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

(GCOS Science Conference, Amsterdam*)*

Douglas Helmuth

Lockheed Martin Space Systems Company

Sunnyvale, CA, USA

Collaboration with

Dr. Daniel Selva

Cornell University

Ithaca, NY

MIT Research Team

MIT Joint Program Science & Policy Global Change

Cambridge Mass.

contact: douglas.b.helmuth@lmco.com

dbhelmuth@comcast.net

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Abstract & Contents

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

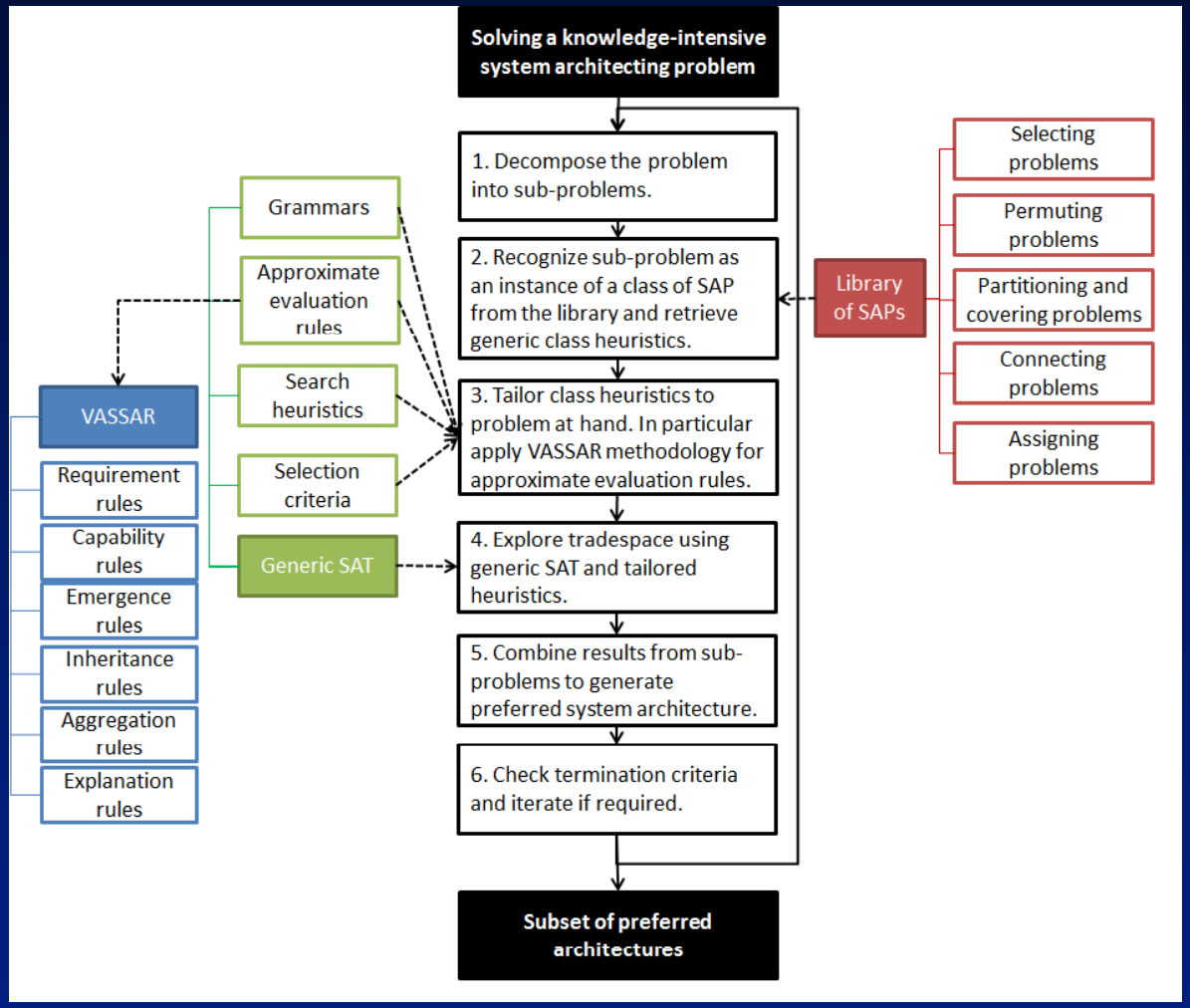
2.3 Satellite platforms and buses

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



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Full VASSAR Representation

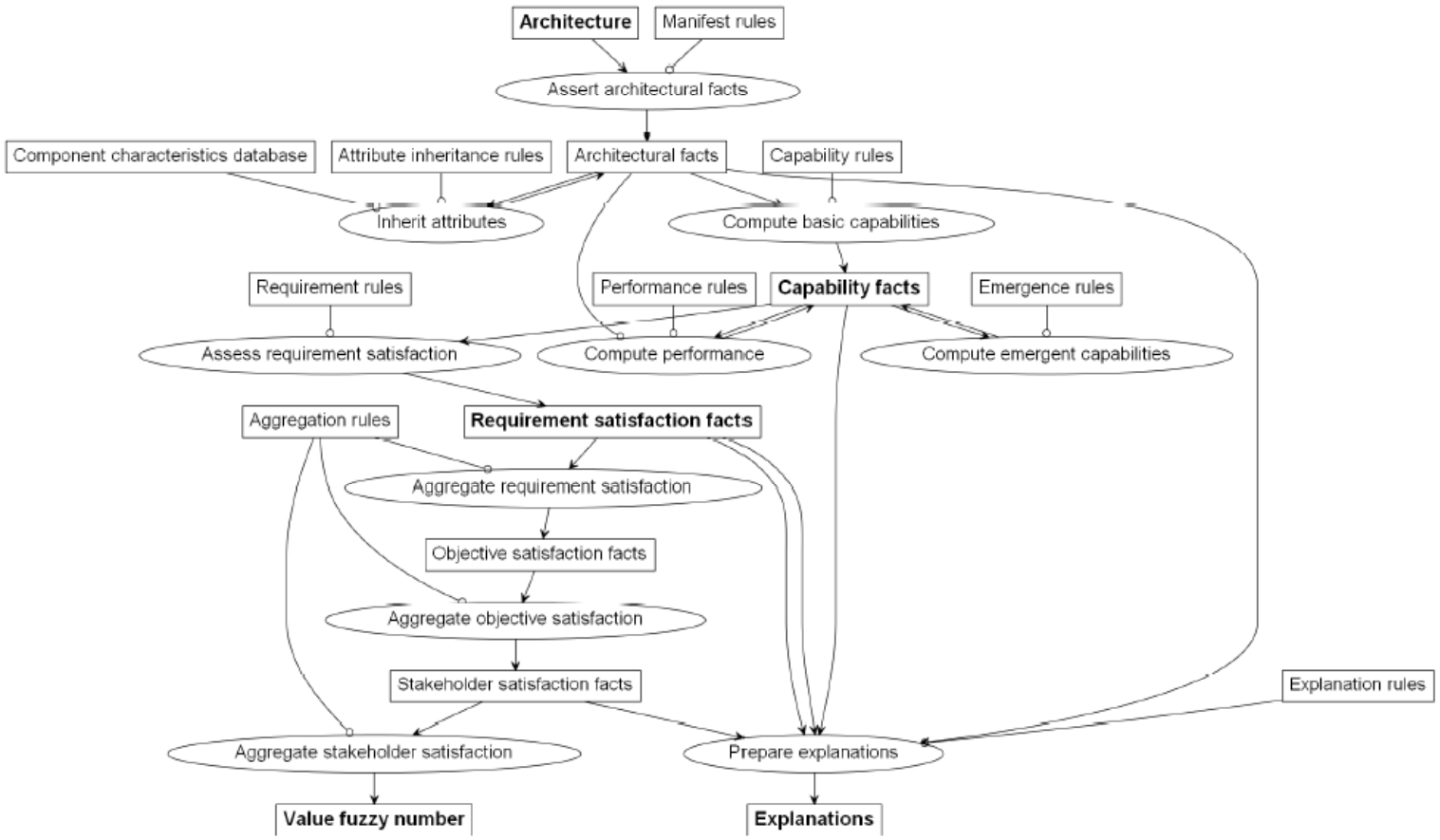

Figure 11. Level 2 VASSAR, step 3b: Prepare explanations

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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,..

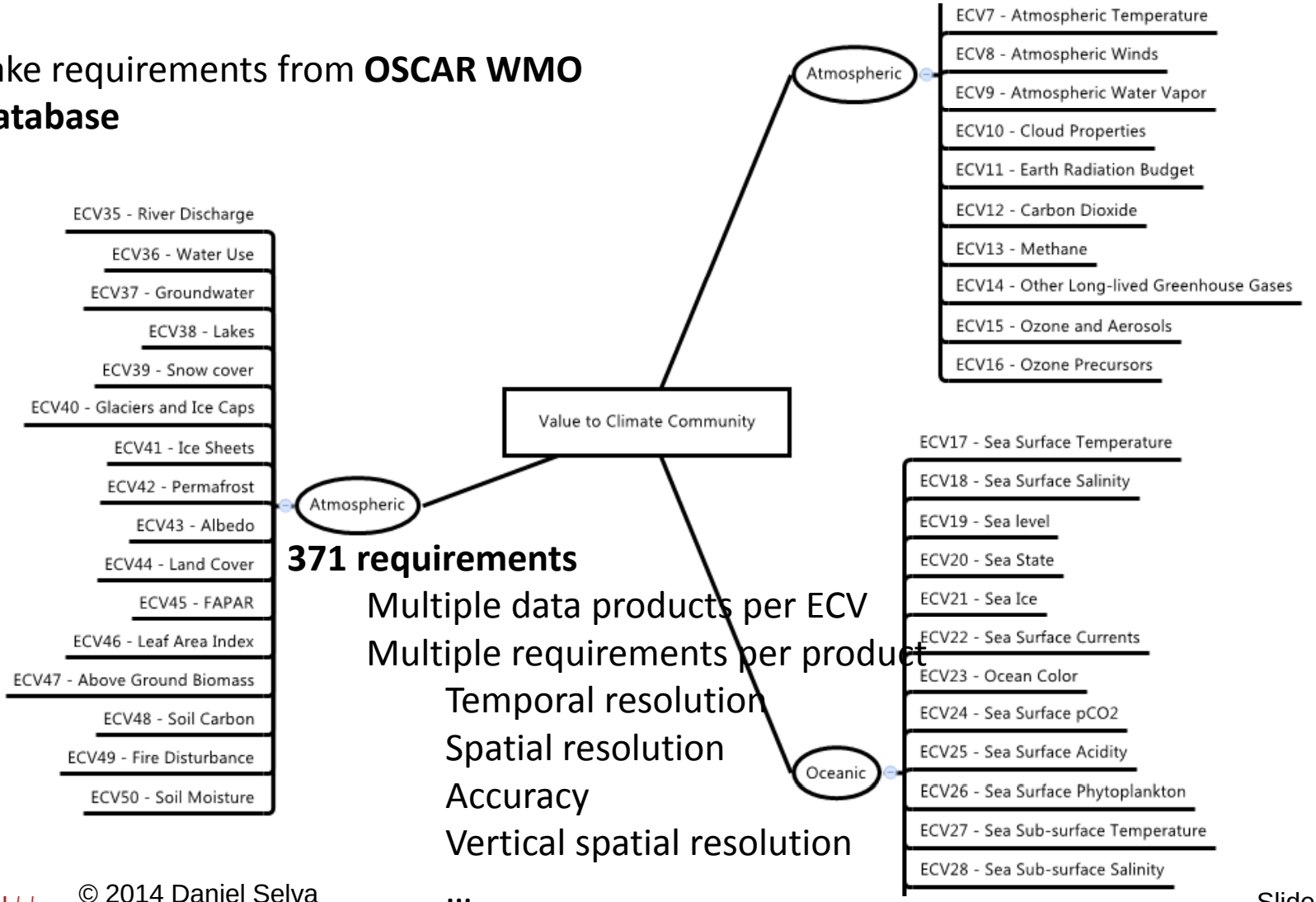
- Common stakeholder value requirements – cost, launch dates, risks,.

- 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**



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

Instrument	Description	Mass (kg)	Power (W)	Data Rate (Mbps)
OCE_SPEC	Ocean color spectrometer	137	132	12.0
AERO_POL	Aerosol Polarimeter	132	152	15.5
AERO_LID	Differential absorption lidar	515	658	11.1
HYP_ERB	SW+LW Hyperspectral Radiation Budget	238	387	160
CPR_RAD	Cloud & Precipitation radar	480	700	20.0
VEG_INSAR	Polarimetric L-band Interferometric SAR	400	500	60.0
VEG_LID	Vegetation/ice green lidar	200	500	1.00
CHEM_UVSPEC	UV/VNIR limb spectrometer	46.0	56.0	0.77
CHEM_SWIRSPEC	SWIR nadir spectrometer	250	208	40.0
HYP_IMAG	SWIR-TIR hyperspectral imager	99.0	78.0	65.0
HIRES_SOUND	IR atmospheric sounder	316	457	7.50
SAR_ALTIM	Wide-swath radar altimeter	300	300	10.0

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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)

