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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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National Environmental Satellite,
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Summary

- Demonstrates how ASPEN can be used to assist and support an overall observing system architecture.
  - ASPEN = Advanced Systems Performance Evaluation tool for NOAA
- Here, we ask what is the optimal constellation of sensors to satisfy the requirements from a subset of all applications and users across the NOAA mission.
- ASPEN is used to calculate the cost and benefits of all possible combinations of two design ensembles of sensors. The benefit vs. cost plot visualizes an efficient frontier (EF) of the optimal constellations
- Please bear in mind: We are using a current version of ASPEN. This is a demonstration and results should not be taken quantitatively, but do indicate the type of study that ASPEN is capable of.

Study components

- ASPEN
- Capability tables of sensors in the JPL catalog of sensors used in the NSOSA study
- A simple cost model for constellations of these sensors
- Application requirement and priority tables developed by the SAT
    - Global NWP
    - Nowcasting applications
        - Six in all: dense fog, fire monitoring, floods, offshore winds and sea ice, thunderstorms, and winter precipitation
    - SAT = Systems performance Assessment Team
- Sensor design ensembles
    - Simple design ensemble (SDE)
    - Enhanced design ensemble (EDE)

ASPEN Approach

- ASPEN compares obs systems capabilities to applications requirements ranges and their priorities, and associates a score to these obs systems: based on their degree of users/needs satisfaction metric (in %)
- ASPEN also accounts for the associated costs of obs systems & computes their benefit/cost ratios
- ASPEN was developed following the NSOSA methodology, expanded to be able to assess all solutions, and to account for all applications and uses
- A major criterion for ASPEN’s trustworthiness is the trustworthiness of its inputs: (1) observing systems detailed capabilities and costs, and (2) users’ observational requirements ranges and priorities
- ASPEN assumes that satisfying users needs close to the maximum level, will lead to maximizing systems skills and performances.
- Similarly, satisfying users needs at the minimum level will lead to minimum levels of performance and skills of those systems

Sensors and costs

- For each of 9 types of sensors there are up to 3 versions—from three sensor classes: the threshold class (TC), the expected class (EC) and the maximal class (MC).
- 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 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.

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

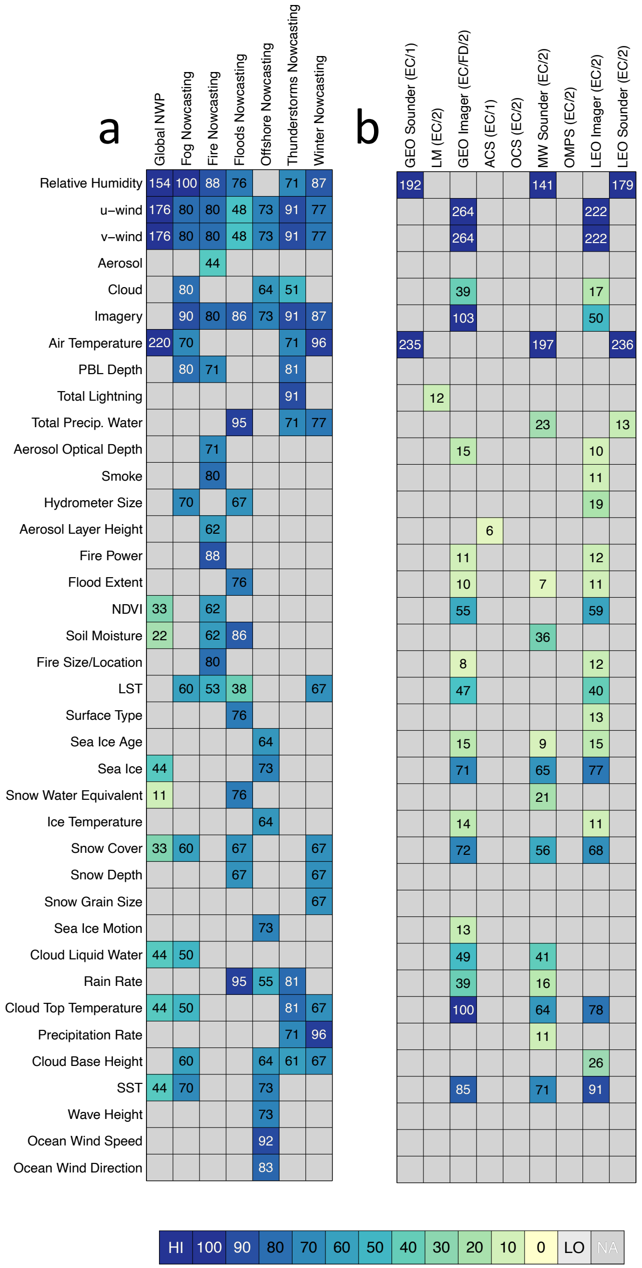
Applications

- For Global NWP, the SAT study 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.
- We converted the results of these studies to the needed ASPEN requirements and (technical) priority tables.
- ASPEN weights benefits of different applications by strategic priorities. In this study the nowcasting applications were weighted equally.

