NOAA Observing Systems Architecture (NSOSA) Study: Lessons Learned for Systems Architecting

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Outline of the Talk

- Quick background on weather forecasting, weather satellites, and satellite constellation architectures
- NSOSA Study, what was it?
- Lessons Learned
- Outline of study approach
- Highlighted Lessons
  - *Architecture as decisions*
  - *Scale and the need for scale*
  - *Choosing the value model level, some notes on MAUT*
  - *Architecture as classes of specific alternatives*
  - *Variance as significance*

Weather Forecasting is a Complex Mission

NOAA = National Oceans and Atmosphere Administration

WEATHER READY NATION

1. Aviation Weather and Volcanic Ash
2. Fire Weather
3. Hydrology and Water Resources
4. Marine Weather and Coastal Events
5. Hurricane/Tropical Storms
6. Routine Weather
7. Severe Weather
8. Space Weather
9. Tsunami
10. Winter Weather
11. Environmental Modeling Prediction
12. Science, Services and Stewardship

National Weather Service

HEALTHY OCEANS

1. Ecosystem Monitoring, Assessment and Forecast
2. Fisheries Monitoring, Assessment and Forecast
3. Habitat Monitoring and Assessment
4. Protected Species Monitoring
5. Science, Services and Stewardship

National Marine Fisheries Service

RESILIENT COASTS

1. Coastal Water Quality
2. Marine Transportation
3. Planning and Management
4. Resilience to Coastal Hazards and Climate Change
5. Science, Services and Stewardship

National Ocean Service

CLIMATE

1. Assessments of Climate Changes and Its Impacts
2. Climate Mitigation and Adaptation Strategies
3. Climate Science and Improved Understanding
4. Climate Prediction and Projections

Office of Oceanic and Atmospheric Research

NOAA Mission Service Areas by Line Office

- NOAA contains the National Weather Service
- NOAA flies all U.S. civilian operational weather satellites

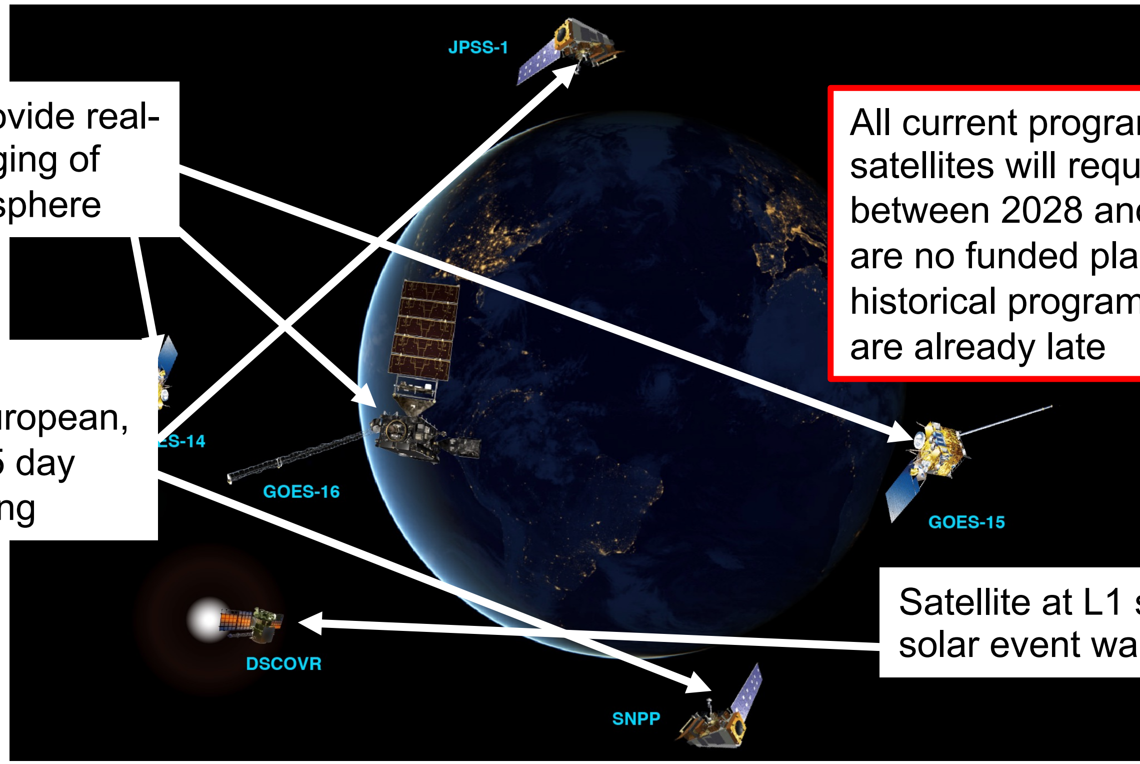
NOAA is not just weather, weather is not just one mission

The NOAA Weather Satellite Problem

Satellite data contributes to all weather mission areas

GEO satellites provide real-time weather imaging of the western hemisphere

Polar satellites, in conjunction with European, provide data for 3-5 day numerical forecasting

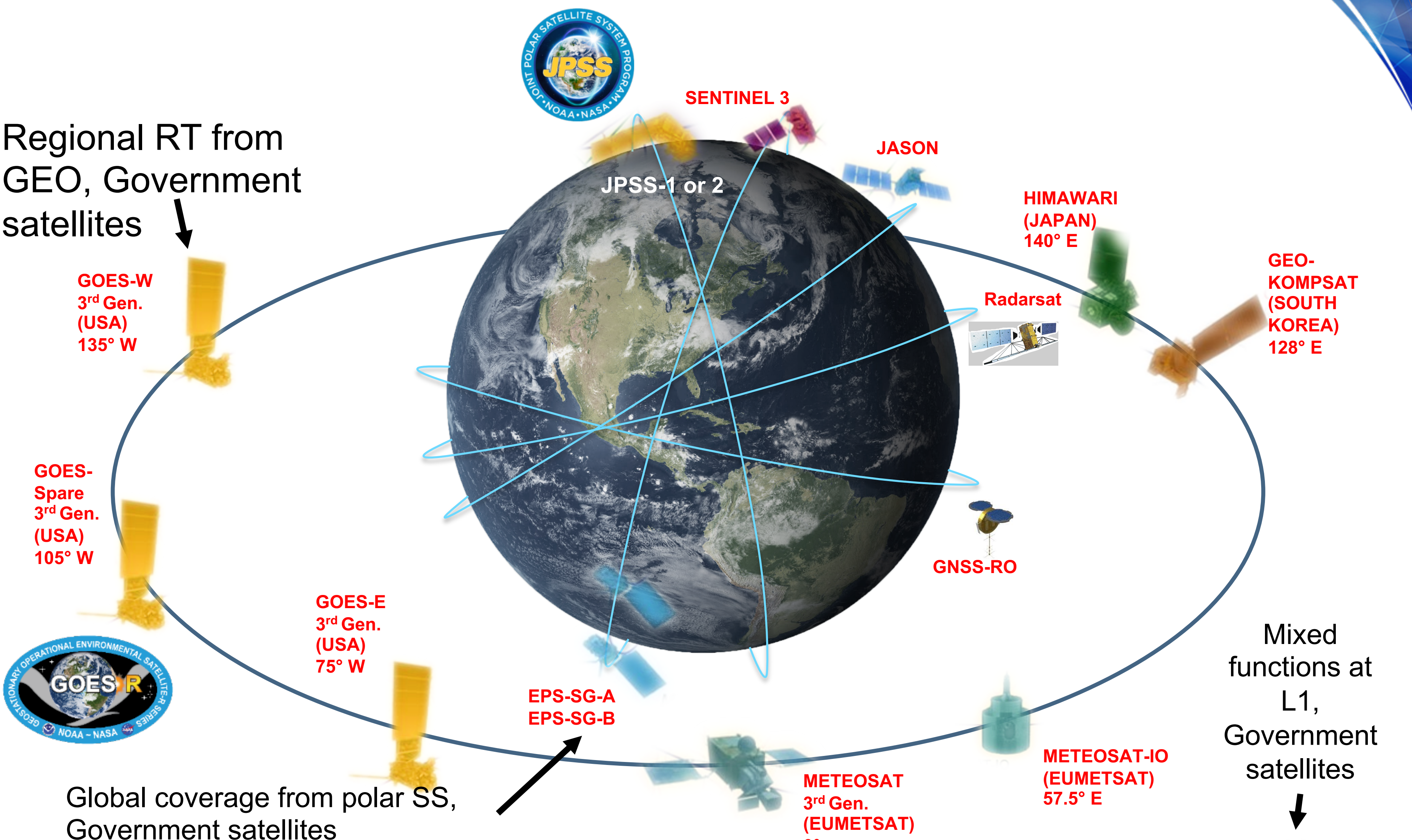


All current program of record satellites will require replacement between 2028 and 2032, there are no funded plans to do so, with historical program durations we are already late