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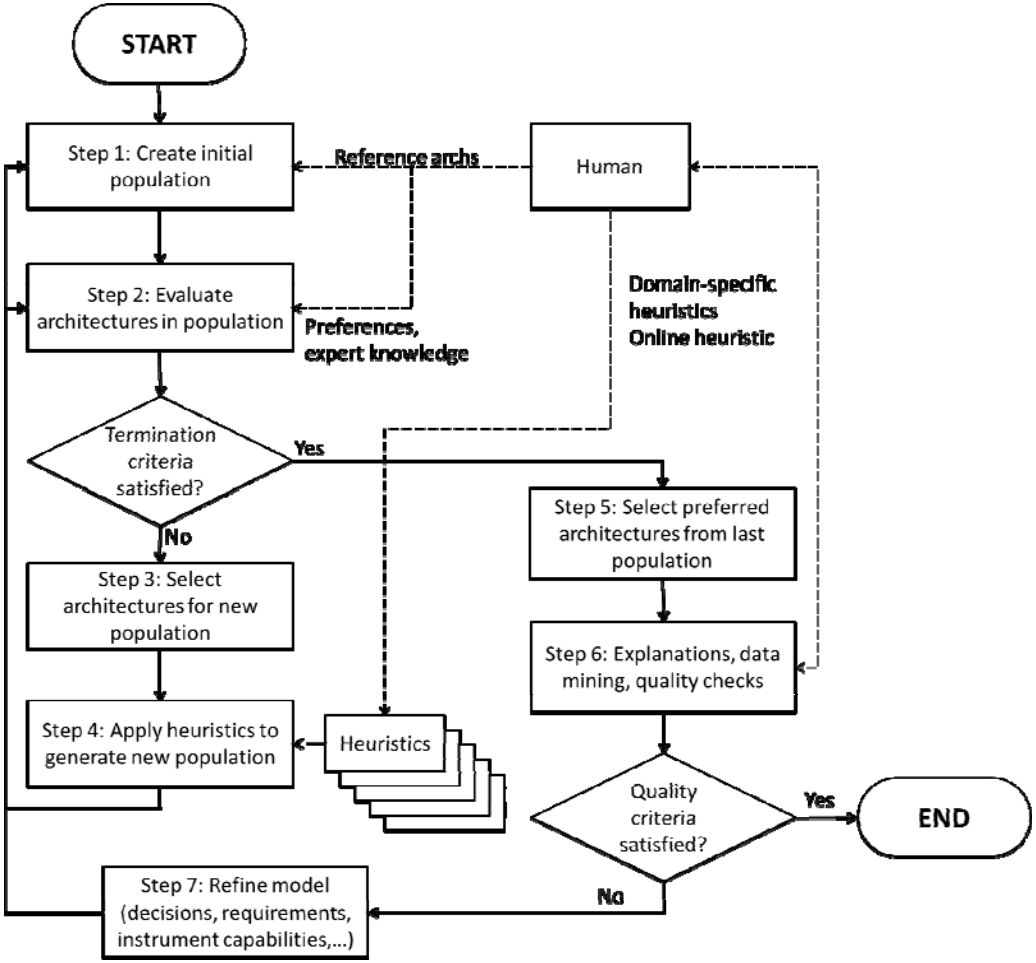
Our approach to system architecture

- Global hyper-heuristic optimization
- With a knowledge-based system
- Direct interaction with the human
- Focus on explanation and learning



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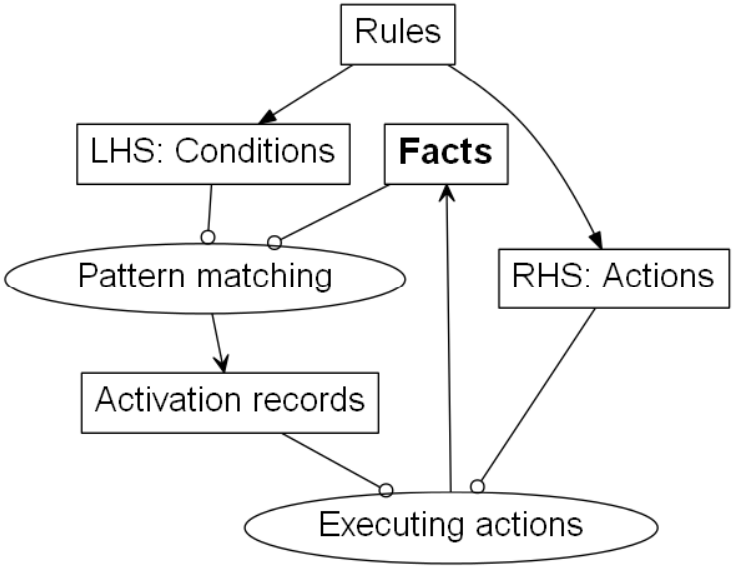
Rule-Based Expert Systems (RBES)