Application priorities and sensor capabilities

a) Which variables are required by which applications
   - For each variable, for each application, the total priority (as a percent x 10)

b) Which variables are observed by which sensors
   - For each variable, for each EC sensor, the total ASPEN benefit (scaled so that a value of 0.035 is plotted as 100)



a

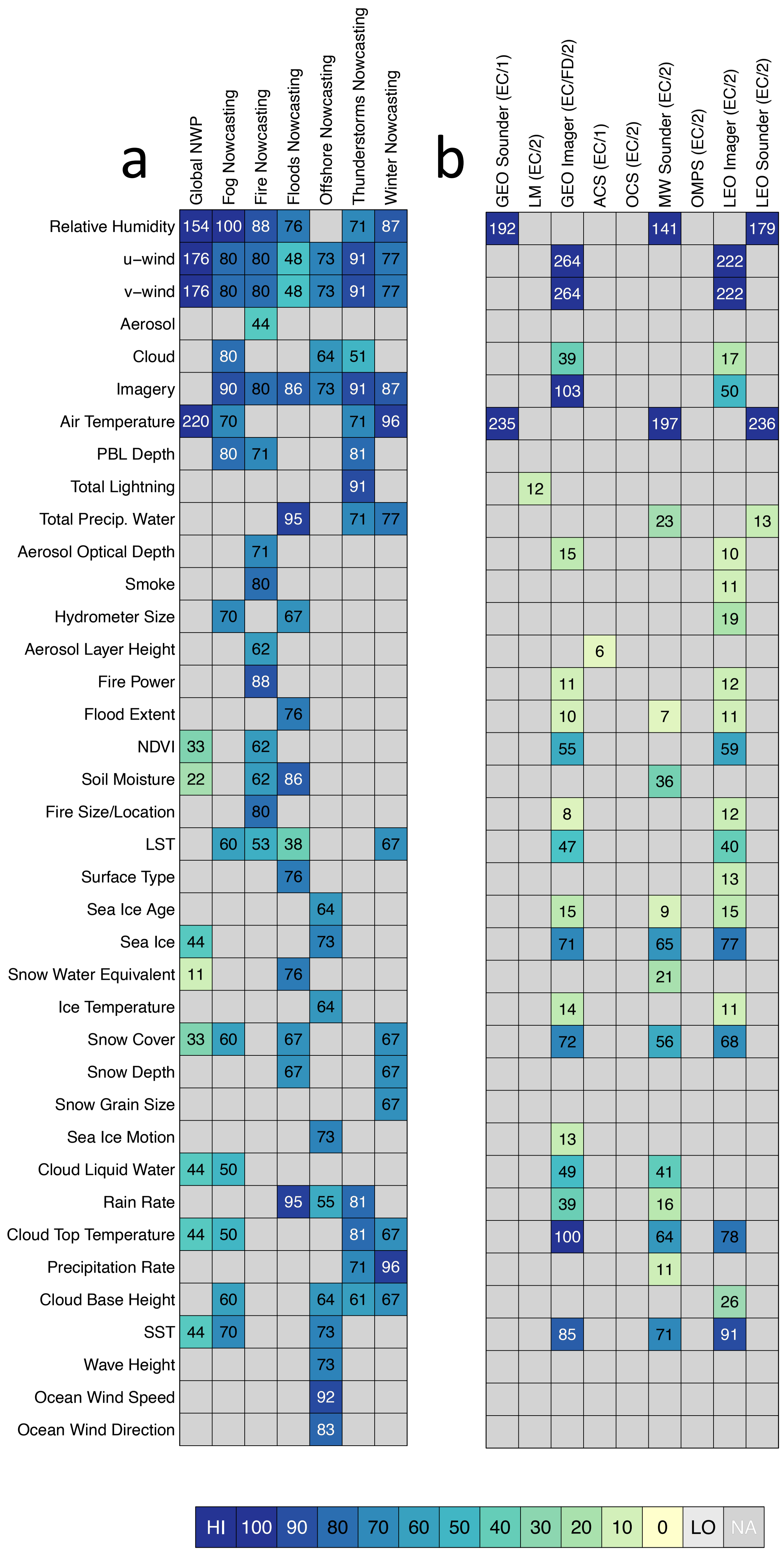
	Global NWP	Fog Nowcasting	Fire Nowcasting	Floods Nowcasting	Offshore Nowcasting	Thunderstorms Nowcasting	Winter Nowcasting
Relative Humidity	154	100	88	76		71	87
u–wind	176	80	80	48	73	91	77
v–wind	176	80	80	48	73	91	77
Aerosol			44				
Cloud		80			64	51	
Imagery		90	80	86	73	91	87
Air Temperature	220	70				71	96
PBL Depth		80	71			81	
Total Lightning						91	
Total Precip. Water				95		71	77
Aerosol Optical Depth			71				
Smoke			80				
Hydrometer Size		70		67			
Aerosol Layer Height			62				
Fire Power			88				
Flood Extent				76			
NDVI	33		62				
Soil Moisture	22		62	86			
Fire Size/Location			80				
LST		60	53	38			67
Surface Type				76			
Sea Ice Age					64		
Sea Ice	44				73		
Snow Water Equivalent	11			76			
Ice Temperature					64		
Snow Cover	33	60		67			67
Snow Depth				67			67
Snow Grain Size							67
Sea Ice Motion					73		
Cloud Liquid Water	44	50					
Rain Rate				95	55	81	
Cloud Top Temperature	44	50				81	67
Precipitation Rate						71	96
Cloud Base Height		60			64	61	67
SST	44	70			73		
Wave Height					73		
Ocean Wind Speed					92		
Ocean Wind Direction					83		