Satellite at L1 supports solar event warnings

Multiple missions, multiple platforms, multiple value streams

The Current Constellation/Architecture

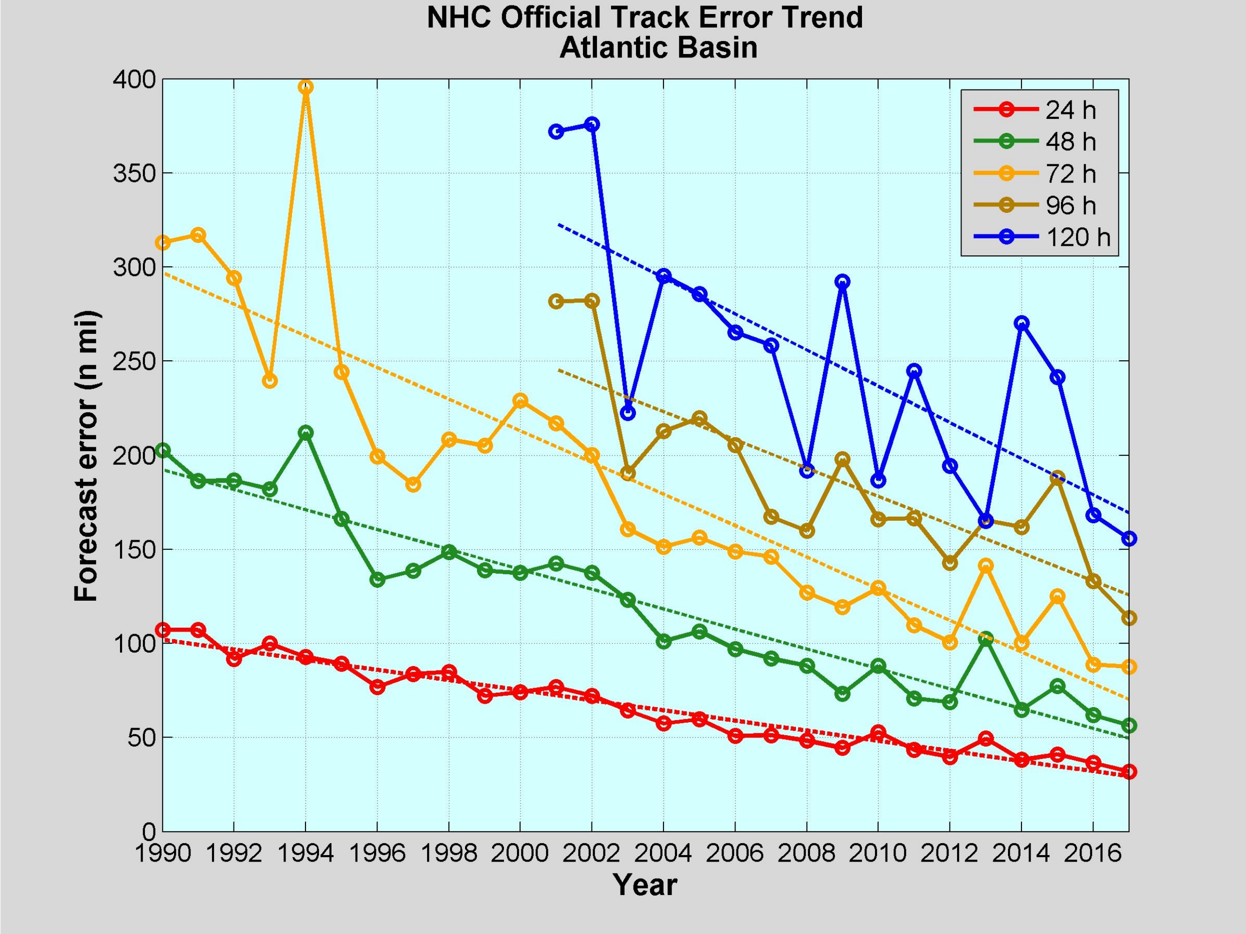


GOES-R and JPSS are the primary US components

Example of Weather Forecasting Value

Hurricane forecasts are among the highest impact cases

- Forecast accuracy is readily measureable, and has gotten much better over time
- Forecasts 72 hours and longer are critical to evacuation and emergency response pre-placement
  - *Movement stop more than 24 hours prior to landfall*
- Forecasts 3+ days our are inherently global
  - *Based on numerical weather computation with global sensor data*

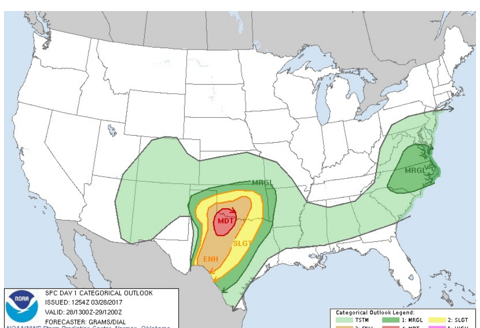


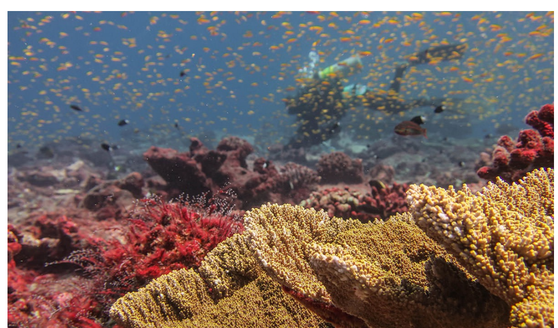
Global forecasts require global observation data, which mostly comes from satellites

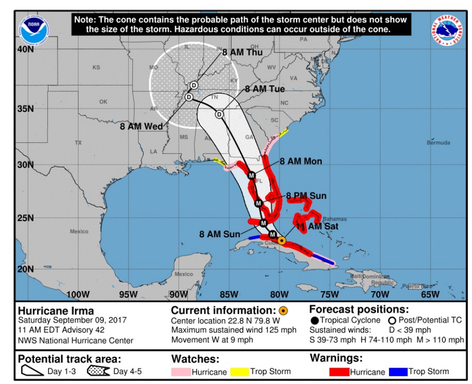
NSOSA Study, What Was It?

