imagery) is provided by the CONUS mode of the VIS IR GEO Imager for Fire Monitoring Nowcasting, while it is provided by the FD mode in all other cases. This is because for Imagery the Fire Monitoring Nowcasting application has more stringent requirements for temporal refresh (15 minutes is minimally useful and 30 seconds is maximally useful) than do the other nowcasting applications (1 hour is minimally useful and 1 minute is maximally useful) and the temporal refresh performance is 5 minutes for CONUS and 10 minutes for FD.

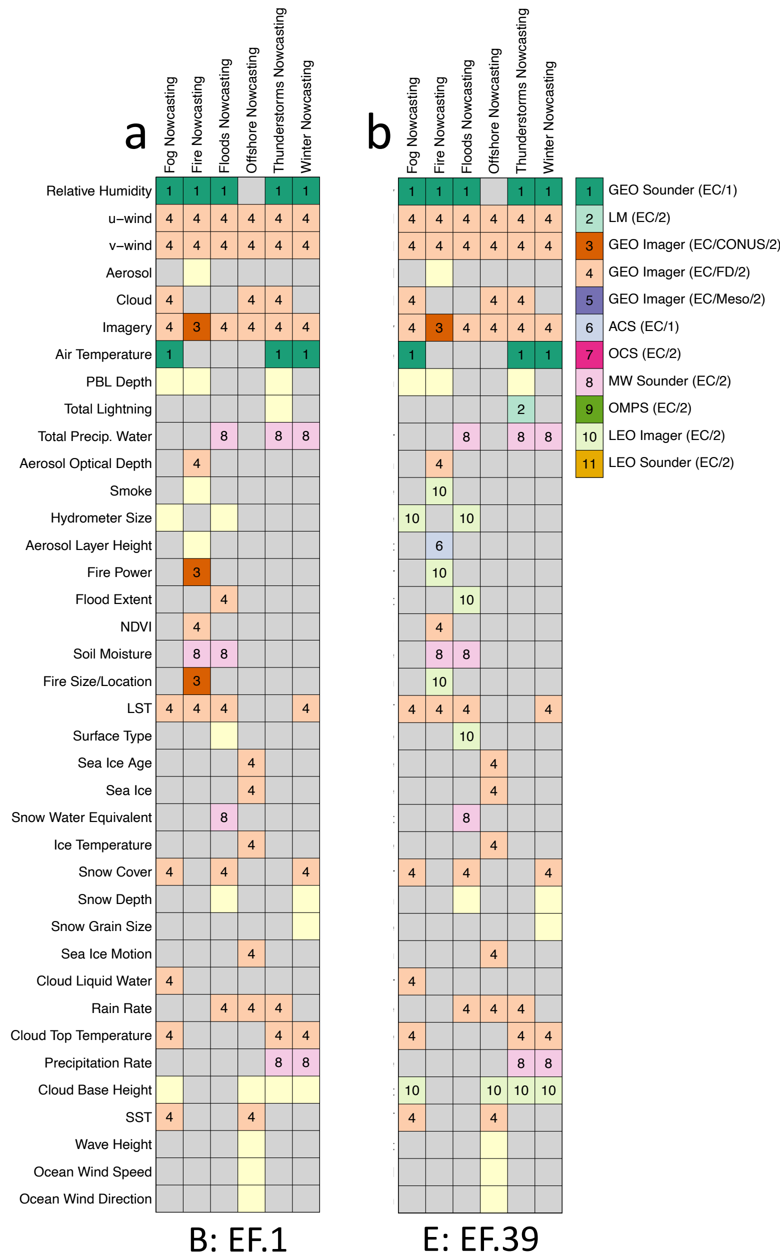


Figure 7. The sensor contribution table for constellations (a) EF.1 and (b) EF.39. Each cell in the plot identifies the sensor (sensor type and sensor option) in the constellation that provided the information for each variable for each of the nowcasting applications. In the figure, grey table cells indicate variables with no application requirements (as in Fig. 1a) and yellow table cells indicate variables with unmet requirements. E.g., cloud base height information (fifth row from the bottom), which is required by 4 of the 6 nowcasting applications, is not provided by any sensor in EF.1 and is provided by the VIS IR LEO Imager (10) in EF.39.

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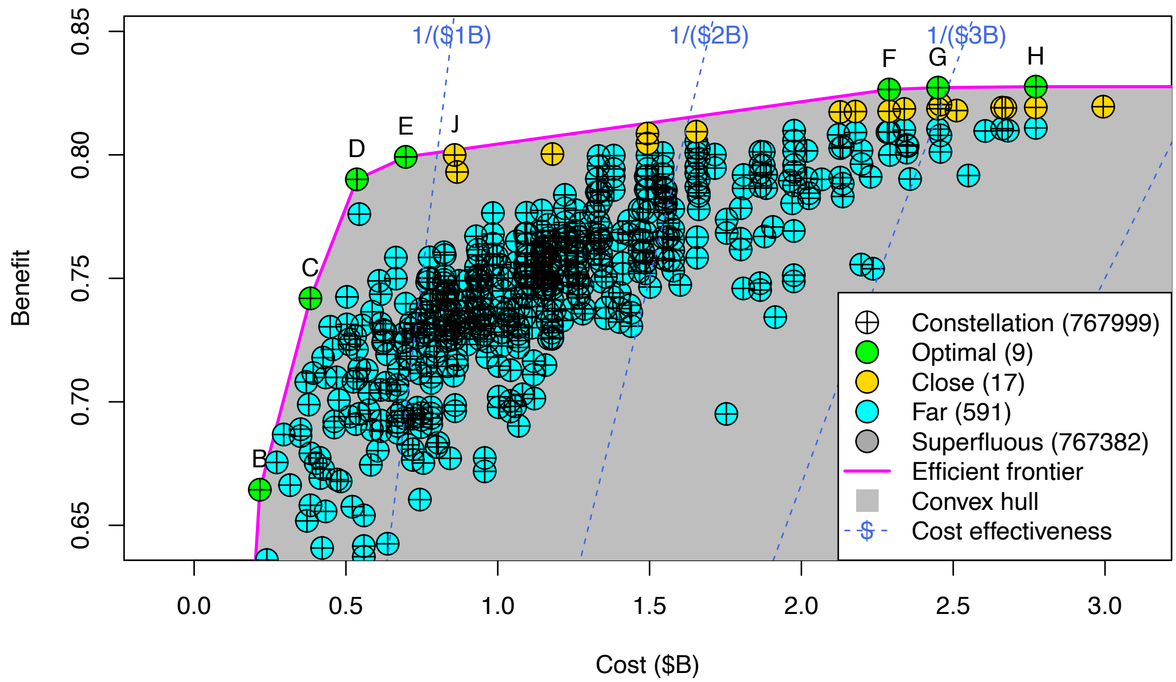
5.3. Global NWP enhanced design ensemble