- 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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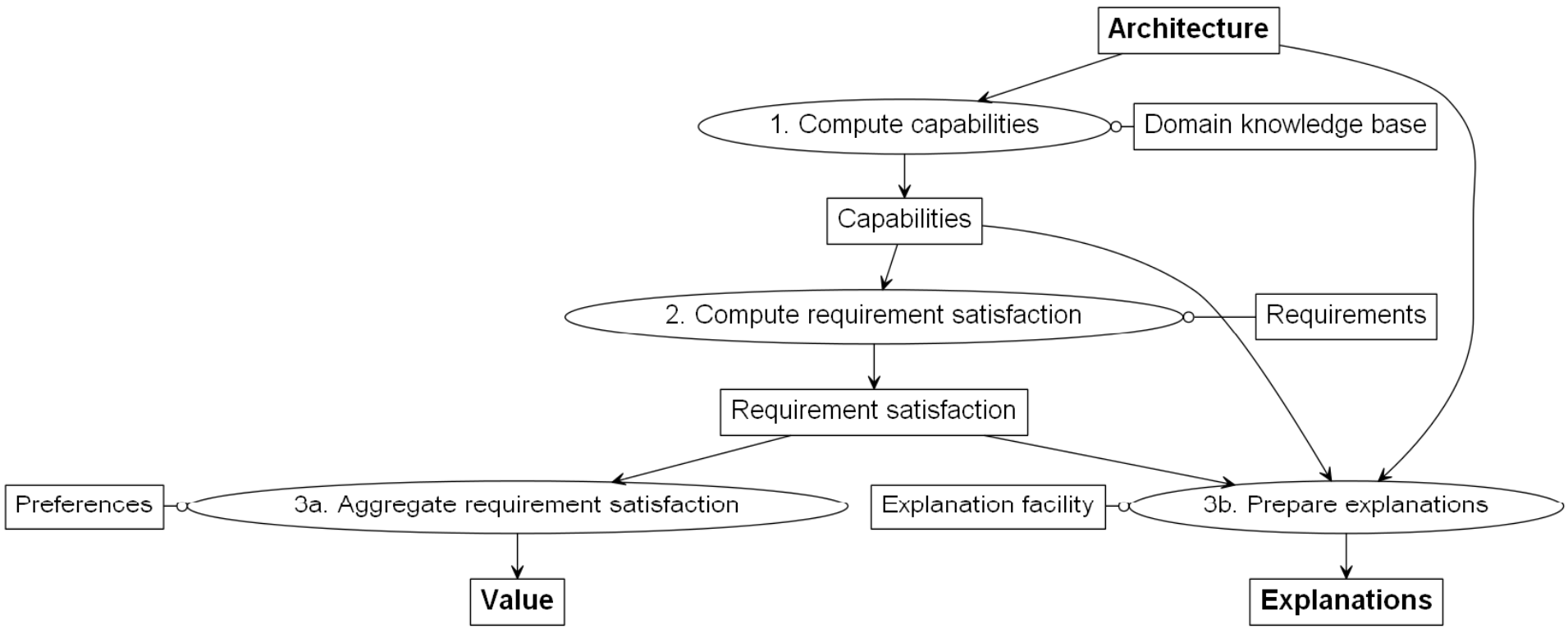
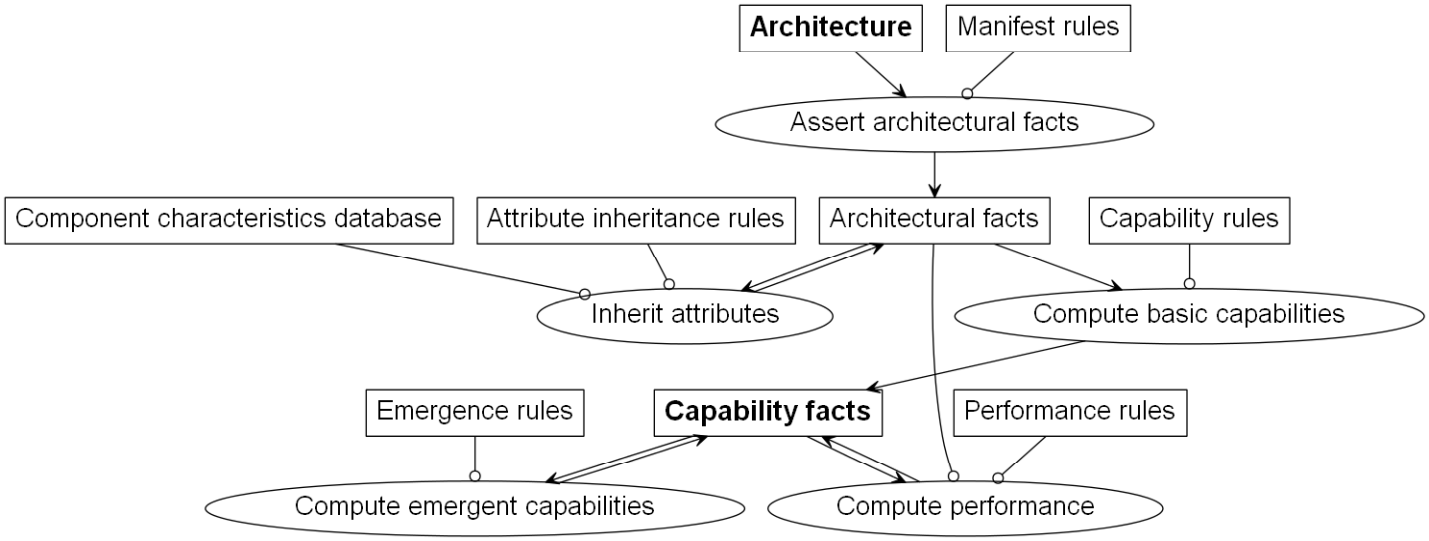
VASSAR matches capabilities with requirements



VASSAR uses rules to model emergent capabilities

Zoom in Step 1: Computing Capabilities



Emergence rule	IF (original data products)	THEN (new data products)
Soil moisture disaggregation algorithm	Soil moisture (**high** accuracy, **low** spatial resolution) Soil moisture (**low** accuracy, **high** spatial resolution)	Soil moisture (**high** accuracy, **medium** spatial resolution)

Reference Architectures – ECV scores

Atmospheric	ECV-1	ECV-2	ECV-3	ECV-4	ECV-5	ECV-6	ECV-7	ECV-8	ECV-9	ECV-10	ECV-11	ECV-12	ECV-13	ECV-14	ECV-15	ECV-16
Ref arch#1	0	0	0	0	0	0	0	0	0.218	0.0455	0	0.4752	0.4752	0.3546	0.2637	0.7092
Ref arch#2	0	0	0	0.0662	0	0	0.0662	0.1671	0.1841	0.1915	0	0.4013	0.4013	0.2995	0.2227	0.599
Ref arch#3	0	0	0	0.1373	0	0.0943	0.1373	0.3464	0.2748	0.2096	0.0641	0.4013	0.4013	0.2995	0.2227	0.599
Ref arch#4	0	0	0	0.1373	0	0.0887	0.1373	0.3464	0.2748	0.2669	0.0603	0.4013	0.4013	0.2995	0.3583	0.599
Ref arch#5	0	0	0	0.1191	0	0.0764	0.1191	0.3004	0.2748	0.314	0.0519	0.4013	0.4013	0.2995	0.4236	0.599

Oceanic	ECV-17	ECV-18	ECV-19	ECV-20	ECV-21	ECV-22	ECV-23	ECV-24	ECV-25	ECV-26	ECV-27	ECV-28	ECV-29	ECV-30	ECV-31	ECV-32	ECV-33	ECV-34
Ref arch#1	0	0	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0
Ref arch#2	0	0	0	0	0.67	0.1066	0	0	0	0	0	0	0	0	0	0	0	0
Ref arch#3	0.1373	0	0	0	0.3229	0.1066	0	0	0	0	0	0	0	0	0	0	0	0
Ref arch#4	0.1373	0	0.0545	0.1106	0.3229	0.2211	0	0	0	0	0	0	0	0	0	0	0	0
Ref arch#5	0.1191	0	0.1089	0.1106	0.67	0.2211	0.0852	0	0	0.1023	0	0	0	0	0	0	0	0