NOAA Observing System Architecture Study

- ***NSOSA study examined the space segment architecture decisions for space systems post current programs***
  - *Constellation architecture: Assignment of functions to orbits, selection of performance levels, launch and replenishment strategies, key technologies*
  - *Should we retain the legacy architecture or seek major change?*
  - *Which observation functions should be improved?*
- ***Addressing NOAA operational needs, but not from binary requirements***
  - *Observations that result in warnings, watches, baseline weather and space weather forecasts, and ocean or fisheries actions*

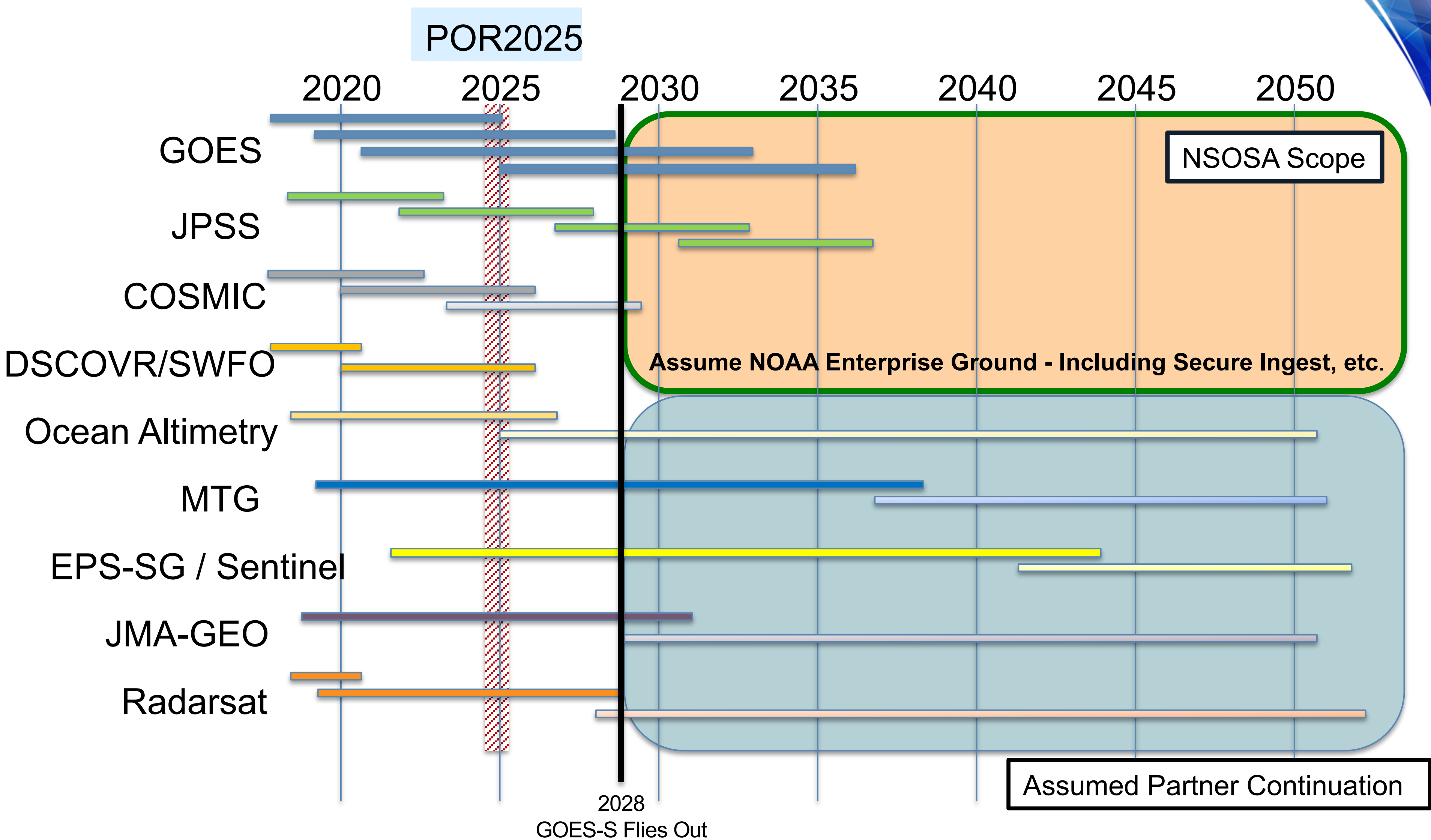






- ***Scoped to address NOAA systems, with a knowledge and inclusion of partner contributions and relationships***
- ***Intended to result in Pre-Phase-A program activities***

Baseline and Study Scope



Lessons of Interest

- Architecture as decisions
  - *Architecture is not diagrams, is not a model, and is not a single, specific constellation*
  - *Architecture is a set of decisions*
- Scale and the need for scale
  - *100's of alternatives (not just a handful, not 1000's)*
- Choosing the value model level
  - *Choosing across a spectrum of abstraction*
- Architecture as classes of specific alternatives
  - *When we recommend an architecture we recommend many possible future constellations, not just one*
- Variance as significance
  - *If Alternative A has ΔValue and ΔCost from Alternative B, how do we know if it is significant?*
  - *A variance-based approach*

Architecture as Decisions

Current satellites will need replacing, what can we do?

- Examples of alternative courses of action
  - *Just buy more of what we are currently buying*
  - *Leave the platforms the same, but upgrade (or downgrade) instrument performance*
  - *Do what the World Meteorological Organization (WMO) says*
    - There is a WIGOS2040 vision for weather satellites, do some of that
  - *Do something radically different than today*
    - Companies are proposing large LEO constellations, heavy outsourcing to commercial constellations, etc.
  - *Try to negotiate changes to the Internationally agreed split in responsibilities*
    - Right now everybody exchanges data but retains extensive mission independence. It could be different.
- What NOAA needs is to understand what actions to take (defined by decisions)
  - *They don't need an OV-1 or any other diagram, unless that diagram defines the relevant decision*
  - *The decision space is large, not small. Many quite disparate alternatives will need to be compared. Major departures from the legacy are very much on the table (have to compete their way into continuity).*

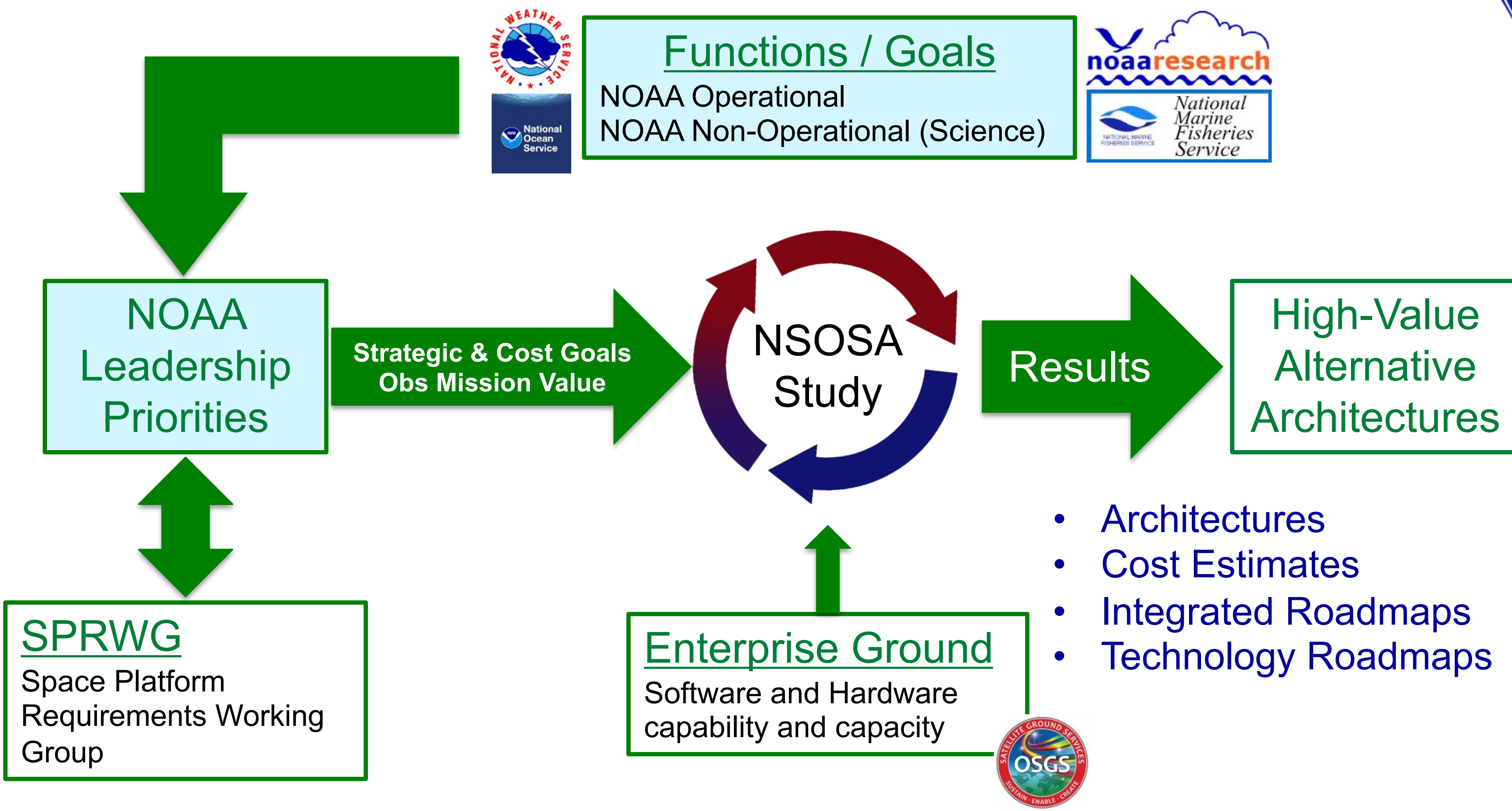
See Maier & Rechtin; Crawley, Cameron & Selva books for this approach