The EDE allows for many more choices with substantial changes to the efficient frontier for Global NWP compared to the SDE. The convex hull in Fig. 8 is steep for the first 4 constellations and then is quite flat starting with the fifth constellation (E). Note that the first and last constellations on the efficient frontier are outside the range of the scatterplot in Fig. 8. The range of benefits and costs is expanded compared to the case of the SDE. Now benefits range from 0.34 to 0.83 (compared to 0.71 to 0.78) and the costs excluding the last "uninteresting" point on the efficient fronter range from \$56M to \$2.8B (compared to \$0.85B to \$1.9B). It turns out that in the EDE case the optimal constellations are more cost effective by making use of the advanced maximal class sounders, but the less expensive threshold class imagers.

The table in Fig. 8 reveals the following progression along the efficient frontier:

- A contains only a single copy of the threshold class MW LEO Sounder and is both cheapest and most cost effective (see discussion of cost effectiveness given for Fig. 4);
- B adds the threshold class VIS IR LEO Imager;
- C changes the class of the MW LEO Sounder from threshold to maximal;
- D replaces the threshold class VIS IR LEO Imager (at GOES Central) in favor of the threshold class VIS IR GEO Imager (at GOES East and West);
- E adds back the threshold class VIS IR LEO Imager;
- F adds 4 copies of the maximal class VIS IR LEO Sounder are added;
- G and H increase the count of the threshold class VIS IR LEO Imager from 1 to 2 to 4; and
- I adds the most expensive versions of the remaining sensors—OMPS, OCS, ACS, and IR GEO Sounder—sensors that do not provide any additional benefit for the Global NWP application.

Constellations close to the efficient frontier with costs between \$0.7B and \$2.3B (i.e., between E and F) are for the most part similar but vary the number of TC VIS IR LEO Imagers and MC VIS IR LEO Sounders.



⊕	ID	Benefit	Cost	Cost Effectiveness	Distance to EF	GEO Sounder	LM	GEO Imager	ACS	OCS	MW Sounder	OMPS	LEO Imager	LEO Sounder
A	EF.768	0.340	0.056	6.135	0.0000						**TC/1**			
B	EF.31488	0.664	0.217	3.069	0.0000						TC/1		**TC/1**	
C	EF.32064	0.742	0.383	1.937	0.0000						**MC/1**		TC/1	
D	EF.1368	0.790	0.536	1.474	0.0000			**TC/2**			MC/1			
E	EF.32088	0.799	0.697	1.147	0.0000			TC/2			MC/1		**TC/1**	
J	CN.39768	0.800	0.858	0.932	0.0020			TC/2			MC/1		**TC/2**	
	CN.47448	0.800	1.180	0.678	0.0071			TC/2			MC/1		**TC/4**	
	CN.646488	0.809	1.493	0.542	0.0042			TC/2			MC/1		**TC/1**	**MC/2**
	CN.262488	0.805	1.493	0.539	0.0082			TC/2			MC/1		TC/1	**EC/4**
	CN.654168	0.809	1.654	0.489	0.0062			TC/2			MC/1		**TC/2**	**MC/2**
	CN.692568	0.817	2.128	0.384	0.0063			TC/2			MC/1			**MC/4**
	CN.722136	0.818	2.178	0.375	0.0070			TC/2			**EC/1**		**TC/1**	MC/4
F	EF.723288	0.826	2.289	0.361	0.0000			TC/2			**MC/1**		TC/1	MC/4
	CN.729816	0.819	2.339	0.350	0.0081			TC/2			**EC/1**		**TC/2**	MC/4
G	EF.730968	0.827	2.450	0.338	0.0000			TC/2			**MC/1**		TC/2	MC/4
	CN.738624	0.820	2.458	0.334	0.0069						MC/1		**TC/4**	MC/4
H	EF.738648	0.828	2.772	0.299	0.0000			**TC/2**			MC/1		TC/4	MC/4
	CN.737880	0.820	2.994	0.274	0.0081			TC/2			**EC/4**		TC/4	MC/4
I	EF.767999	0.828	7.759	0.107	0.0000	**MC/1**	**MC/2**	**MC/2**	**EC/1**	**EC/2**	**MC/4**	**EC/4**	**MC/4**	MC/4

Figure 8. Benefit vs. cost ($B) for constellations in the EDE for the Global NWP application. As in Fig. 4, but only for part of the range of cost and benefit and without plotting the superfluous constellations. The total number of constellations in the EDE is 767999 but only 617 (0.08%) are not superfluous in the case of the Global NWP application. In the table all the efficient frontier constellations but only the 10 closest of the CN constellations are listed.

