Optimizing operational space collections of ECVs and reducing uncertainties in MIT Intergrated Global System Modeling

(GCOS Science Conference, Amsterdam)

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Collecting the earth’s critical climate signatures over the next 30 years is an obvious priority for many world governments and international organizations. Implementing a solution requires bridging from today’s scientific missions to ‘operational’ constellations that are adequate to support the future demands of decision makers, scientific investigators and global users for trusted data.

Certain converged architecture discussions are instructive based on the time when they occurred, and their refinement of environmental & climate variables and associated trade space(s).

The example(s) of required environment parameters (NPOESS), leads into essential climate variables (GCOS) and can become a critical part of the knowledge domain space for a new rule based decision architecting tool that can iterate to an optimized best value constellation solution as its goal.

The process of discovering new architectural alternatives reinforces the necessity for international collaborative efforts and elicits identification by and responses from key stakeholders.
History

Key objective - the Next Gen system must ensure continuity of critical signatures sufficient to support world governments, global climate user community with trusted data.

2.1 Orbits

2.2 Sensors, missions & ‘in situ’ data measurements

2.3 Satellite platforms and buses

2.4 Revisit periods and resolution

2.5 Processing to standard products

2.6 Cost efficiencies and incremental systems
A Framework for Knowledge-Intensive System Architecting

1. Decompose the problem into sub-problems.
2. Recognize sub-problem as an instance of a class of SAP from the library and retrieve generic class heuristics.
3. Tailor class heuristics to problem at hand. In particular apply VASSAR methodology for approximate evaluation rules.
4. Explore tradespace using generic SAT and tailored heuristics.
5. Combine results from sub-problems to generate preferred system architecture.
6. Check termination criteria and iterate if required.

Library of SAPs

- Selecting problems
- Permuting problems
- Partitioning and covering problems
- Connecting problems
- Assigning problems
Full VASSAR Representation

Figure 11. Level 2 VASSAR, step 3b: Prepare explanations
Specific Challenge

So what would it take to generate optimized best value architectural solution(s) for -

- GCOS 26 ECV’s with detailed definition of the spatial resolution, revisit, accuracy, swath and image size, computation requirements,..

- Common stakeholder value requirements – cost, launch dates, risks,

- Available international satellite platforms – at least 12

- Use existing TRL 7 sensor/ instruments with build to print specifications and space pedigree - at least 24
Operational climate monitoring: What are the needs and “requirements”?

Take requirements from OSCAR WMO database

ECV35 - River Discharge
ECV36 - Water Use
ECV37 - Groundwater
ECV38 - Lakes
ECV39 - Snow cover
ECV40 - Glaciers and Ice Caps
ECV41 - Ice Sheets
ECV42 - Permafrost
ECV43 - Albedo
ECV44 - Land Cover
ECV45 - FAPAR
ECV46 - Leaf Area Index
ECV47 - Above Ground Biomass
ECV48 - Soil Carbon
ECV49 - Fire Disturbance
ECV50 - Soil Moisture

ECV17 - Sea Surface Temperature
ECV18 - Sea Surface Salinity
ECV19 - Sea level
ECV20 - Sea State
ECV21 - Sea Ice
ECV22 - Sea Surface Currents
ECV23 - Ocean Color
ECV24 - Sea Surface pCO2
ECV25 - Sea Surface Acidity
ECV26 - Sea Surface Phytoplankton
ECV27 - Sea Sub-surface Temperature
ECV28 - Sea Sub-surface Salinity

371 requirements
Multiple data products per ECV
Multiple requirements per product
Temporal resolution
Spatial resolution
Accuracy
Vertical spatial resolution
...

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Operational climate monitoring: What instruments are available?

- Candidate instruments chosen from compromise between computational complexity and representativity of current and future instruments
- Many instruments left out for this simple case study

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<thead>
<tr>
<th>Instrument</th>
<th>Description</th>
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<th>Power (W)</th>
<th>Data Rate (Mbps)</th>
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Operational climate monitoring: What orbits are available?