Scale and the Need for Scale

How Many Alternatives to Examine?

- It could be a lot
  - *Many orbit possibilities (GEO, standard LEO, non-standard LEO, All-LEO, High-inclined, All-MEO). And then there are orbit optimizations.*
  - *Range of instrument performance levels, and costs. NSOSA defined from Study Threshold to Maximum Effective for 38 distinct measurements.*
  - *Then there are launch and replenishment strategies, and combinations of U.S. Gov traditional programs and non-traditional elements (e.g. hosted payload platforms)*
  - *There are no obvious, a-priori reasons for ruling most alternatives out. A large number are at least plausible.*
- Scaling issues
  - *With ~10 alternatives the design and scoring process can be mostly manual*
  - *With ~1,000+ alternatives the design and scoring process has to be fully automated*
  - *We ended up with ~100 alternatives in the main study. Used a mixed manual and automated process.*
  - *Around 100 alternatives appeared to be enough cover the stakeholder concerns and adequately populate the decision space*
    - This was driven by <u>this sponsor's </u>relative concern for comprehensiveness of search versus fidelity of analysis on each individual case

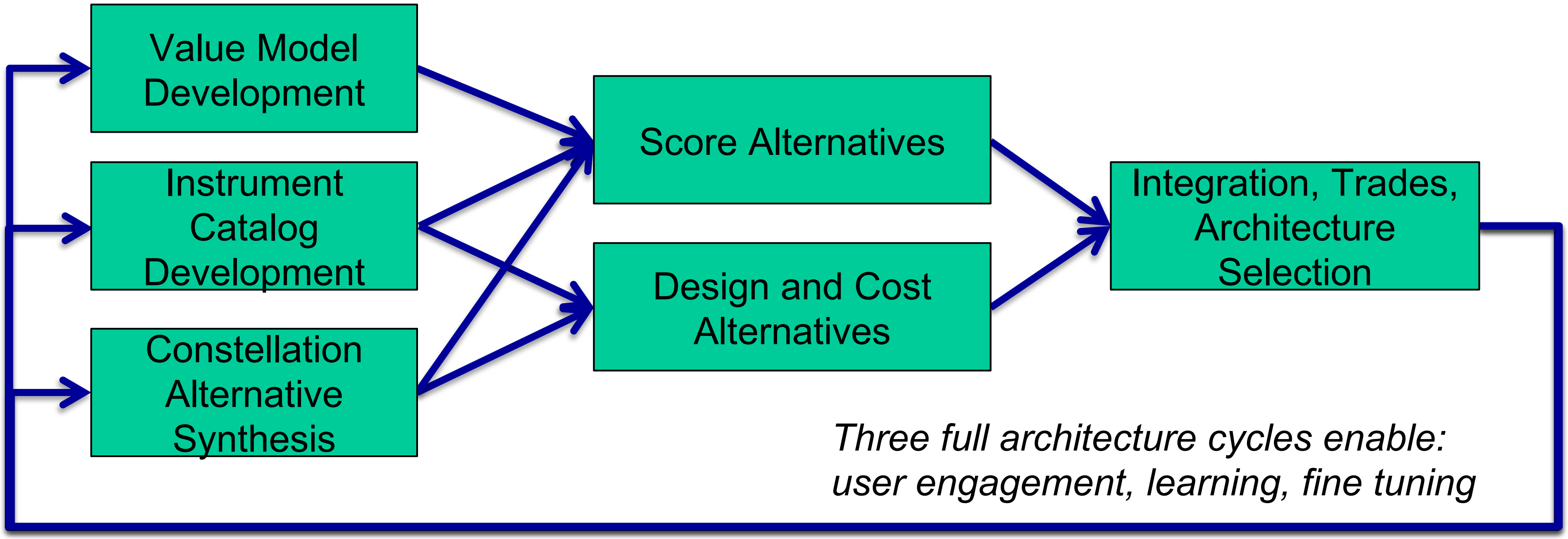
Study Methodology Overall



NSOSA Study Approach

Defining the major technical components

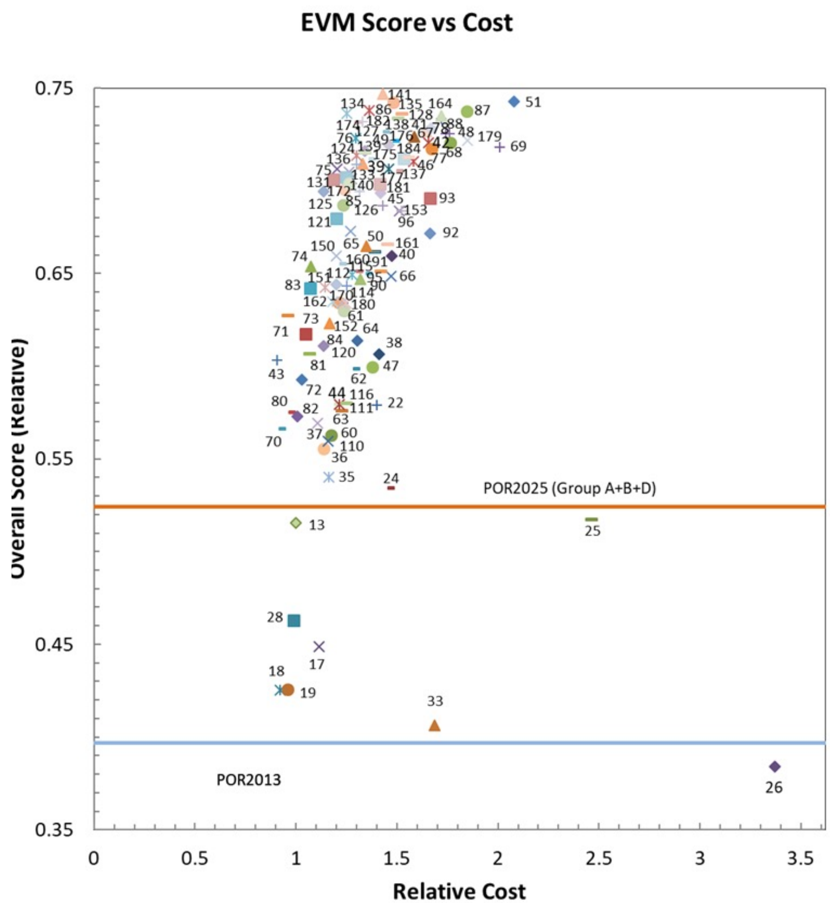
- ***Study was organized into 3 major lines of effort built around 3 major design cycles***
  - *Three Lines: Value Model, Instrument Catalog, Constellation Synthesis*
  - *Each design cycle does complete, end-to-end designs of multiple alternative architectures*