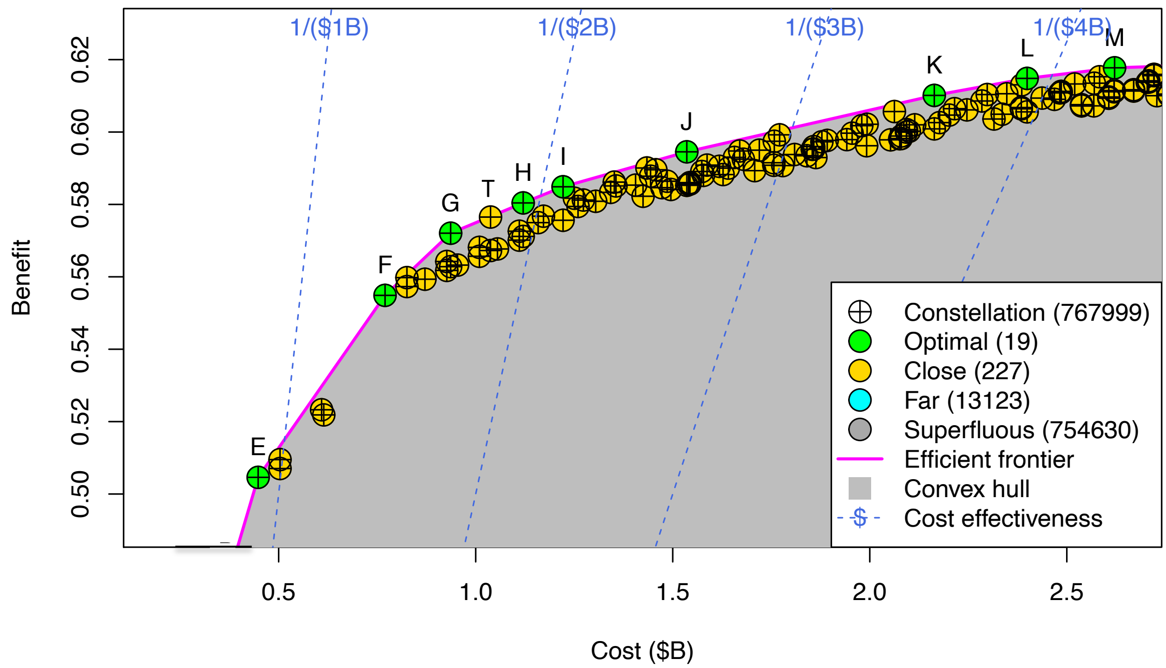
5.4. Nowcasting enhanced design ensemble

The convex hull for the nowcasting EDE case in Fig. 9 is like that for the Global NWP case—steep for the first several constellations and then quite flat. The first 4 and last 6 points of the efficient frontier are outside the bounds of the scatterplot in Fig. 9. Compared to the nowcasting SDE case, the range of benefits along the efficient frontier is now 0.11 to 0.62

(compared to 0.49 to 0.58) and costs range from $56M to $5.5B (compared to $0.85B to $1.94B).

The table in Fig. 9 reveals the following progression along the efficient frontier :

- A contains only a single copy of the TC MW LEO Sounder (as in the Global NWP case);
- B contains only a single copy of the TC VIS IR LEO Imager (at GOES Central);
- C combines these two sensors (and is the same as the second efficient frontier constellation for Global NWP);
- D is the baseline case of a MW LEO Sounder and 2 VIS IR GEO Imagers, choosing TC sensors for both;
- E adds the TC IR GEO Sounder;
- F adds the EC VIS IR LEO Imager;
- G replaces the TC MW LEO Sounder with the MC MW LEO Sounder;
- H adds the EC LM;
- I adds the EC ACS;
- J replaces the TC VIS IR GEO Imager with the EC VIS IR GEO Imager;
- K replaces the EC VIS IR GEO Imager with the MC VIS IR GEO Imager;
- L replaces the TC IR GEO Sounder with the MC IR GEO Sounder;
- M increases the count from 1 to 2 for the MC MW LEO Sounder;
- N replaces the EC VIS IR LEO Imager with the MC VIS IR LEO Imager;
- O increases the count from 2 to 4 for the MC MW LEO Sounder;
- P replaces the EC LM with the MC LM;
- Q replaces the MC VIS IR LEO Imager with 4 EC VIS IR LEO Imagers;
- R replaces the 4 EC VIS IR LEO Imagers with 4 MC VIS IR LEO Imagers;
- S adds the most expensive versions of the remaining sensors—OMPS, OCS, and VIS IR LEO Sounder—sensors that do not provide any additional benefit for the nowcasting applications.