- We could only choose 5 orbits for computational reasons:

- Orbits were chosen among the most popular for Earth observation, with the goal of taking different combinations of altitudes inclinations
  - 1 polar 600km
  - 1 SSO AM 600km
  - 1 SSO PM 800km
  - 1 SSO DD 600km
  - 1 SSO DD 800km

- This choice has a strong effect on results
  - Actual case study should include more orbits (400km, 700km, 1300km, 30deg, 51.6deg, 66deg, different repeat track orbits)
Our approach to system architecture

- Global hyper-heuristic optimization
- With a knowledge-based system
- Direct interaction with the human
- Focus on explanation and learning
Rule-Based Expert Systems (RBES)

- Experts store their knowledge in “chunks” that fit well the structure of *logical rules* ([Newell & Simon, 1972](#)).

- Idea: solve complex problems by using hundreds or thousands of logical rules in a computer program, imitating human reasoning.
  - First Rule-based System: **MYCIN experiment** ([Buchanan & Shortliffe, 1984](#)).

**Rule:**
- LHS: “**IF** the stain of the organism is gramneg, its morphology is rod, and its aerobicity is aerobic...”
- RHS: “**THEN** there is strongly suggestive evidence that the class of organism is enterobacteriaceae”

**Facts:**
- The stain of organism 123 is gramneg
- Organism 123 is aerobic
- Organism 123 is rod-shaped

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VASSAR matches capabilities with requirements

1. Compute capabilities
   - Domain knowledge base
   - Capabilities
   - 2. Compute requirement satisfaction
     - Requirements
     - Requirement satisfaction
     - 3a. Aggregate requirement satisfaction
     - 3b. Prepare explanations
     - Explanation facility
     - Preferences
     - Value
     - Explanations
   - Architecture
VASSAR uses rules to model emergent capabilities

**Zoom in Step 1: Computing Capabilities**

- **Architecture**
- **Manifest rules**
  - Assert architectural facts
  - Inherit attributes
  - Compute basic capabilities
- **Capability facts**
  - Compute emergent capabilities
  - Compute performance

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<th>THEN (new data products)</th>
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## Reference Architectures – ECV scores

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- A lot of Oceanic ECVs are not satisfied
  - Sub-surface variables
- These and others require non-space-based systems to be fully satisfied
Pareto Front – Good Architectures

- Run optimization algorithm for 100 generations + local search around last Pareto frontier

<table>
<thead>
<tr>
<th>Good Arch#</th>
<th>LEO-600-polar</th>
<th>SSO-600-AM</th>
<th>SSO-600-DD</th>
<th>SSO-800-PM</th>
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- Max scores around 40%, and costs upwards of $10B
  - Need system of systems (ground, air, space)
  - Need international cooperation (too costly otherwise)
Good Architectures – ECV scores

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<td>Good arch #1</td>
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<td>Good arch #2</td>
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<td>Good arch #1</td>
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</table>

- New words required
Assessing the robustness of the results

- Change constraint of 3Tbit/day/orbit to 10 Tbit/day/orbit

<table>
<thead>
<tr>
<th>Good Arch#</th>
<th>LEO-600-polar</th>
<th>SSO-600-AM</th>
<th>SSO-600-DD</th>
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- All scores have increased, and we see more instruments in each orbit
- Features have also changed: high data rate instruments appear more often
- Strong impact of communication systems capabilities!
Conclusion

- The VASSAR tool can be used as an executable science traceability matrix, to explore the architectural space of Earth Observing System architectures
  - It’s one more step in the direction of model-based systems engineering (documents ➞ models, static ➞ dynamic, text ➞ data, knowledge)

- The tool was demonstrated on a climate-centric case study based on ECVs
  - Space segment alone is not sufficient to satisfy ECV requirements
  - International cooperation is necessary
  - Design of Earth observing missions and communications systems are highly coupled
  - Dominant features include flying core chemistry sensors in an afternoon orbit, flying a TIR imager, an L-band SAR and a wide-swath altimeter in a polar orbit

- The next case study needs to be expanded with more instruments, more orbits, and more information.
MIT’s IGSM and EPPA

Human System

Economic Projection and Policy Analysis (EPPA)
National and/or Regional Economic Development,
Emissions & Land Use

Earth System

Atmosphere
2-Dimensional Dynamical, Physical & Chemical Processes

Urban Airshed
Air Pollution Processes

Ocean
2- or 3-Dimensional Dynamical, Biological, Chemical & Ice Processes

Land
Water & Energy Budgets (CLM)
Biogeochemical Processes (TEM & REd)

Coupled Ocean, Atmosphere, and Land

- Exchanges represented in standard runs of the system
- Exchanges utilized in targeted studies
- Implementation of feedbacks is under development

Figure 2: The schematic depicts the MIT Integrated Global System Modeling framework.