Scale Achieved

Used a mixed manual/automated process

- Constellation design and costing done in Aerospace Corporation Concept Design Center (CDC) using special tools to run many satellite designs per day
- Value scoring done with EDR Value Model (EVM) with custom tools (and manual operations) by MIT Lincoln Labs
- Ultimate goal was efficient frontier analysis (then architecture extensions)
  - *See raw version at right*



Choosing the Value Model Level

Value Models are the key to architecture studies

- Value Model: A model (in the NSOSA case quantitative) of the value of a constellation alternative. Inherent need in efficient frontier analysis.
  - *Represent value as a scalar number, integrated over all stakeholders or broken out by individual stakeholders*
  - *Approach is standard from Multi-Attribute Utility Theory (MAUT)*
  - *The MAUT model starts with the "objectives"*
- Objective: Something we want to do or achieve. Functional and Strategic.
  - *Functional example: Provide Regional Real-Time Weather Imagery, Provide On Earth-Sun Axis Coronagraph Imagery*
  - *Strategic example: Availability of Core Capabilities*
- Measures of Performance: Technical measures associated with objectives
  - *Used a three-point, closed end approach to performance quantification*
  - *Others are valid, too, this approach worked for us*
- Developed in conjunction with the Space Platform Requirements Working Group (SPRWG)

Once you have the value model many of the architecture trades are determined (even if you don't know what they are yet)

Example Entry: Regional RT Weather Imaging

Attribute	Program of Record 2025	Study Threshold (ST)	Expected (EXP)	Maximum Effective (ME)
Geo. Coverage and latency spec.	GOES-16, S, T and U		70	
GIFOV nadir view				
Visible	0.5 km	2 km	0.5 km	0.25 km
IR	2.0 km	4 km	2 km	1 km
Near IR	1 km	3 km	1 km	0.3 km
Sampling frequency (update rate)	5 min	30 minutes	5 minutes	2.5 minutes
Latency (image time to delivery)	1 min	10 minutes	5 minutes	2.5 minutes
Mesoscale (movable 1000kmx1000km)				
Number of Regions in CONUS	2 (moveable)	1 in CONUS (fixed domain)	2 (moveable)	5 (moveable)
Update rate	0.5 min	7 min	30 s	15 s
Latency (image time to delivery)	0.5 min	7 min	30 s	15 s
Wavelengths covered				
Lower edge of coverage	0.47 microns	0.630 microns	0.47 microns	0.4 microns
Upper edge of coverage	13.7 microns	11 microns	13.35 microns	13.7 microns
Day-night bands (DNB)	0	0 [None]	0.001 [None]	1 band at 0.64 microns
Number of specific bands	16	4 bands (LWIR, SWIR, WV, Vis)	16	32
Radiometric accuracy	0.1 NeDT (mostly IR bands)	0.2K	0.1K	0.05K
Navigation accuracy	1.0 km at nadir	3.0 km at nadir	1.0 km at nadir	0.5 km at nadir

NSOSA Value Model Specific Goals

- Comprehensive and parsimonious: Covers all important stakeholder needs, not necessarily every single need
  - *Identify and quantify the driving needs*
  - *Full requirements development comes after architecture selection, during program formulation*
- Projects needs out to 2030+
  - *Not just a list of current products collected plus incremental wish-list*
- Fit for architecture selection
  - *Distinguishes between alternative architectures, not just "should we add the green band?"*
- Can be efficiently assessed on 100+ alternative constellations
- Explainable and "invertible"
  - *Can explain why one alternative is superior to another*
  - *Can use the model to develop an order-of-buy based on incremental cost effectiveness*
  - *Reasonably simple (want at most 10's of objectives, not 100's)*
- Can be calibrated so we can objectively assess the significance of differences (has error bar process)

Key Lesson: Where to Establish Objectives

Several levels could be chosen, but don't all work well

More or less abstract

Mission Metrics (e.g., hurricane track forecast accuracy) — Desirable, not feasible

Generic, aggregated data classes (e.g., Regional RT Weather Imagery, 3D Winds) — Our selected point

Specific Environmental Data Records (e.g., Ocean Temperature)

Individual data requirements (e.g., current level one specifications, COURL)

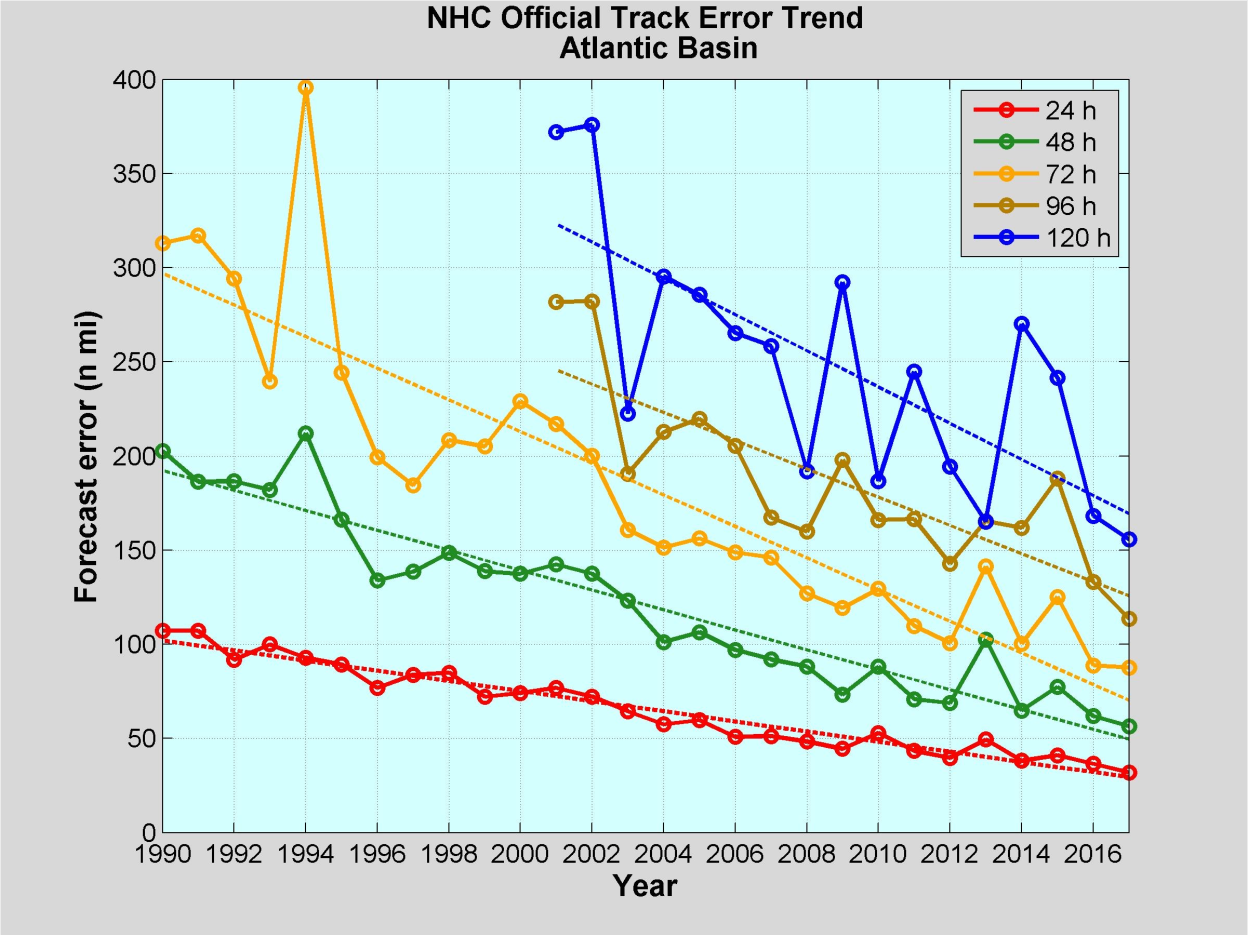
(Specific Environmental Data Records and Individual data requirements:) Too specific, too tied to current operations, too many

Finding the value model "sweet spot" is a repeated issue in studies like this. Examples seem to rarely be published.