⊕	ID	Benefit	Cost	Cost Effectiveness	Distance to EF	GEO Sounder	LM	GEO Imager	ACS	OCS	MW Sounder	OMPS	LEO Imager	LEO Sounder
A	EF.768	0.105	0.056	1.885	0.0000						**TC/1**			
B	EF.30720	0.312	0.161	1.937	0.0000								**TC/1**	
C	EF.31488	0.384	0.217	1.776	0.0000						**TC/1**		TC/1	
D	EF.792	0.476	0.370	1.287	0.0000			**TC/2**			TC/1			
E	EF.794	0.505	0.448	1.126	0.0000	**TC/1**		TC/2			TC/1			
F	EF.8474	0.555	0.770	0.721	0.0000	TC/1		TC/2			TC/1		**EC/1**	
G	EF.9050	0.572	0.937	0.611	0.0000	TC/1		TC/2			**MC/1**		EC/1	
T	CN.9098	0.577	1.038	0.556	0.0001	TC/1		TC/2	**EC/1**		MC/1		EC/1	
H	EF.9054	0.580	1.121	0.518	0.0000	TC/1	**EC/2**	TC/2			MC/1		EC/1	
I	EF.9102	0.585	1.222	0.479	0.0000	TC/1	EC/2	TC/2	**EC/1**		MC/1		EC/1	
J	EF.9090	0.595	1.536	0.387	0.0000	TC/1	EC/2	**EC/2**	EC/1		MC/1		EC/1	
K	EF.9114	0.610	2.164	0.282	0.0000	TC/1	EC/2	**MC/2**	EC/1		MC/1		EC/1	
L	EF.9115	0.615	2.399	0.256	0.0000	**MC/1**	EC/2	MC/2	EC/1		MC/1		EC/1	
M	EF.9307	0.618	2.621	0.236	0.0000	MC/1	EC/2	MC/2	EC/1		**MC/2**		EC/1	
	CN.9311	0.618	2.805	0.220	0.0002	MC/1	**MC/2**	MC/2	EC/1		MC/2		EC/1	
N	EF.55387	0.619	2.943	0.210	0.0000	MC/1	**EC/2**	MC/2	EC/1		MC/2		**MC/1**	
	CN.16987	0.618	2.943	0.210	0.0004	MC/1	EC/2	MC/2	EC/1		MC/2		**EC/2**	
	CN.9499	0.619	3.065	0.202	0.0001	MC/1	EC/2	MC/2	EC/1		**MC/4**		**EC/1**	
	CN.55391	0.619	3.127	0.198	0.0001	MC/1	**MC/2**	MC/2	EC/1		**MC/2**		**MC/1**	
	CN.9503	0.620	3.249	0.191	0.0002	MC/1	MC/2	MC/2	EC/1		**MC/4**		**EC/1**	
O	EF.55579	0.620	3.387	0.183	0.0000	MC/1	**EC/2**	MC/2	EC/1		MC/4		**MC/1**	
P	EF.55583	0.621	3.571	0.174	0.0000	MC/1	**MC/2**	MC/2	EC/1		MC/4		MC/1	
	CN.24859	0.621	4.031	0.154	0.0002	MC/1	**EC/2**	MC/2	EC/1		MC/4		**EC/4**	
	CN.63259	0.621	4.031	0.154	0.0003	MC/1	EC/2	MC/2	EC/1		MC/4		**MC/2**	
Q	EF.24863	0.622	4.215	0.147	0.0000	MC/1	**MC/2**	MC/2	EC/1		MC/4		**EC/4**	
	CN.63263	0.622	4.215	0.147	0.0001	MC/1	MC/2	MC/2	EC/1		MC/4		**MC/2**	
	CN.70939	0.622	5.319	0.117	0.0003	MC/1	**EC/2**	MC/2	EC/1		MC/4		**MC/4**	
R	EF.70943	0.623	5.503	0.113	0.0000	MC/1	**MC/2**	MC/2	EC/1		MC/4		MC/4	
S	EF.767999	0.623	7.759	0.080	0.0000	MC/1	MC/2	MC/2	EC/1	**EC/2**	MC/4	**EC/4**	MC/4	**MC/4**

Figure 9. Benefit vs. cost ($B) for constellations in the EDE for the nowcasting applications. As in Fig. 8, but only optimal and closest constellations are plotted. For the nowcasting applications only 13369 (1.74%) of all constellations are not superfluous.

5.5. Satisfying a budget constraint

Given a hypothetical budget of $1B, the most beneficial choice is the constellation with the maximum benefit among all those with costs less than or equal to the budget of $1B. The choice is the baseline constellation (EF.128 or 4A for constellation A in Fig. 4) for the Global NWP SDE, and CF.4 (6G) for the nowcasting SDE. Constellation CF.4 (6G) adds the ACS to the baseline constellation. The choice is CN.39768 (8J) for the Global NWP EDE and EF.9050 (9G) for the nowcasting EDE. The actual costs and benefits for these constellations and some neighboring constellations are given in Fig. 10. It is interesting to consider nearby constellations, including some that break the budget by a small amount but provide additional benefit. For the Global NWP SDE, EF.1 (4B) adds the IR GEO Sounder to EF.128 (4A) for a total cost of only $1.007B, increasing the benefit from 0.710 to 0.744 (i.e., by 4.8%). For the nowcasting SDE, CN.5 (6H) adds the IR GEO Sounder to CF.4 (6G) for a total cost of $1.108B increasing the benefit from 0.493 to 0.521 (i.e., by 5.6%). For the Global NWP EDE, the choice CN.39768 (8J) could be replaced with EF.32088 (8E) with a savings of $161M and a negligible decrease in benefit. These constellations are identical except that EF.32088 (8E) has 1 TC VIS IR LEO Imager and CN.39768 (8J) has two. For the nowcasting EDE, CN.9098 (9T) adds the ACS to the choice EF.9050 (9G) for a total cost of only $1.038B marginally increasing the benefit from 0.572 to 0.577 (i.e., by 0.8%).

DE	App.	⊕	ID	Benefit	Cost	Cost Effectiveness	Distance to EF	GEO Sounder	LM	GEO Imager	ACS	OCS	MW Sounder	OMPS	LEO Imager	LEO Sounder
SDE	NWP	4A	EF.128	0.710	0.850	0.835	0.0000			**EC/2**			**EC/2**			
		4B	EF.1	0.744	1.007	0.738	0.0000	**EC/1**		EC/2			EC/2			
	Now.	6A	EF.128	0.488	0.850	0.575	0.0000			EC/2			EC/2			
		6G	CF.4	0.493	0.951	0.518	0.0134			EC/2	**EC/1**		EC/2			
		6B	EF.1	0.517	1.007	0.513	0.0000	**EC/1**		EC/2			EC/2			
		6H	CN.5	0.521	1.108	0.470	0.0036	EC/1		EC/2	**EC/1**		EC/2			
EDE	NWP	8E	EF.32088	0.799	0.697	1.147	0.0000			**TC/2**			**MC/1**		**TC/1**	
		8J	CN.39768	0.800	0.858	0.932	0.0020			TC/2			MC/1		**TC/2**	
	Now.	9G	EF.9050	0.572	0.937	0.611	0.0000	**TC/1**		TC/2			MC/1		**EC/1**	
		9T	CN.9098	0.577	1.038	0.556	0.0001	TC/1		TC/2	**EC/1**		MC/1		EC/1	

Figure 10. Optimal and near optimal constellation satisfying or nearly satisfying a budget of $1B. Similar to the table part of Fig. 4 but adding columns on the left listing the design ensemble (DE; column 1) and the application (App.; column 2) and adding figure number to the letters (in column 3).