b

	GEO Sounder (EC/1)	LM (EC/2)	GEO Imager (EC/FD/2)	ACS (EC/1)	OCS (EC/2)	MW Sounder (EC/2)	OMPS (EC/2)	LEO Imager (EC/2)	LEO Sounder (EC/2)
Relative Humidity	192					141			179
u–wind			264					222	
v–wind			264					222	
Aerosol									
Cloud			39					17	
Imagery			103					50	
Air Temperature	235					197			236
PBL Depth									
Total Lightning		12							
Total Precip. Water						23			13
Aerosol Optical Depth			15					10	
Smoke								11	
Hydrometer Size								19	
Aerosol Layer Height				6					
Fire Power			11					12	
Flood Extent			10			7		11	
NDVI			55					59	
Soil Moisture						36			
Fire Size/Location			8					12	
LST			47					40	
Surface Type								13	
Sea Ice Age			15			9		15	
Sea Ice			71			65		77	
Snow Water Equivalent						21			
Ice Temperature			14					11	
Snow Cover			72			56		68	
Snow Depth									
Snow Grain Size									
Sea Ice Motion			13						
Cloud Liquid Water			49			41			
Rain Rate			39			16			
Cloud Top Temperature			100			64		78	
Precipitation Rate						11			
Cloud Base Height								26	
SST			85			71		91	
Wave Height									
Ocean Wind Speed									
Ocean Wind Direction									