Desirable but not Feasible Metrics

We'd like to use metrics directly on high impact forecasts, like…

- Unfortunately, state of the art in predicting the impact of constellations on metrics like this won't support this study
  - *Too complex and slow, may require months to compute a single alternative*
  - *Not "invertible." Can't back out direction of "steepest ascent" in performance.*



Many examples of these exist, but were outside practical scope of study

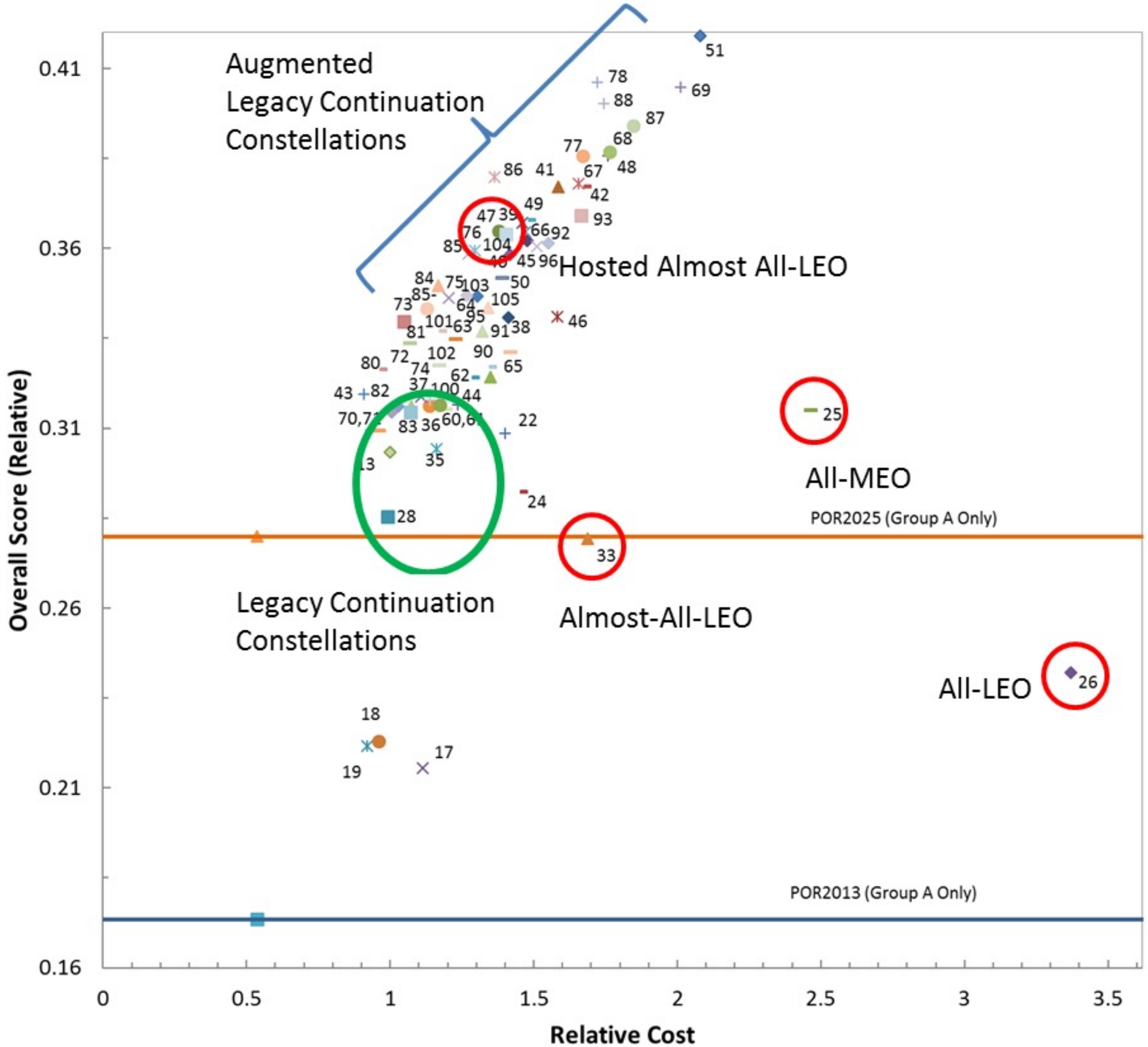
Criticality of the Value Model

- Building the value model is of profound importance to this type of study
- It is typically much harder (conceptually and practically) than you think it will be
  - *The difficulties are more conceptual, and turning theory into practice*
  - *If a "magic genie" told you what the objectives should be actually building the model would be pretty easy*
- Most difficult aspect is finding the sweet spot of where to write the objectives
  - *It's easy to find objectives that correspond to what you really want, but are impossible to measure reliably at design time (see example of hurricane tracks/intensity, consider example of research outcomes)*
  - *It's easy to find objectives that are easy to measure, but may not be related to what you really want to accomplish*
  - *Expect to have to write a bunch of objectives, rip them up, and start over*
  - *Find people who have experience in this, it is really hard*
- Once you have the value model the outcome of the study is probably determined, but you won't know what it is yet

Example of Value Model Direct Implications

Analysis of Radical Alternatives

- All-MEO and All-LEO don't look good at all, but how many examples do we need to build?
- By looking at the value model, and the design parameters, we can conclude that all such examples will be poor, as long as certain conditions on the value and cost models hold
- Don't need more examples, just need to examine the value and cost model assumptions