Terrestrial	ECV-35	ECV-36	ECV-37	ECV-38	ECV-39	ECV-40	ECV-41	ECV-42	ECV-43	ECV-44	ECV-45	ECV-46	ECV-47	ECV-48	ECV-49	ECV-50
Ref arch#1	0	0	0	0	0.2245	0	0	0	0.67	1	0.67	0.67	0	1	0.33	0
Ref arch#2	0	0.165	0	0	0.2245	0.0795	0	0.0795	0.67	1	0.67	0.67	0.2163	1	0.33	0.3229
Ref arch#3	0	0.0795	0	0	0.1614	0.0795	0	0.0795	0.2788	0.4819	0.2788	0.2788	0.2163	0.4161	0.1373	0.3229
Ref arch#4	0	0.165	1	1	0.2211	0.335	0.165	0.0795	0.2788	0.4819	0.2788	0.2788	0.4489	0.4161	0.1373	0.3229
Ref arch#5	0	0.165	1	1	0.335	0.335	0.165	0.165	0.2418	1	0.2418	0.3608	0.4489	0.3608	0.1191	0.67

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

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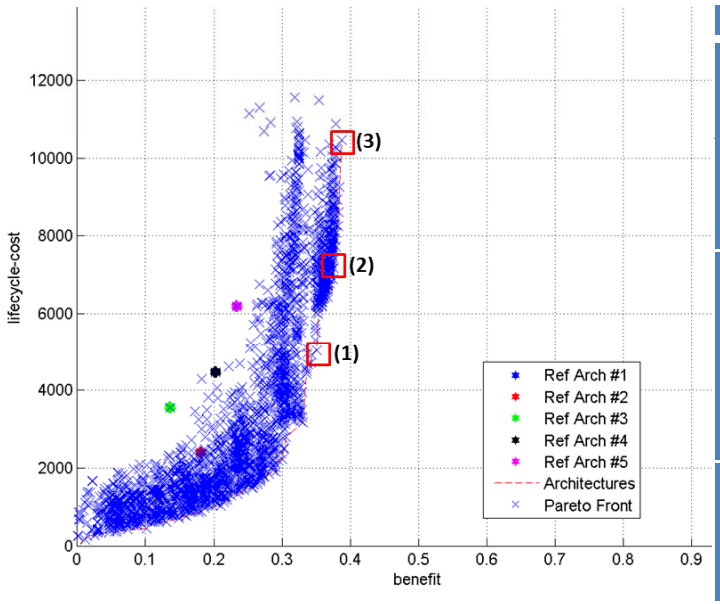
Pareto Front – Good Architectures

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



	LEO-600-polar	SSO-600-AM	SSO-600-DD	SSO-800-PM	SSO-800-DD
Good Arch# (3)	HYP_ERB VEG_INSAR HYP_IMAG VEG_LID SAR_ALTIM	OCE_SPEC CHEM_UVSPEC VEG_LID HIRES_SOUND	AERO_LID CPR_RAD	AERO_POL HYP_ERB CHEM_SWIRSPEC CHEM_UVSPEC HYP_IMAG HIRES_SOUND	CPR_RAD VEG_INSAR SAR_ALTIM
Good Arch# (2)	VEG_INSAR HYP_IMAG SAR_ALTIM	OCE_SPEC VEG_LID CHEM_UVSPEC HIRES_SOUND		AERO_POL HYP_ERB SAR_ALTIM CHEM_UVSPEC HYP_IMAG HIRES_SOUND	CPR_RAD VEG_INSAR SAR_ALTIM
Good Arch# (1)	VEG_INSAR HYP_IMAG	OCE_SPEC VEG_LID HIRES_SOUND CHEM_UVSPEC	SAR_ALTIM	CHEM_UVSPEC AERO_POL HIRES_SOUND	CPR_RAD VEG_INSAR

- Max scores around 40%, and costs upwards of $10B
  - Need system of systems (ground, air, space)
  - Need international cooperation (too costly otherwise)

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Good Architectures – ECV scores

Atmospheric	ECV-1	ECV-2	ECV-3	ECV-4	ECV-5	ECV-6	ECV-7	ECV-8	ECV-9	ECV-10	ECV-11	ECV-12	ECV-13	ECV-14	ECV-15	ECV-16
Good arch #3	0	0	0	0.3	0.5	0.1	0.3	0.8	0.6	1	0.1	0	0	0.3	0.7	0.3
Good arch #2	0	0	0	0.3	0.3	0	0.3	0.8	0.6	0.8	0	0	0	0.3	0.6	0.3
Good arch #1	0	0	0	0.3	0.3	0	0.3	0.8	0.6	0.8	0	0	0	0.5	0.9	0.5

Oceanic	ECV-17	ECV-18	ECV-19	ECV-20	ECV-21	ECV-22	ECV-23	ECV-24	ECV-25	ECV-26	ECV-27	ECV-28	ECV-29	ECV-30	ECV-31	ECV-32	ECV-33	ECV-34
Good arch #3	0.7	0	0.2	0.2	1	0.2	0.6	0	0	0.7	0	0	0	0	0	0	0	0
Good arch #2	0.3	0	0.3	0.3	1	0.3	0.6	0	0	0.7	0	0	0	0	0	0	0	0
Good arch #1	0	0	0	0.1	0.7	0.2	0.6	0	0	0.7	0	0	0	0	0	0	0	0

Terrestrial	ECV-35	ECV-36	ECV-37	ECV-38	ECV-39	ECV-40	ECV-41	ECV-42	ECV-43	ECV-44	ECV-45	ECV-46	ECV-47	ECV-48	ECV-49	ECV-50
Good arch #3	0	0.2	1	1	1	0.3	0.2	0.7	0.7	1	0.7	1	0.4	1	0.7	0.7
Good arch #2	0	0.2	1	1	1	0.3	0.2	0.7	0.7	1	0.7	1	0.4	1	0.7	0.7
Good arch #1	0	0.2	1	1	0.7	0.3	0.2	0.7	0.7	1	0.7	1	0.4	1	0.3	0.7

- New words required

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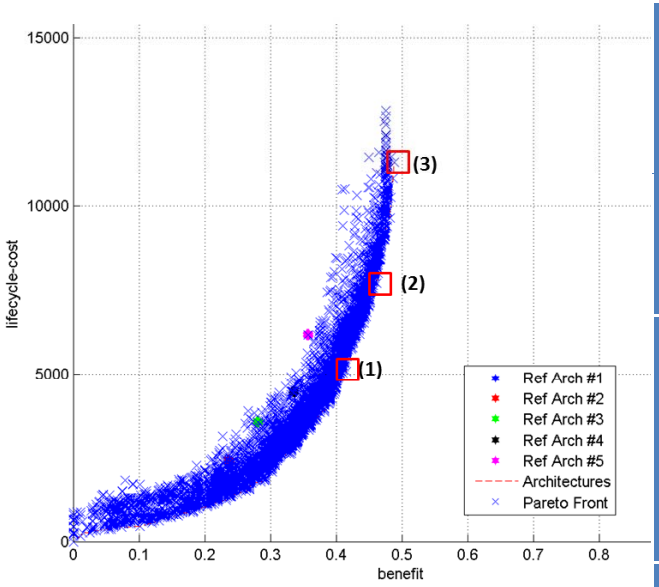
Assessing the robustness of the results