HI	100	90	80	70	60	50	40	30	20	10	0	LO	NA

Application priorities and sensor capabilities, larger



a

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b

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Ocean Wind Speed									
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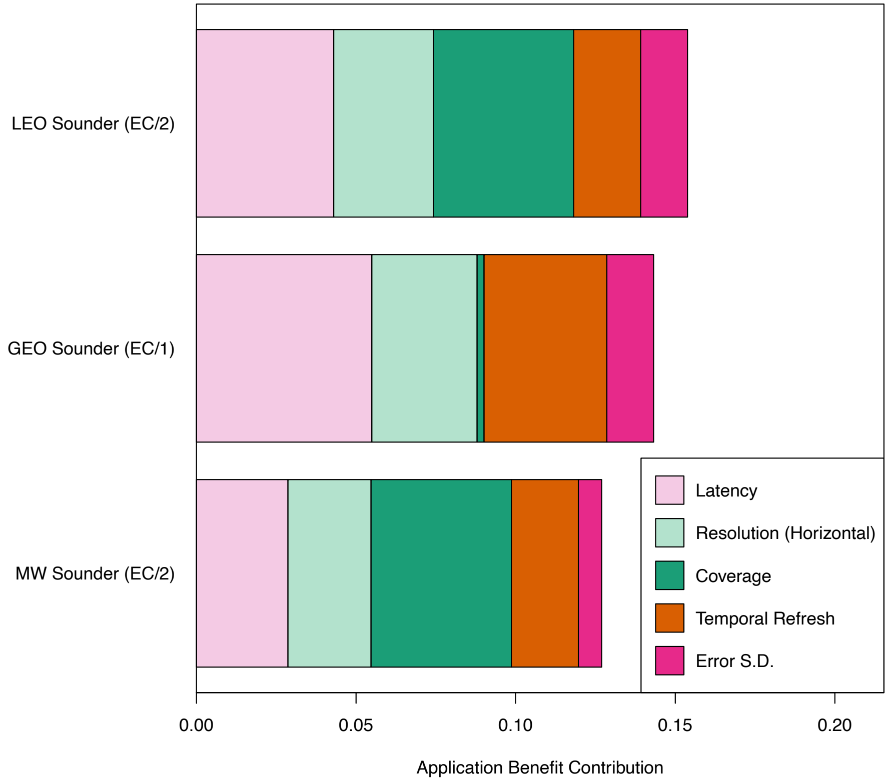
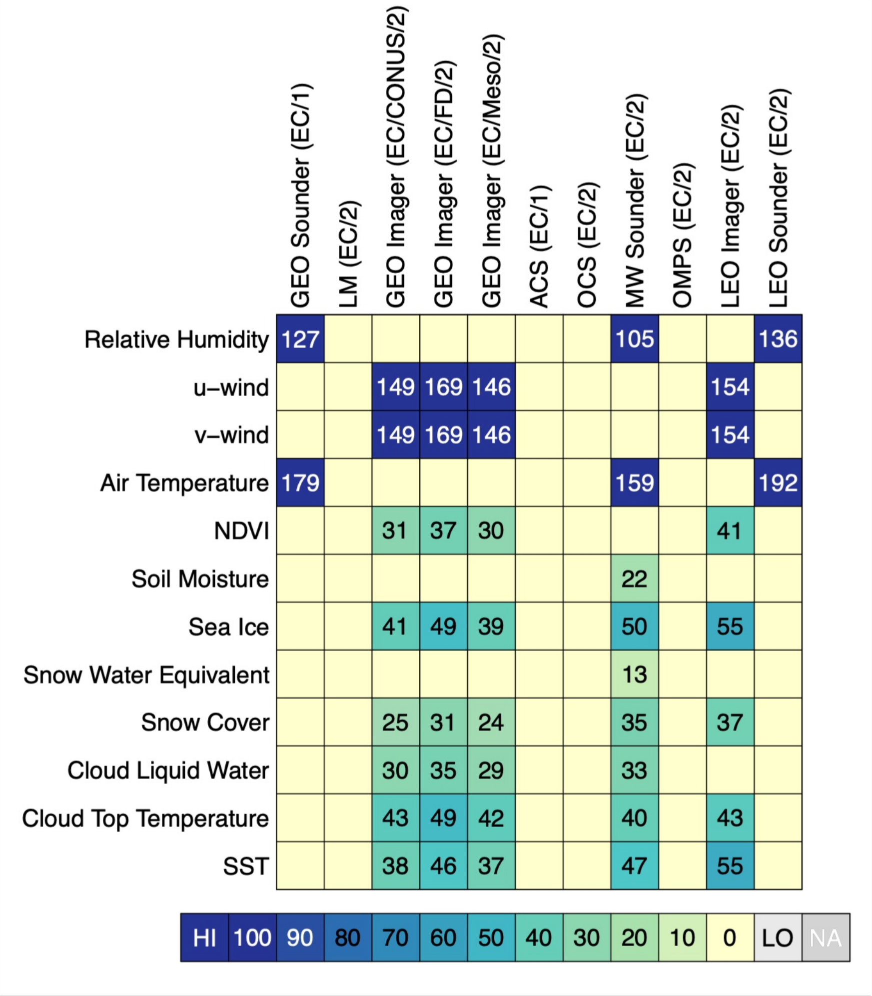
Traceability in ASPEN



The ASPEN benefit components for the Temperature Sounding for Global NWP. Shown for each attribute (color) for each Sounder (rows).