Comparing the constellations in Fig. 10 for the SDE and EDE, all cases include the baseline sensors—two VIS IR GEO Imagers and one or two MW LEO Sounders. However, given its additional degrees of freedom, the EDE optimal constellations choose the less capable TC VIS IR GEO Imagers and 1 of the more capable MC MW LEO Sounder instead of the 2 EC MW

LEO Sounders. Similarly, the nowcasting EDE optimal constellations include a less capable (TC rather than EC) IR GEO Sounder. With these budget savings on the GEO sensors, the EDE constellations can afford adding a VIS IR LEO Imager.

6. Summary and concluding remarks

Many factors drive the design, evolution and planning of the observing systems of the future. A goal of ASPEN is to influence this design in a way to maximize science benefit and cost effectiveness to targeted applications. This maximization should be "democratic" in that all relevant applications should have a voice, and that all observing systems candidates and combinations should be considered. The merit of the observing systems should be judged based on their abilities to maximize the ASPEN satisfaction metric (i.e., benefit). The ASPEN benefit combines the degree to which the application requirements are fulfilled by the observing systems performances, weighted by the application priorities. ASPEN comparisons of observing systems performances to applications requirements are observing system neutral because the ASPEN interface characterizes the Earth System in terms of geophysical observables and their attributes.

ASPEN is designed to be a science-based and efficient tool for comparative assessment of observation systems. This comparative assessment can support sensor design, payload optimization, and constellation planning. This could be ~~very~~ useful ~~for instance~~ in space agencies' future planning and in international global constellation optimization activities. It could also be useful in supporting public/private or public/commercial sector partnerships. This is especially true if the intent is to design observing systems and/or networks to optimize the value to the applications targeted by these Earth-observations. ASPEN is designed to support the decision process leading to the design, selection and ultimately deployment of new space-based or ground-based assets or to the select acquisition of commercial data either as complement or as a baseline component of the Global Observing System.

In the current proof of concept study, ASPEN is used to support constellation optimization by calculating the efficient frontier in the space of constellation cost vs. benefit. This is done in four cases—for Global NWP and 6 nowcasting applications, and for a simple and an enhanced design ensemble containing 128 and 767999 potential constellations, respectively. Visualizing the results as cost-benefit efficient frontier scatterplots identifies the most efficient constellations—the constellations that maximize benefit for a given cost. The optimal constellation depends strongly on the budget, the applications considered, and design ensemble. In the SDE (simple design ensemble) the MW LEO Sounder and the VIS IR GEO Imager are assumed to be in every constellation. These sensor types are also included in almost every constellation on or near the efficient frontier in the EDE (enhanced design ensemble) cases. Beyond these two sensors, the sensor adding the most benefit is an IR hyperspectral sounder, usually the VIS IR LEO Sounder for Global NWP and always the IR GEO Sounder for the nowcasting applications. Thus, the optimal constellations for Global NWP are (not surprisingly) different from those for nowcasting. For illustration a simple decision rule is applied to select the optimal constellation for a given budget (set at $1B in annualized sensor costs for the purpose of illustration in this study). In practice such guidance must be carefully considered in the context of neighboring constellations in the efficient frontier scatterplot.

The characteristics, assumptions, limitations, applicability, and potential of ASPEN are all summarized by Boukabara and Hoffman (2022). In the current study the following limitations and caveats must be kept in mind:

- We only considered the Global NWP and nowcasting applications and only some of the NOAA GEO and LEO sensors. We did not consider non-NOAA sensors such as those provided in the current global observing system by EUMETSAT and others. The constellations considered are limited to the SDE and the EDE (Section 4). A more comprehensive list of applications is required to properly represent all of NOAA's interests. In particular, space weather sensors and applications are not included in the current study. Near-future application inputs to ASPEN will include atmospheric composition applications for air quality monitoring and forecasting, stratospheric composition, and climate monitoring. Ultimately, one would want to optimize the Next-Gen architecture using all observing systems that might potentially contribute including LEO, GEO, space weather system, commercial data products, and ground-based systems. For example, since we do not include ground-based observing systems, the benefits to nowcasting due to weather radars is not included. For some nowcasting applications and for some variables, weather radars would likely displace the MW LEO Sounder in some constellations. However, given the

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limitations of the current study, the MW LEO Sounder is present in many efficient constellations. First, in the SDE cases the MW LEO Sounder is included in all constellations considered. In addition, the TC MW LEO Sounder is the least expensive sensors considered (Table 1), and of all these sensors the MW LEO Sounder is the only source of information for some variables—Soil Moisture, Snow Water Equivalent, Precipitation Rate—and is the best sensor for Total Precipitable Water (Fig.1).