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



	LEO-600-polar	SSO-600-AM	SSO-600-DD	SSO-800-PM	SSO-800-DD
Good Arch# (3)	HYP_ERB VEG_INSAR HYP_IMAG SAR_ALTIM	OCE_SPEC CPR_RAD CHEM_UVSPEC CHEM_SWIRSPEC HIRES_SOUND	VEG_LID SAR_ALTIM	AERO_POL OCE_SPEC CPR_RAD VEG_LID HYP_ERB CHEM_SWIRSPEC CHEM_UVSPEC HYP_IMAG HIRES_SOUND	CPR_RAD VEG_INSAR
Good Arch# (2)	HYP_ERB VEG_INSAR HYP_IMAG SAR_ALTIM	OCE_SPEC CHEM_SWIRSPEC CHEM_UVSPEC HIRES_SOUND		AERO_POL CPR_RAD HYP_ERB CHEM_SWIRSPEC CHEM_UVSPEC HYP_IMAG HIRES_SOUND	VEG_INSAR
Good Arch# (1)	VEG_INSAR HYP_ERB CHEM_SWIRSPEC HYP_IMAG	OCE_SPEC HIRES_SOUND CHEM_UVSPEC		CHEM_UVSPEC CHEM_SWIRSPEC HYP_ERB HYP_IMAG HIRES_SOUND	SAR_ALTIM

- 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!

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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.

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MIT's IGSM and EPPA

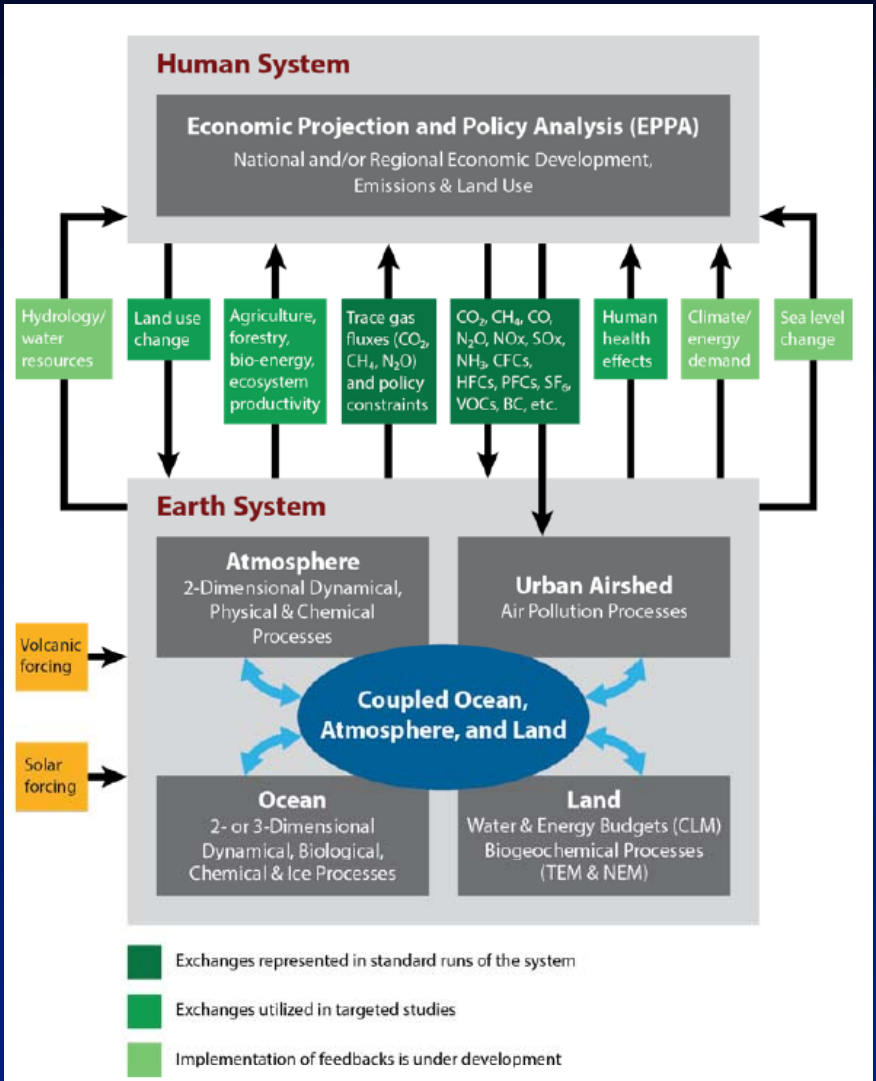
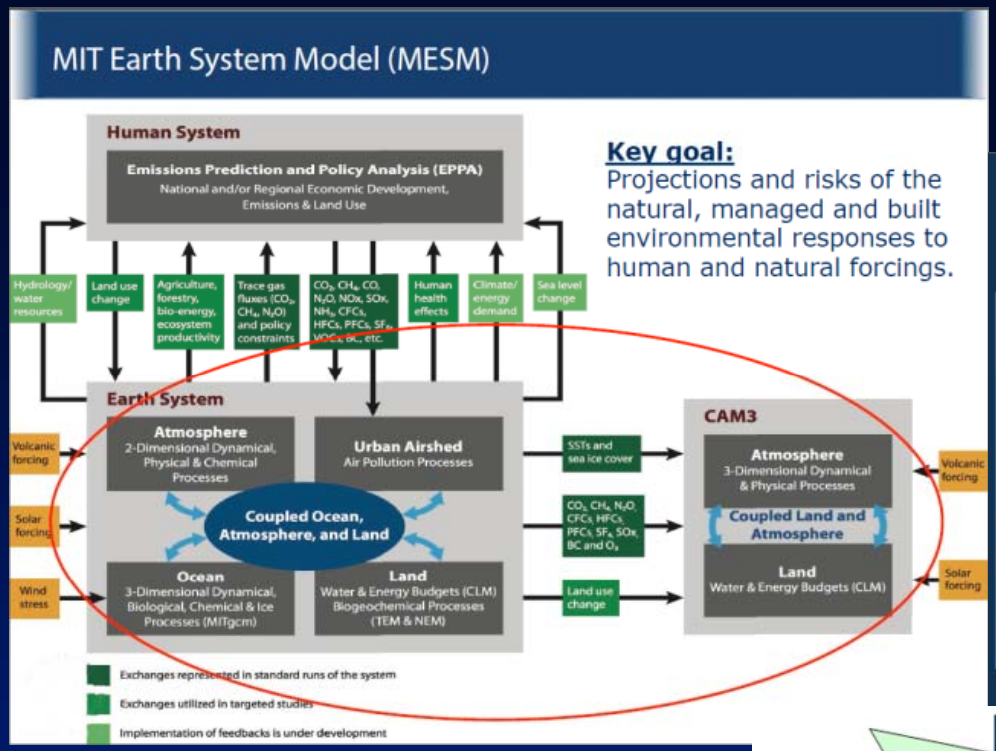


Figure 2. The schematic depicts the MIT Integrated Global System Modeling framework.