	GEO Sounder (EC/1)	LM (EC/2)	GEO Imager (EC/CONUS/2)	GEO Imager (EC/FD/2)	GEO Imager (EC/Meso/2)	ACS (EC/1)	OCS (EC/2)	MW Sounder (EC/2)	OMPS (EC/2)	LEO Imager (EC/2)	LEO Sounder (EC/2)
Relative Humidity	127							105			136
u–wind			149	169	146					154	
v–wind			149	169	146					154	
Air Temperature	179							159			192
NDVI			31	37	30					41	
Soil Moisture								22			
Sea Ice			41	49	39			50		55	
Snow Water Equivalent								13			
Snow Cover			25	31	24			35		37	
Cloud Liquid Water			30	35	29			33			
Cloud Top Temperature			43	49	42			40		43	
SST			38	46	37			47		55	

The components of ASPEN benefit summed over attributes to Global NWP for each required variable for each sensor in the SDE. Scaled so that a plotted value of 100 is an actual value of 0.80.

Sensor design ensembles

Each design ensemble lists all possible constellations under consideration.

- The simple design ensemble (SDE) has all the EC sensors and each is in a predetermined orbital configuration
  - In the SDE every constellation includes the MW LEO Sounder and VIS IR GEO Imager sensors.
    - All LEO sensors if present are in a 2-orbit configuration
    - The GEO sensors orbital configuration follows GeoXO plans
      - The VIS IR GEO Imager, the LM, and the OCS if present are on both the East and West platforms
      - The IR GEO Sounder and ACS if present are on the Central platform
  - The SDE has 128 members.
- The enhanced design ensemble (EDE) allows choices from all classes of sensors and several LEO orbital configurations
  - The LEO sensors if present may be in a 1-, 2-, or 4-orbit configuration
  - The GEO sensors orbital configuration follows GeoXO plans as in the SDE
  - In each constellation a single class and single orbital configuration may be included
  - The EDE has approximately 3/4 of a million members.

Efficient Frontier, Nowcasting, Simple Design Ensemble (SDE)