- We did not consider radio occultation in the NWP application, despite the fact that radio occultation sounding data are one of the most cost-effective and impactful data sources in NWP.
- We used the prototype version of ASPEN and available ASPEN data bases. The list of variables and the definitions of attributes are under development for the next version of ASPEN. The prototype version of ASPEN uses the maximum benefit by variable (MBV) approach to combine sensors in a constellation. The effect of exclusions, e.g., due to cloud cover, precipitation, surface types, and solar zenith angle, are not included in the prototype version of ASPEN.
- ASPEN reliability depends on trustworthiness of its inputs (performances and costs of the observing systems, and requirements ranges and priorities of the applications). In this study the sensors performances were obtained using a combination of the MIT/LL and JPL instrument catalogs developed for the NSOSA study. These sensors are not exactly the sensors considered by the GeoXO and LEO programs but are considered close. Costs are estimated from public sources and the JPL instrument catalog. We used only the Global NWP and nowcasting applications in this study because these are considered highly reliable. In the nowcasting calculations the 6 nowcasting applications are given equal weighting (i.e., equal strategic priorities). The application requirement ranges and priorities used in this study are current. These should be projected to account for advances in applications that are likely to take place in the run up to the Next-Gen architecture deployment.
- Costs for EC sensors with legacy equivalents in the JPSS and GOES-R program are those total program's costs allocated to each sensor based proportionally to each

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sensor's build costs. Costs for other sensors are based on simple scaling arguments. The constellation cost model simply sums the annualized per sensor allocation of the total system costs. By construction, this method reproduces the JPSS and GOES-R program costs for identical EC constellations. The costs of adoption are not included. These costs might consider the time to actually use new data in operations. If the mission lifetime is 4 years but it takes 2 years to operationalize the new data, then the total mission cost should be divided by 2, not 4, to get the annual cost. Costs should be more rigorously and consistently estimated.

It is critical that the ASPEN data bases uniformly and consistently reference common definitions of the geophysical variables, their attributes, and how the attribute values should be estimated. This is required for independent groups to describe observing system performances or application requirements in a way that can be fairly compared. A major concern in this regard is the definition of attributes that characterize error. A uniform definition and sampling approach must be used for estimates of these attributes to be comparable. This is necessary on a per variable basis since different users may have different interpretations of the variables which then impact the estimated error statistics. For example, in the current study, we struggled with the definition of precision for specific humidity and relative humidity. Are these in terms of the original variables or normalized variables? If normalized, how normalized. In a more complicated example, are there different definitions of “flood” in use by the algorithm developer, nowcasting, disaster monitoring, and climate communities? What about clouds—are we talking about cloud cover (%) or cloud mask (0/1)? And what is the definition of the edge of the cloud? Similar questions occur for other variables (e.g., snow cover, fire). If these definitions cannot be agreed upon, collaboration between diverse communities could result in incomparable values.

Traditionally, Earth observing systems are expensive and have long lifetimes. This paradigm is shifting, with new sources of information from commercial data buys and fleets of small refreshable satellites. Investment decisions in these systems are fraught but can be supported by ASPEN. This is the case because ASPEN collects and validates information from multiple sources and experts yet provides traceability from the ASPEN calculated benefits to the validated information. Of course, ASPEN is a work in progress, and we welcome community collaboration and coordination, which so far has been organized through the SAT. There are many possible

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extensions and enhancements to ASPEN. A current focus of the ASPEN team is collecting and validating the observing system capabilities, application requirements, and application priorities. This is critical because ASPEN results are limited by the quality of the ASPEN inputs. With further advances we expect ASPEN will become an increasingly valuable addition to the observing systems assessment toolbox.

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Data availability statement.

Please contact the authors. We will be happy to explore ways to collaborate with members of the science community. The inputs for the calculations shown in this paper are available as excel files from the authors.

APPENDICES

7. Sensors

The sensors are briefly described in this appendix, ordered as in Table 1. Sensor performances are summarized from the ASPEN data base used in this study. Other sensor characteristics are summarized from the NSOSA instrument catalog (Zuffada and Beatty 2016) and from the GeoXO website (https://www.nesdis.noaa.gov/next-generation/geostationary-extended-observations-geoxo).

Sensor	N	Coverage	Density (Horizontal)	Resolution (Horizontal)	Temporal Refresh	Vertical Resolution	Latency
Units	count	logical	(100 km)-2	km	min	km	min
GEO Sounder (TC)	4	CONUS	[0.04,39]	5	30	[5,25]	3
GEO Sounder (EC)	8	CONUS	[0.04,39]	5	30	[3,25]	3
GEO Sounder (MC)	8	CONUS	[0.04,39]	4	15	[3,25]	3
LM (EC)	3	Full Disk	1.5625	[8,500]	1.67E-05	1	0.5
LM (MC)	1	Full Disk	1.5625	4	1.67E-05	1	0.333
GEO Imager (TC/CONUS)	21	CONUS	[6.93,40000]	[1,4]	[1,5]	1	[1,210]
GEO Imager (EC/CONUS)	21	CONUS	[6.93,40000]	[1,2]	5	1	[1,210]
GEO Imager (MC/CONUS)	21	CONUS	[6.93,40000]	[0.3,1]	2.5	1	[1,210]
GEO Imager (TC/FD)	21	Full Disk	[6.93,40000]	[1,4]	15	1	[1,210]
GEO Imager (EC/FD)	21	Full Disk	[6.93,40000]	[1,2]	10	1	[1,210]
GEO Imager (MC/FD)	21	Full Disk	[6.93,40000]	[0.3,1]	5	1	[1,210]
GEO Imager (TC/Meso)	21	Meso	[6.93,40000]	[1,4]	0.167	1	[1,210]
GEO Imager (EC/Meso)	21	Meso	[6.93,40000]	[1,2]	0.5	1	[1,210]
GEO Imager (MC/Meso)	21	Meso	[6.93,40000]	[0.3,1]	0.25	1	[1,210]
ACS (EC)	8	CONUS+AK+HI	[49.87,371]	[5.192,14.16]	180	[1,2]	5
OCS (EC)	1	CONUS+AK+HI+US EEZ	40000	0.3	180	1	5
MW Sounder (TC)	10	Global	16	23	180	[1,5]	180
MW Sounder (EC)	14	Global	16	25	720	[1,8]	180
MW Sounder (MC)	14	Global	16	5	60	[1,8]	90
OMPS (EC)	4	Global	13	25	720	[1,3]	90
LEO Imager (TC)	23	Global	10000	1	720	[1,3]	90
LEO Imager (EC)	26	Global	[1,71111]	0.75	720	[1,3]	90
LEO Imager (MC)	25	Global	[1,71111]	0.5	720	[1,3]	90
LEO Sounder (TC)	5	Global	[0.04,39]	13.5	1440	[0.5,7]	90
LEO Sounder (EC)	8	Global	[0.04,39]	10	720	[1,10]	90
LEO Sounder (MC)	8	Global	[0.04,39]	2	720	[1,10]	15