Credit - MIT Joint Program Global Change
Key goal:
Projections and risks of the natural, managed and built environmental responses to human and natural forcings.

Key Uncertain Elements in Climate Change

- Emissions Uncertainty
- Climate Sensitivity (change in temperature due to change in radiative forcing)
- Heat uptake by deep ocean & carbon uptake
- Radiative Forcing of Aerosols
- CO2 Fertilization Effect on Ecosystem (wide range)
- Trends in Precipitation Frequency

Figure 2: Schematic of the Global Land System (GLS), highlighting the linkages between the biogeochemical and biogeochemical land modules as well as interactions with the atmosphere-ocean-chemistry sub-models in the IGSM Version 2.

Credit - MIT Joint Program Global Change
NASA Current Satellite Operating Missions – value to Land schematics

SMAP: Soil moisture and its control on terrestrial heat, carbon, and nitrogen fluxes.
GRACE: Deep soil-water storage and aquifers.
LandSat: Land cover/use – how it relates to climate and economics.
GPM: Precipitation – its role in natural and managed water cycling.

others that relate to IGSM schematics…

Credit - MIT Joint Program Global Change & NASA
Future Missions
(http://eospso.nasa.gov/future-missions)

- 3D-winds: Air quality
- Aerosol-Cloud-Ecosystems:
  - ECOsystem Spaceborne Thermal Radiometer Experiment for Space Station (ECOSTRESS)
- GOES
- Global Ecosystem Dynamics Investigation Lidar
- GRACE follow on
- Surface Water Ocean Topography (SWOT)
- Snow and Cold Land Processes

Credit - MIT Joint Program Global Change & NASA
Strategy Towards an Architecture for Climate Monitoring from Space

1. Executive Summary

This report focuses on satellite observations for climate monitoring from space, and the need for an international architecture that situates delivery of those observations over the time frames required for analysis of the earth’s climate systems. The report outlines a strategy such as an architecture — a strategy that is environmentally high-level, conceptual, and inclusive, so that a broad consensus can be reached, and all relevant entities can identify their potential contributions. The strategy, however, is not sufficient in itself, and therefore also presents a logical architecture that represents an initial step in the development of a physical architecture. An end to end system capable of delivering the necessary observations for climate monitoring from space.

The report was written by a team of people representing a number of different organizations involved in climate monitoring and related areas. The report’s approach is based on an understanding of the need for an international, collaborative, and comprehensive approach to climate monitoring from space.

In terms of the overall strategy, several important points are worth noting:

- Achieve clarity in the general up-front strategy, in engaging national and international organizations and their associated programs, but not without a broader consideration of the potential for regional and national contributions.
- Achieve alignment with the scientific community and the conceptual frameworks used by the scientific community.
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The report does not attempt to address the technical details that are necessary to implement the strategy, but instead provides a high-level overview of the key components and potential benefits of the proposed architecture.

The report’s broad scope includes a wide range of topics, from the technical aspects of satellite observations to the policy and institutional frameworks that are necessary to support ongoing efforts. The report also highlights the need for continued collaboration and coordination among stakeholders to ensure the successful implementation of the proposed architecture.

The report concludes by emphasizing the importance of continued collaboration and coordination among stakeholders to ensure the successful implementation of the proposed architecture. It also highlights the need for continued investment in research and development to support ongoing efforts.

The report is concluded by acknowledging the contributions of the authors and the organizations involved in the development of the proposed architecture. It also highlights the need for continued collaboration and coordination among stakeholders to ensure the successful implementation of the proposed architecture.
So What’s Next,…

With a converging list of critical climate parameters/variables and a new tool kit to exhaustively explore and optimize a best value constellation solution or family of solutions - there isn’t a System Engineering obstacle preventing us from generating a requirements traceable and optimized ‘global operational constellation’ solution(s) for climate monitoring for the next 20-30 years.
Audience Challenge

- If this objective strikes a chord with you and your organization, please take the time to identify your interest in person or by e-mail douglas.b.helmuth@lmco.com

- dbhelmuth@comcast.net (local)