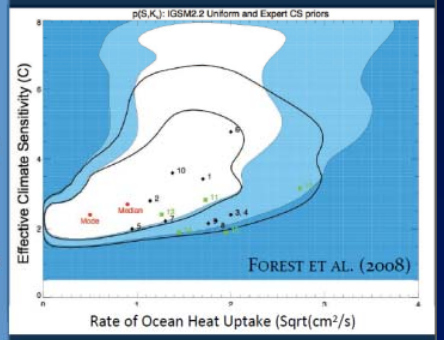
Credit - MIT Joint Program Global Change



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
- CO_2 Fertilization Effect on Ecosystem (wide range)
- Trends in Precipitation Frequency



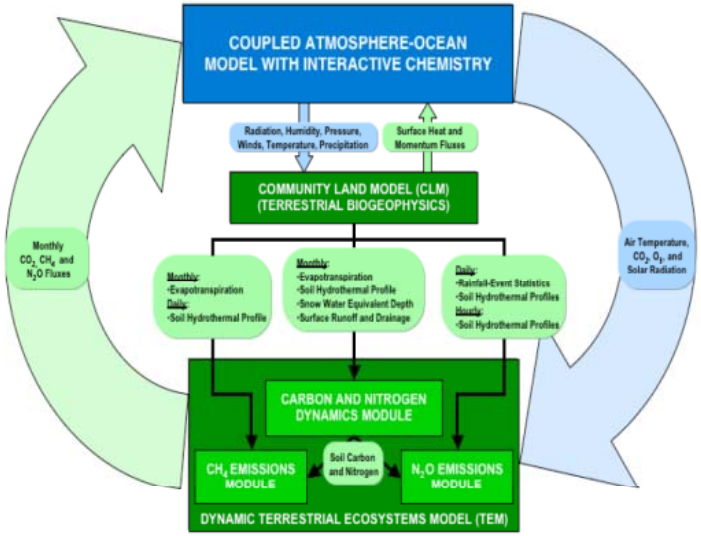
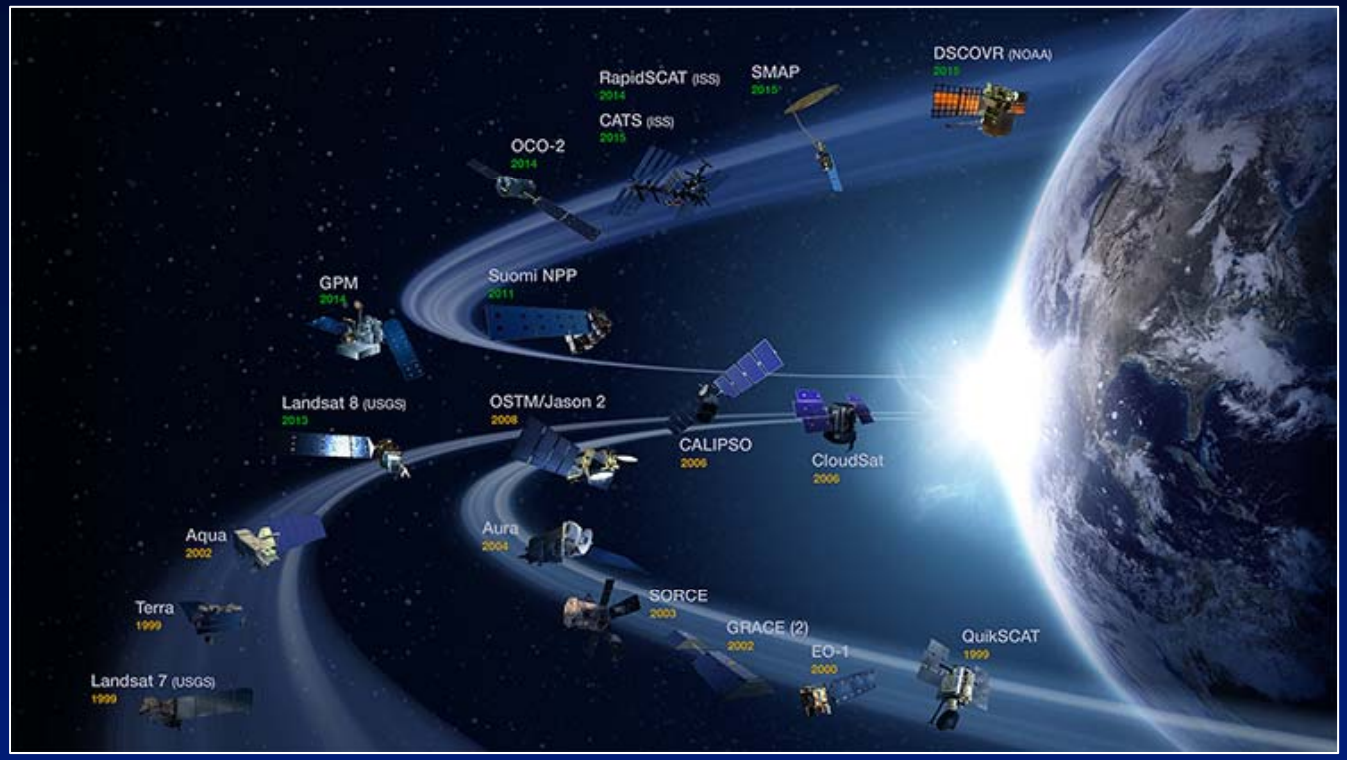


Figure 2. Schematic of the Global Land System (GLS), highlighting the linkages between the biogeophysical and biogeochemical land modules as well as interactions with the atmosphere-ocean-chemistry sub-models in the IGSM Version 2.