Figure 11. Selected attributes for different sensor classes and modes. The second column (labeled N) gives the number of variables observed by the sensor. In the following columns, intervals give the minimum and maximum taken over all variables for the attribute and sensor. If the minimum and maximum are the same only a single value is given.

Of the 9 sensor types listed in Table 1, 3 are sounders and 2 are imagers. The sounders are used to derive vertical profiles of temperature and water vapor from multiple spectral channels that are sensitive to different vertical levels. The imagers make observations in multiple spectral bands including panchromatic day night bands (DNBs), which provide 24 h coverage.

7.1. Sensor geophysical performances

Sensor performances extracted from the ASPEN data base used in this study are summarized in the tables of Fig. 11 and Fig. 12.

7.2. Sensor spectral characteristics and modes of operation

The IR GEO Sounder is designed to provide regional real time vertical profiles of temperature and water vapor. Spectral resolution is 1.0, 0.625 and 0.625 cm^{-1} for the TC, EC, and MC sensors. The TC spectral range is restricted to the near IR (4.08 to 5.13 microns), while the EC and MC spectral ranges cover the near and far IR (3.9 to 13.3 and 4.4 to 14.7 microns, respectively).

The Lightning Mapper (LM) is designed to provide real time regional lightning observations. Like the Geostationary Lightning Mapper (GLM), the LM is a single channel, high detection efficiency, near IR, optical transient detector that is sensitive to all forms of lightning during both day and night.

The VIS IR GEO Imager is designed to provide real time regional weather imagery with IR, visible and DNB bands. All classes include Full Disk and CONUS coverage, and the EC and MC class sensors include 2 and 5 respectively moveable 1000 km x 1000 km mesoscale regions. Spectral range is 0.47 to 13.6 microns for the TC and EC sensors and 0.47 to 13.7 microns for the MC sensor. Spectral resolution varies, with 17 bands (including 1 DNB) for the TC and EC sensors and 157 (including 3 DNBs) for the MC sensor.

The Atmospheric Composition Sensor (ACS) is designed to provide real time regional monitoring of air quality, stratospheric ozone, aerosols, and volcanic ash. ACS is a hyperspectral ultraviolet to the visible spectrometer.

The Ocean Color Sensor (OCS) is designed to provide real time regional observations of ocean biology, chemistry, and ecology. OCS is a hyperspectral, ultraviolet through near-infrared passive imaging radiometer.

The MW LEO Sounder is designed to provide global vertical profiles of temperature and water vapor as well as several surface quantities (see Fig. 1b). Spectral bands that are exploited are the 90, 118, and 183 GHz bands for the TC sensor, and the 24, 31, 50-60, 90, 165, and 183 GHz bands for the EC and MC sensors. As a result, the TC spectral range is restricted to the shortwave (millimeter) MW spectrum (90 to 205 GHz), while the EC and MC spectral ranges cover the mid-wave and shortwave part of the MW spectrum (23 to 183 and 18 to 183 GHz, respectively).

Variable	Error S. D.	Sensor(s)	Error S. D.	Sensor(s)	Error S. D.	Sensor(s)	Error S. D.	Sensor(s)
Relative Humidity (%)	10	GEO Sounder and LEO Sounder	25	MW Sounder (TC)	20	MW Sounder (EC/MC)		
u/v-wind (m/s)	6	GEO Imager	7.5	LEO Imager				
Aerosol (/m3)								
Cloud (Fraction)	0.87	GEO Imager	0.15	LEO Imager				
Ozone (DU)	10	GEO Sounder (EC/MC) and LEO Sounder (EC/MC)	9	ACS (EC)	1	OMPS (EC)		
Imagery (NA)								
Incoming SW (W/m2)	65	GEO Imager						
Air Temperature (K)	1	GEO Sounder and LEO Sounder (EC/MC)	2.5	MW Sounder (TC)	1.5	MW Sounder (EC/MC)	2	LEO Sounder (TC)
Carbon Dioxide (ppm)	4	GEO Sounder and LEO Sounder						
Total Lightning (%)	80	LM (EC/MC)						
Methane (ppmv)	80	GEO Sounder (EC/MC)	20	LEO Sounder (EC/MC)				
Carbon Monoxide (ppbv)	0.08	GEO Sounder	20	LEO Sounder				
Sulfur Dioxide (DU)	1	ACS						
Total Precip. Water (mm)	3	MW Sounder (TC) and LEO Sounder (EC/MC)	4	MW Sounder (EC/MC) and LEO Sounder (TC)				
Aerosol Optical Depth (unitless)	0.06	GEO Imager	0.2	LEO Imager				
Ozone profile (%)	10	GEO Sounder (EC/MC) and OMPS and LEO Sounder (EC/MC)	0	ACS				
Nitrogen Dioxide (ppb)	0.08	GEO Sounder (EC/MC)	1	ACS				
Smoke (unitless)	0.5	LEO Imager						
Hydrometer Size (%)	50	LEO Imager (EC/MC)						
Aerosol Refractive Index (TBD)								
Effective reflectivity (%)	3	LEO Imager						
Aerosol Layer Height (km)	0.8	ACS						
UV Aerosol Index (km)	2	ACS	10	OMPS				
Formaldehyde (molecules/m2)	1E+20	ACS						
Glyoxal (molecules/m2)	1E+19	ACS						
Fire Power (MW/km2)	110000	GEO Imager	2500	LEO Imager				
Flood Extent (%)	50	GEO Imager and LEO Imager	0.2	MW Sounder				
NDVI (unitless)	0.04	GEO Imager	0.05	LEO Imager				
Soil Moisture (m3/m3)	0.2	MW Sounder						
Land Surface Albedo (unitless)	0.08	GEO Imager and LEO Imager						
Fire Size/Location (km)	0.25	GEO Imager	0.2	LEO Imager				
LST (K)	2.5	GEO Imager	1.4	LEO Imager				
Surface Type (unitless)	0.78	LEO Imager						
Sea Ice Age (yr)	1	GEO Imager	0.5	LEO Imager				
Sea Ice (%)	10	GEO Imager	16	MW Sounder (EC/MC)	5	LEO Imager		
Snow Water Equivalent (cm)	3.5	MW Sounder (EC/MC)						
Ice Temperature (K)	2	GEO Imager	1	LEO Imager				
Snow Cover (%)	30	GEO Imager	20	MW Sounder (EC/MC) and LEO Imager				
Sea Ice Motion (m/s)	0.03	GEO Imager						
Cloud Liquid Water (g/m2)	17	GEO Imager	4	MW Sounder				
Rain Rate (mm/hr)	6	GEO Imager	0.7	MW Sounder				
Cloud Drop Size (micron)	10	LEO Imager						
Cloud Top Temperature (K)	2	GEO Imager and MW Sounder	6	LEO Imager				
Precipitation Rate (mm/hr)	0.7	MW Sounder						
Cloud Base Height (km)	2	LEO Imager (EC/MC)						
Ocean Color (mg/m3)	4	OCS and LEO Imager (EC/MC)	0.624	LEO Imager (TC)				
SST (K)	2	GEO Imager	3.2	MW Sounder	0.2	LEO Imager		