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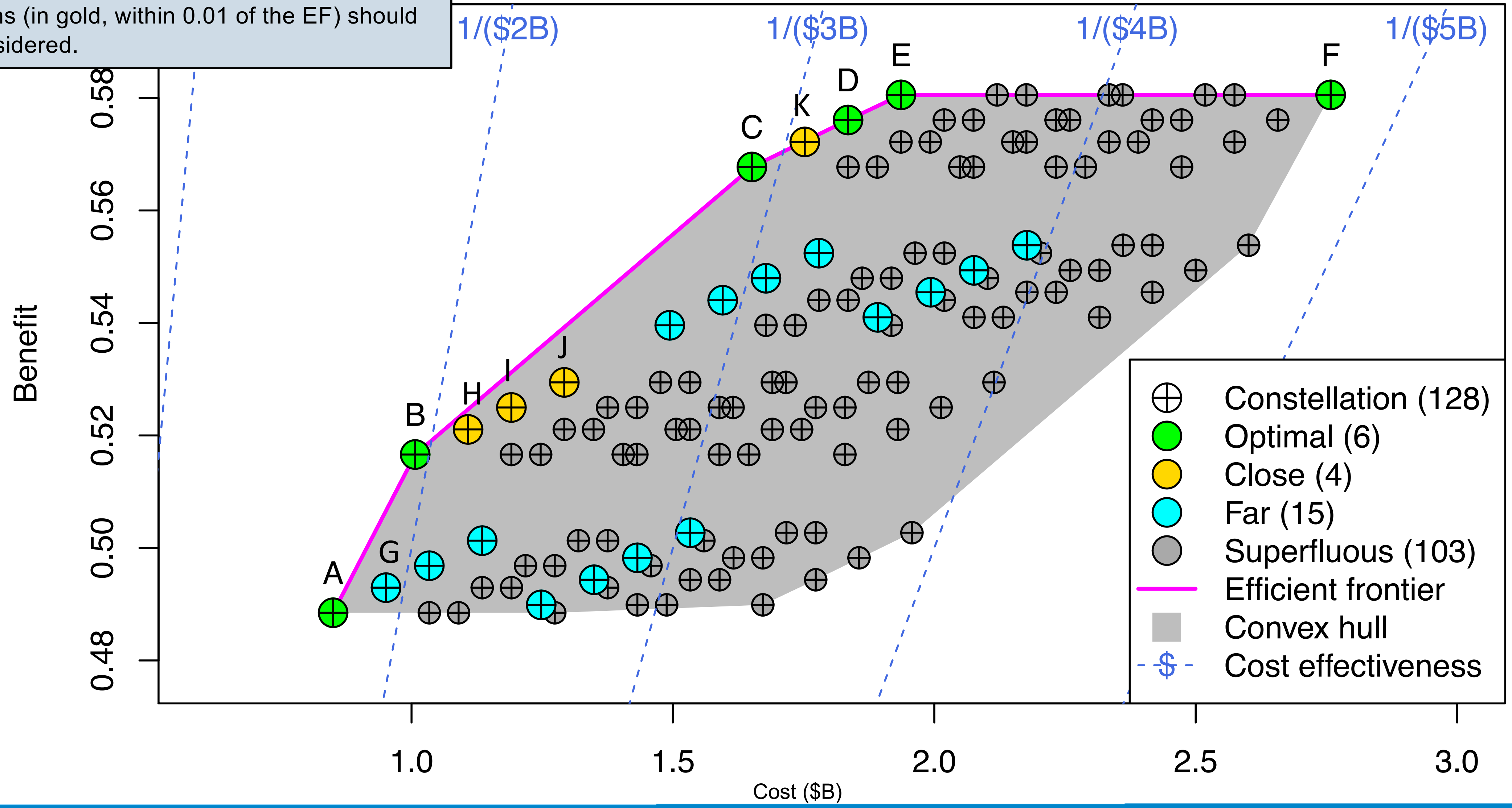
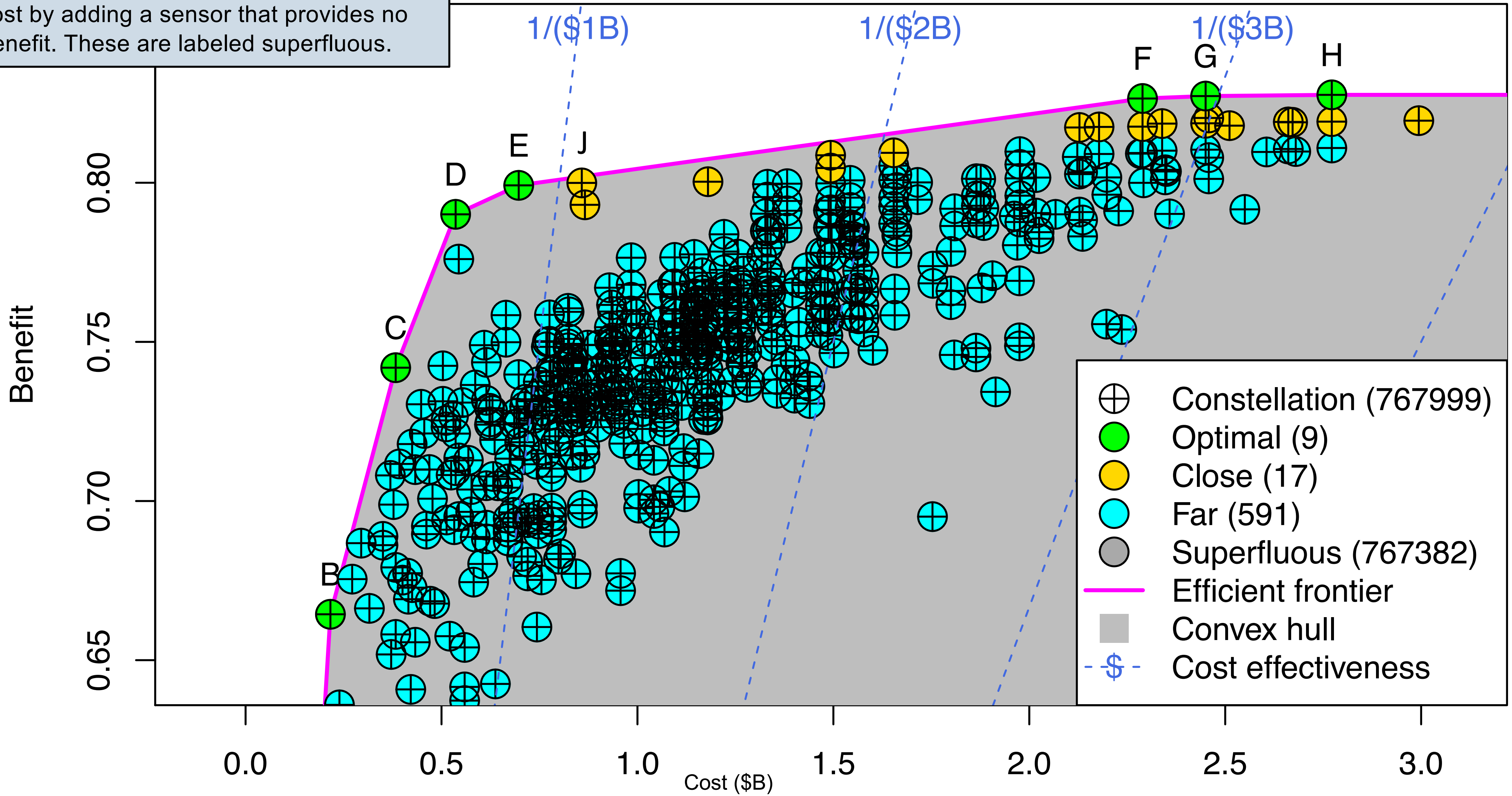
The constellations defining the efficient frontier (EF) in green are optimal, but other near-optimal constellations (in gold, within 0.01 of the EF) should also be considered.