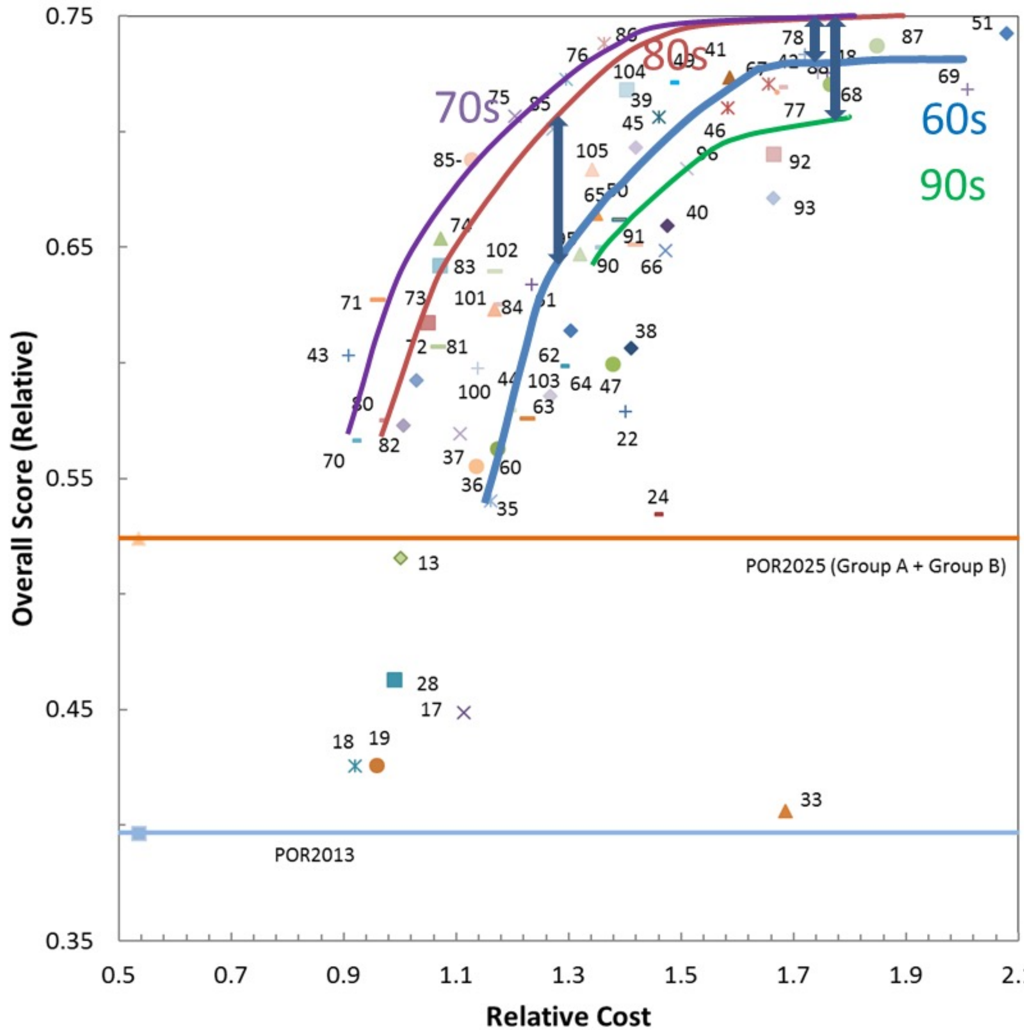


Given the value model, the radical alternatives will consistently underperform

Architecture as Classes of Alternatives

The constellations are not independent, groups share core decisions

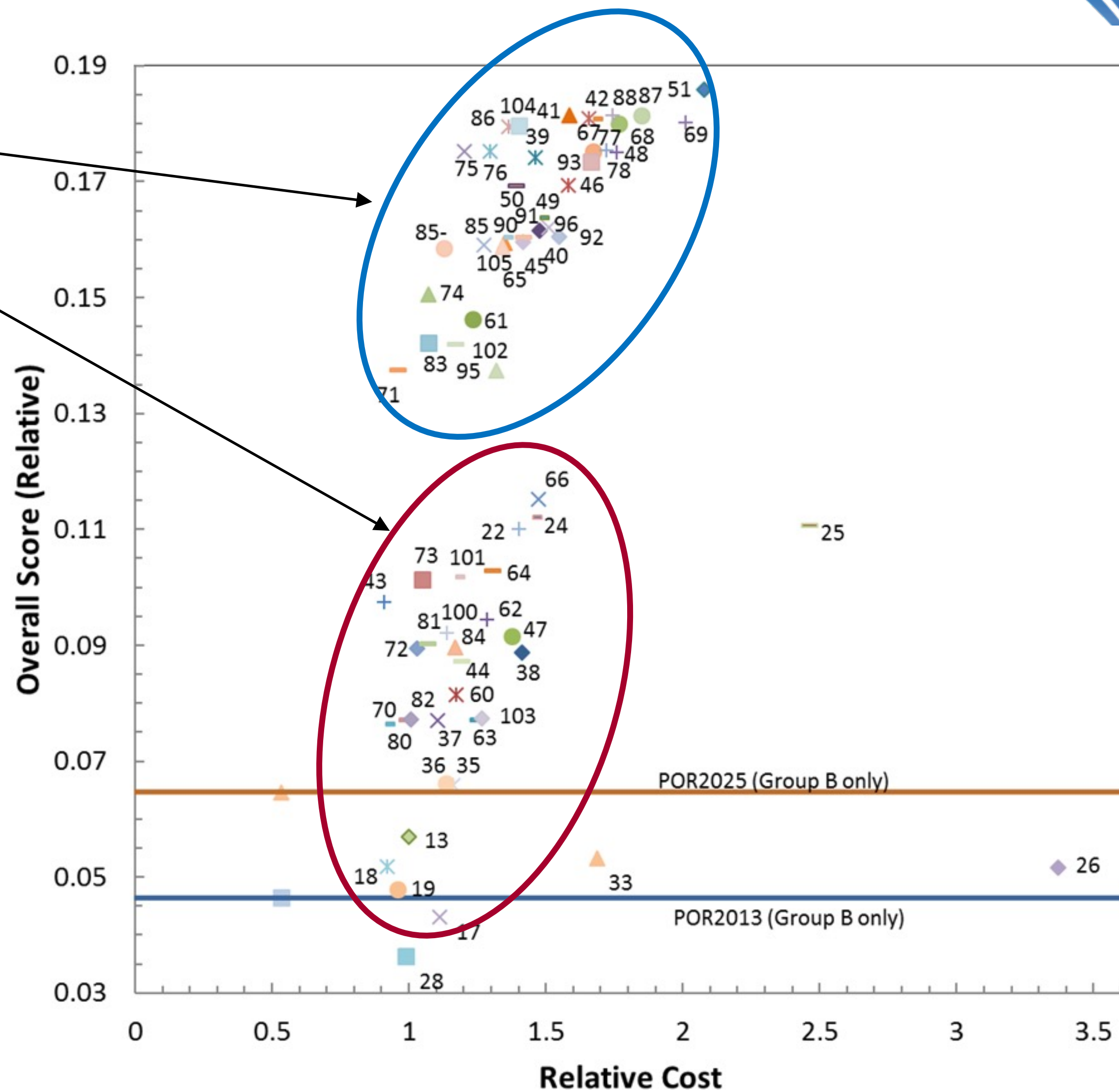
- 60, 70, 80, and 90 each define an <u>architecture</u>
  - *In the sense of a common set of distinct structural decisions*
  - *There are multiple constellations within an architecture (many more than shown)*
  - *The behavior of an architecture is more important (in the sense of decisions) than a particular constellation*
  - *Helps bring in hard-to-quantify differences not in EVM (such as risk differences between 70's and 80's)*