Figure 12. Precision values for different variables. For the sensor classes and modes used in this study there are up to 4 values of precision per variable. For each value of precision we list the associated sensors. For the VIS IR GEO Imager all modes have the same precision. In many cases all classes of a sensor type also have the same precision. Classes are indicated only for cases where precision is different for different classes.

The Ozone Mapper Profile Suite (OMPS) used in this study is the same as the JPSS OMPS, but without the limb sensor. OMPS includes nadir total column and a nadir profiler spectrometers operating at 300-420 and 250-310 nm with 1.1 nm spectral resolution. See Flynn et al. (2014) and references therein for details.

The VIS IR LEO Imager is designed to provide global weather imagery. Spectral resolution varies, with 12 bands for the TC sensor and 28 for the EC sensor. The MC sensor is hyperspectral with an additional DNB.

The VIS IR LEO Sounder is designed to provide global vertical profiles of temperature and water vapor. Spectral resolution varies, with 625, 2208, and 1920 channels for the TC, EC, and MC sensors. The TC spectral range is restricted to the near IR (4.08 to 5.13 microns), while the EC and MC spectral ranges cover the near and far IR (3.9 to 15.4 and 3.76 to 15.4 microns, respectively).

8. Acronyms

Acronyms used in the text are listed here. Acronyms used only in a table are defined in the table caption. Common acronyms (e.g., NWP, MW, and VIS) and proper names (e.g., names of specific institutions and systems such as NOAA and ATMS) are not expanded in the text when first used.

ABI: Advanced Baseline Imager
ACX: GeoXO Atmospheric Composition Instrument
ASPEN: Advanced Systems Performance Evaluation tool for NOAA
ATMS: Advanced Technology Microwave Sounder
CISESS: Cooperative Institute for Satellite Earth System Studies (College Park, Maryland)
CMI: cloud and moisture imagery
CN: constellation near to the efficient frontier
CONUS: Continental U.S.
COURL: Consolidated Observing User Requirement List
CrIS: Cross-track Infrared Sounder
EC: expected class
EDE: enhanced design ensemble
EF: efficient frontier
FD: full disk
FSOI: Forecast Sensitivity to Observation Impact

GEO: geosynchronous equatorial orbit; geostationary Earth orbit
GeoXO: Geostationary Extended Observations (satellite system)
GLM: Geostationary Lightning Mapper
GOES: Geostationary Operational Environmental Satellite
GXI: GeoXO Imager
GXS: GeoXO Sounder
ID: Identification
IR: Infrared
JPSS: Joint Polar Satellite System
LEO: low Earth orbit
LM: Lightning Mapper
MBV: maximum benefit by variable
MC: maximal class
MSA: mission service area
MW: microwave
NA: not available
NASA: National Aeronautics and Space Administration
NDVI: normalized difference vegetation index
NESDIS: National Environmental Satellite, Data, and Information Service (NOAA)
NOAA: National Oceanic and Atmospheric Administration
NOSIA: NOAA Observing System Integrated Analysis
NSOSA: NOAA Satellite Observing Systems Architecture
NWP: numerical weather prediction
OCS: Ocean Color Sensor
OCX: GeoXO Ocean Color Instrument
OMPS: Ozone Mapper Profile Sensor
OSAAP: Office of Systems Architecture and Advanced Planning
OSCAR: Observing Systems Capability Analysis and Review (WMO)
OSSE: observing system simulation experiment
SAT: Systems performance Assessment Team
SDE: simple design ensemble
SPRWG: Space Platform Requirements Working Group
SST: sea surface temperature
STAR: (Center for) Satellite Applications and Research
TC: threshold class
VIIRS: Visible Infrared Imaging Radiometer Suite
VIS: visible
WMO: World Meteorological Organization (Geneva)
XORWG: GeoXO Requirements Working Group

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