Efficient Frontier, Global NWP, Enhanced Design Ensemble (EDE)

For the EDE, most of the constellations are not interesting because they provide the same benefit at additional cost by adding a sensor that provides no additional benefit. These are labeled superfluous.



Given a hypothetical budget of $1B, which constellation maximizes the benefit

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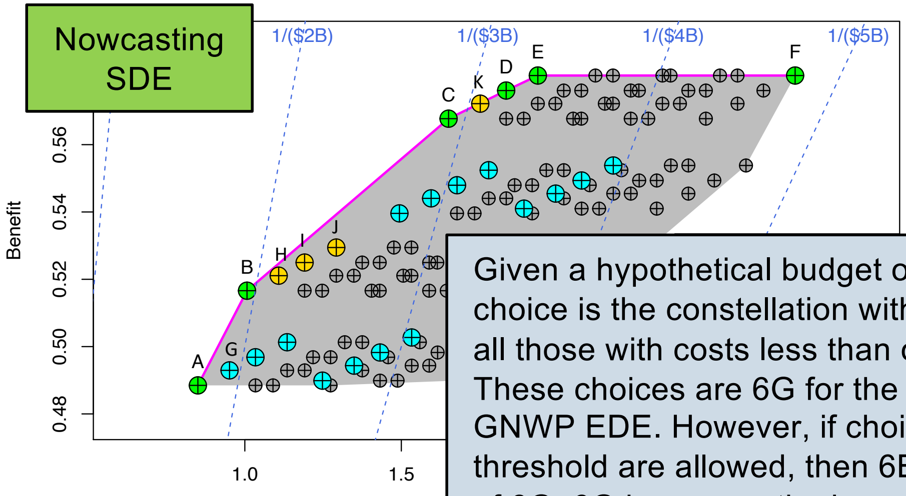
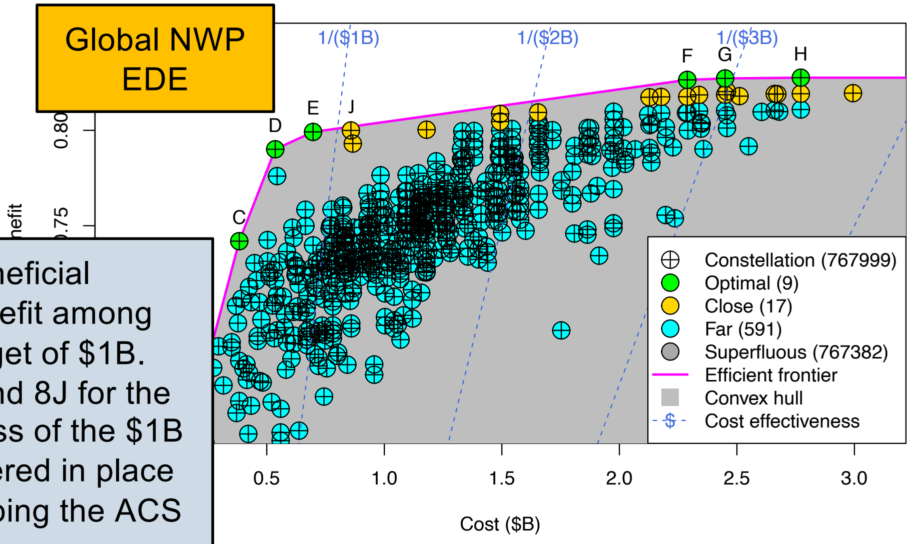
DE	App.	⊕	ID	Benefit	Cost	Cost Effectiveness	Distance to EF	GEO Sounder	LM	GEO Imager	ACS	OCS	MW Sounder	OMPS	LEO Imager	LEO Sounder
SDE	NWP	4A	EF.128	0.710	0.850	0.835	0.0000			**EC/2**			**EC/2**			
		4B	EF.1	0.744	1.007	0.738	0.0000	**EC/1**		EC/2			EC/2			
	Now.	6A	EF.128	0.488	0.850	0.575	0.0000			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	