Can extend to examining individual decisions, isolating architectural aspects

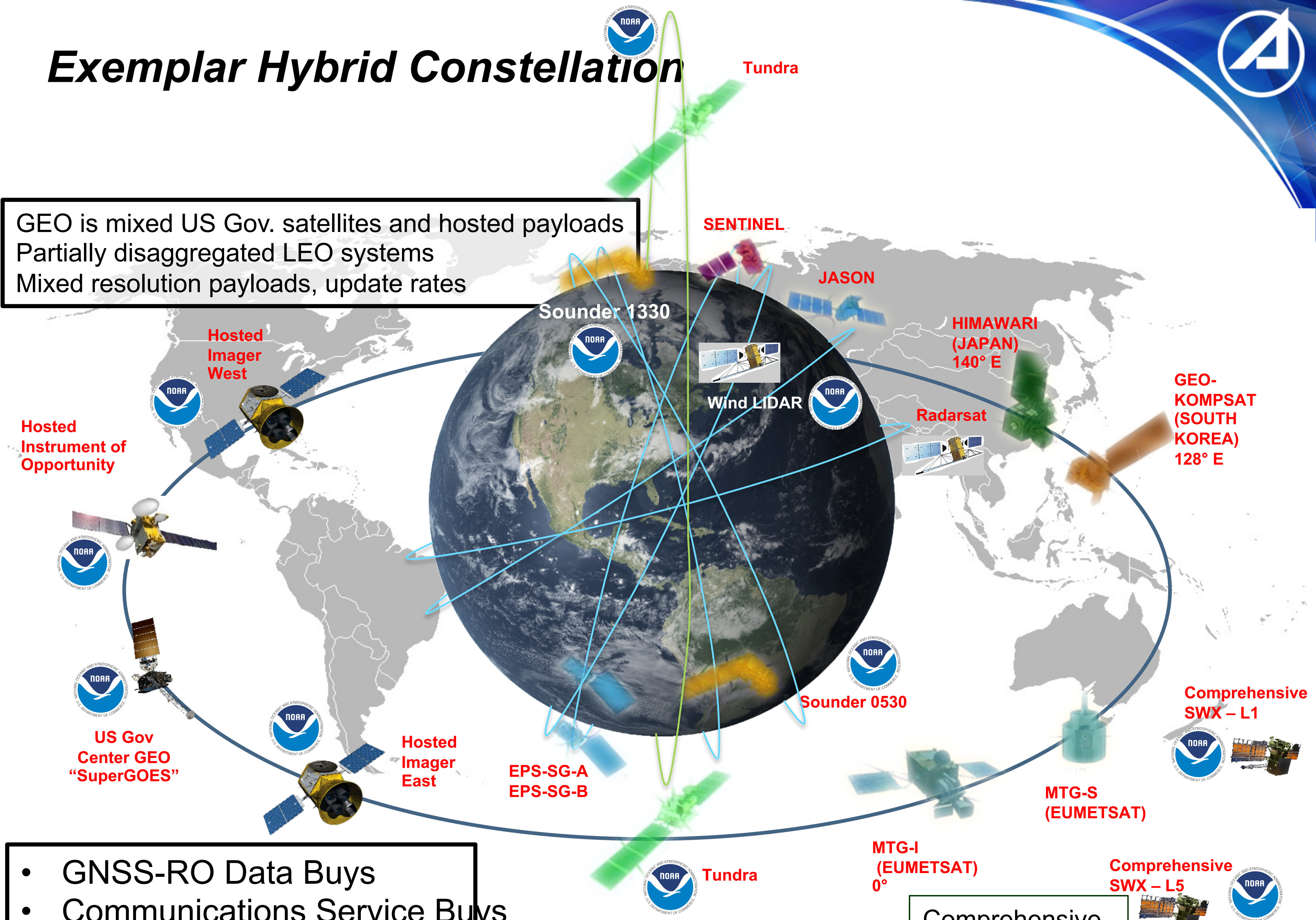
Easy Case, Space Weather Macro Choices

- Have capability A
- Don't have capability A
- Is it clear what we should do?
- Example of order-of-buy analysis. Unfortunately, rarely this easy.



Exemplar Hybrid Constellation

GEO is mixed US Gov. satellites and hosted payloads
Partially disaggregated LEO systems
Mixed resolution payloads, update rates



- GNSS-RO Data Buys
- Communications Service Buys

Comprehensive space weather

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Uncertainty, Variance, and Significance

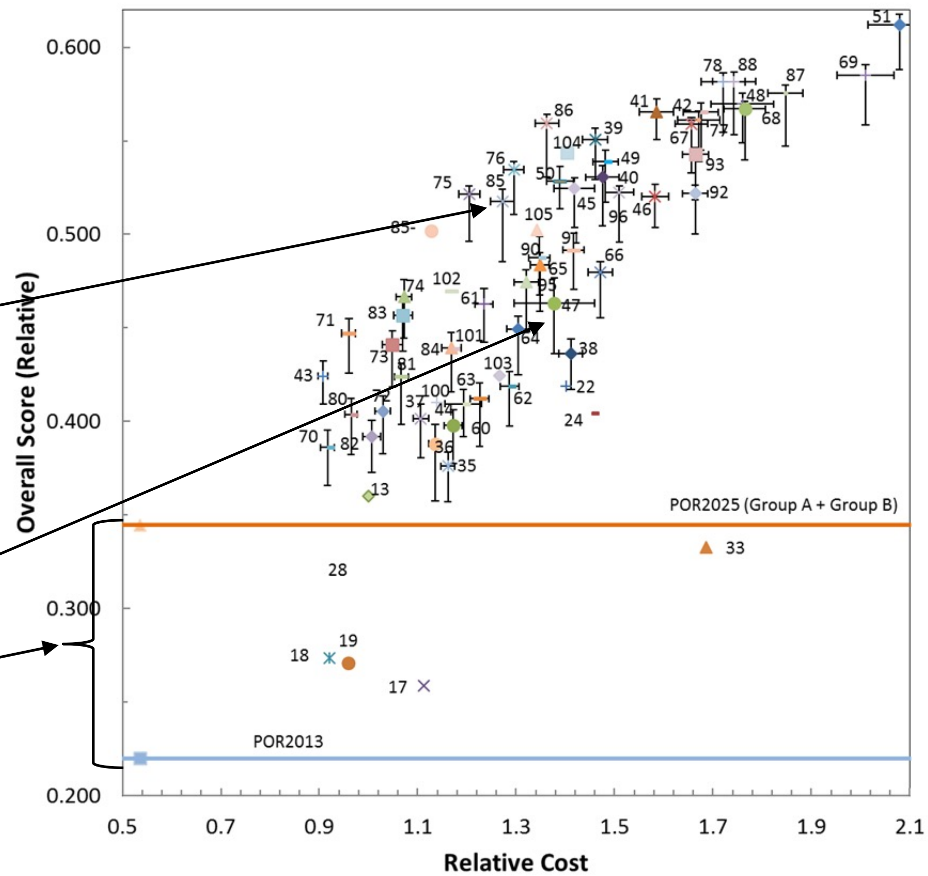
How do we assess "significant differences?"

- In any study like this (large number of alternatives, aggregated value model), how do we assess the significance of differences in the value metric or in the cost metric?
  - *Is the difference between 0.45 and 0.50 on the EVM "significant?"*
  - *If two alternatives have value differences of 0.05 is that a reliable indicator that one is better than the other?*
  - *How much of an estimated cost difference is a reliable indicator that one alternative is more expensive than another?*
    - How far can we trust absolute (as opposed to relative) cost values?
- Study of both value model and cost model uncertainty or variance has been very useful
  - *Allows confidence estimation of the results*
  - *Provides answers to all of the above questions*
- Significant work was done to get these benefits
  - *Translation of stakeholder observations into value variance models*
  - *Incorporation of deep correlations between alternatives*
  - *Cost uncertainty validation approaches*

Variance as Significance

How do we assess "significant differences?"

- Value variance computed from
  - *Observed scoring uncertainty*
  - *Observed swing weight disagreement*
- Cost variance based on established cost risk model (FRISK) extended to full co-varying model for shared components
- Can compare value delta to uncertainty size
  - *Measure of significance, except for strong correlation effects*
- Can compare cost delta to uncertainty
- Value delta between POR2013 and POR2025 provides additional significance benchmark



Conclusions

Really Lessons Learned

- Architecture as decisions
  - *Concept worked very well, full customer buy-in*
  - *Many decisions were provisional, identified as needing to be further studied with more in-depth information captured*
- Scale and the need for scale
  - *Scale of ~100 was a "sweet spot" for depth versus breadth. Mixed manual and automated processes worked well.*
- Choosing the value model level
  - *Never simple, worked in this case*
- Architecture as classes of specific alternatives
  - *A key point, not as widely understood as I thought. Tension exists between need for specific solutions in decision discussions and need for deferred decisions in program construction.*
- Variance as significance
  - *Interesting new take on what is otherwise a difficult point*

Some References

- Anthes, R, Maier, M. W., et. Al., Developing Priority Observational Requirements from Space Using Multi-Attribute Utility Theory, Bulletin of the American Meteorological Society, 100:9, pp. 1753-1754, 2019.
- Maier, M. W., Wendoloski, E., Value Uncertainty Analysis in Architecture and Trade Studies, IEEE Systems Journal, published electronically, print to appear.
- Maier, M. W., et al, The NOAA Satellite Observing Systems Architecture Study, Bulletin of the American Meteorological Society, should be available on-line in a few months.
- Various conference papers if you wish to search