Nowcasting SDE

Global NWP EDE





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. These choices are 6G for the nowcasting SDE and 8J for the GNWP EDE. However, if choices slightly in excess of the $1B threshold are allowed, then 6B should be considered in place of 6G. 6G increases the benefit by 4.8% by dropping the ACS and adding the GEO Sounder.

Summary

- In this proof-of-concept study, ASPEN calculates the efficient frontier (EF) in the space of constellation cost vs. benefit.
- The EF visualization 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 the design ensemble.
- Thus, the optimal constellations for Global NWP are different from those for nowcasting.

Limitations and caveats

- We only considered the Global NWP and nowcasting applications and only some of the NOAA GEO and LEO sensors.
- In particular, we did not consider radio occultation, despite the fact that radio occultation sounding data are one of the most cost-effective and impactful data sources in NWP.
- We used the current version of ASPEN and available ASPEN data bases.
- ASPEN reliability depends on trustworthiness of its inputs (performances and costs of the observing systems, and requirements ranges and priorities of the applications).

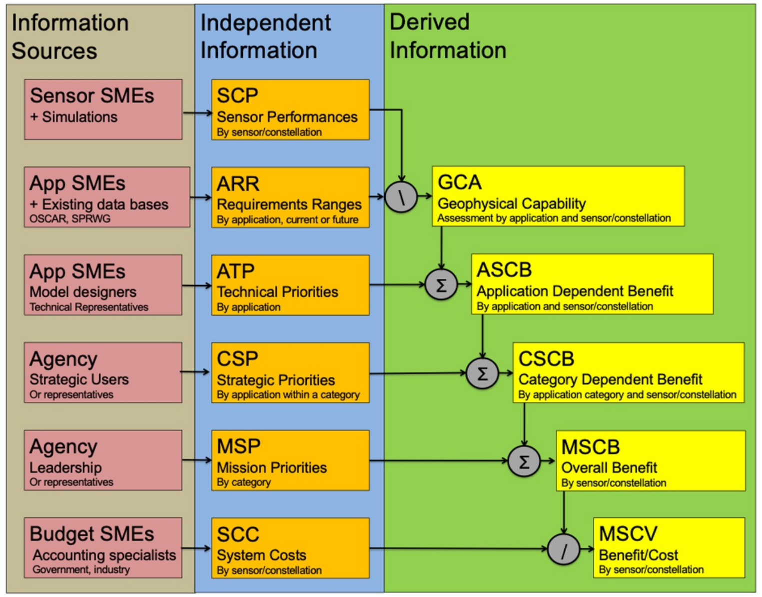
In conclusion

- Earth observing systems are expensive and have long lifetimes.
- Investment decisions in these systems can be supported by ASPEN.
- ASPEN is a work in progress, and we welcome community collaboration and coordination.
- With further advances we expect ASPEN will become an increasingly valuable addition to the observing systems assessment toolbox.

That’s all! For more...

- email: rnh@umd.edu
- ASPEN description
  - Oct 2022 BAMS paper doi: 10.1175/bams-d-22-0004.1
  - https://ams.confex.com/ams/103ANNUAL/meetingapp.cgi/Paper/410548

General Methodology of ASPEN



Information Sources

Sensor SMEs
+ Simulations

App SMEs
+ Existing data bases
OSCAR, SPRWG

App SMEs
Model designers
Technical Representatives

Agency
Strategic Users
Or representatives

Agency
Leadership
Or representatives

Budget SMEs
Accounting specialists
Government, industry

Independent Information

SCP
Sensor Performances
By sensor/constellation

ARR
Requirements Ranges
By application, current or future

ATP
Technical Priorities
By application

CSP
Strategic Priorities
By application within a category

MSP
Mission Priorities
By category

SCC
System Costs
By sensor/constellation

Derived Information

GCA
Geophysical Capability
Assessment by application and sensor/constellation

ASCB
Application Dependent Benefit
By application and sensor/constellation

CSCB
Category Dependent Benefit
By application category and sensor/constellation

MSCB
Overall Benefit
By sensor/constellation

MSCV
Benefit/Cost
By sensor/constellation