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

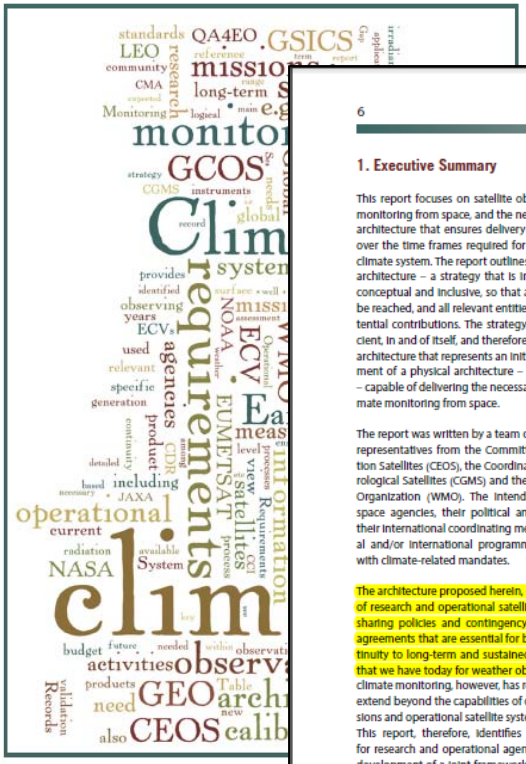
Future Missions

(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 ensures delivery of these observations over the time frames required for analysis of the Earth's climate system. The report outlines a strategy for such an architecture – a strategy that is intentionally 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 and of 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 comprised of representatives from the Committee on Earth Observation Satellites (CEOS), the Coordination Group for Meteorological Satellites (CGMS) and the World Meteorological Organization (WMO). The intended audiences include space agencies, their political and budget authorities, their international coordinating mechanisms, and national and/or international programmes and organisations with climate-related mandates.

The architecture proposed herein, calls for a constellation of research and operational satellites, broad, open data-sharing policies and contingency planning. It includes agreements that are essential for bringing the same continuity to long-term and sustained climate observations that we have today for weather observations. The task of climate monitoring, however, has requirements that must extend beyond the capabilities of one-time research missions and operational satellite systems in existence today. This report, therefore, identifies an important activity for research and operational agencies to undertake: the development of a joint framework for stewardship of climate information. Climate record processing requires a sustained expert understanding of both new and legacy climate sensors as well as a sustained web of support activities, including a significant effort on calibration and validation; research to reduce uncertainties, establish "community reference standards"; and collaborative product assessment and intercomparison. The sustained involvement of both research and operational agencies is a prerequisite for success.

Significant aspects evidenced in the report include, but are not limited to:

- In general, current observing systems h
  been primarily designed with a climate p
  tive, therefore, inventories are needed t
  ment the contributions of current and p
  observing systems for climate purposes.
- Requirements for mission continuity and
  gency need improvement through intern
  collaboration of space agencies.
- Sustained Climate Data Record (CDR
  grammes will provide an avenue to repla
  tage algorithms and data sets with impro
  sions once they are successfully demon
  validated and available.
- There is an imperative need to ensure trac
  along harmonised practices.

In terms of the way forward, some concrete act
clude, but are not limited to:

- Achieve a consensus on the general ap
  first engaging, in an ongoing manner, w
  relevant coordination bodies and their
  lary groups (including, but not restric
  CEOS, CGMS and WMO).
- Further involve the scientific communit
  viewing the proposed approach as a seco
  in the consensus building process.
- Verify that the proposed logical architect
  equately supports, in a top-down cont
  depiction of the required information flo
  the decision-making process back to the
  capacity/requirements,
- Design a physical architecture that captu
  current and planned implementation str
  on an Essential Climate Variable (ECV)-
  basis.
- Define an optimum "macroscale" space
  configuration and its components (in t
  of sub-constellations for each ECV or gr
  ECVs), as well as the respective ground
  from the combined perspective of the
  and physical architectures.
- Develop the physical architecture as an i
  process with continuous/periodic upd
  new observational capabilities become a
  or existing ones mature so that gaps an
  falls can be addressed.
- Verify the overall robustness of the archit
  structure for new applications, and for co
  maintenance, with a clear view of the
  end information flows as the architectu
  tures and the development of climate
  becomes further defined.

The report clearly identifies an imperative need for further and wider coordination among all stakeholders, both technical and policy-related, in order to optimise efforts to measure and document traceability and to secure the necessary resources for implementation. From a technical perspective, there is a need to seek greater involvement from the scientific community, relevant technical groups and utilise other available mechanisms for further development of the physical architecture. From a policy perspective, the proposed logical architecture must be verified to ensure that the information flows (from requirements to decision-making) are capable of meeting both policy and user-service needs.

While much has been done over the last decade and longer to better address the monitoring of Earth's climate from space, more remains to be done. The strategy presented in this report not only leverages the historic work and accomplishments of operational and research and development space agencies (and their partners), but extends that work to ensure that the requirements for observing the Earth's climate system on a routine and sustained basis can be met.

2. Introduction and Objectives

The role that satellites have played in observing the variability and change of the Earth system has increased substantially over the last few decades. Significant progress has been made in observing the Earth globally, with higher temporal and spatial resolution, which before the advent of satellites was all but impossible. With satellite observations of the Earth, we have been able to construct global views of many variables across the atmospheric, oceanic and terrestrial domains, including ozone, cloud cover, precipitation, aerosol optical depth, sea surface topography, changes in polar ice masses, and changes to the land surface. Indeed, with some satellite observations now spanning more than 40 years, the value of this information for climate monitoring purposes is becoming increasingly evident. Yet, more remains to be done. Although the subject of this report focuses on satellite observations for climate monitoring, the role that *in situ* observations play must not be overlooked. Existing *in situ* networks[1] provide observations of some parameters that are difficult and/or impossible to measure from space. These can serve validation purposes for satellite observations, can be used in joint analyses with satellite data, and in specific cases (e.g. optical measurements of land and ocean surfaces) provide a means of vicariously calibrating the space-based observations. Therefore, the combination of satellite and ground-based observations is essential. While recognising the importance of integrated observing systems, *the initial focus of this architecture effort lies with the space-based component*.

Many observations have been derived from satellites and sensors which were either not designed for climate purposes, or were not intended to operate over the long time frames needed for climate assessments. Contingency agreements between space agencies have been instituted for weather observations to ensure continuous observations for global numerical weather prediction, but not specifically for climate purposes. While much progress has been made recently, data-sharing policies and practices are still not as robust for climate data, as they are for weather data. And, reinforcing the need for this strategy, there currently exists no international, comprehensive task definition and planning, or even a design for undertaking this task, for climate monitoring from space. An architecture calling for a constellation of research and operational satellites, a broad, open data-sharing policy, and contingency planning is essential in order to bring the same continuity to long-term and sustained climate observations that we have for weather. Ultimately, such an architecture should result in a combination of existing constellations (both virtual and real) and dedicated satellite missions for climate variables that are not currently addressed, or poorly addressed through existing monitoring capabilities. It must include end-to-end climate information stewardship, consisting of data collection, data quality, archiving, processing and re-processing, discovery and access required for climate data record production. The discussions being held today for climate monitoring are remarkably similar to the early discussions for a globally coordinated "architecture" for weather monitoring, which have led to the successful end-to-end meteorological system that we have today (see Section 4 for more detail).

There are international, as well as national, policy mandates or structures regarding climate and climate change. In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to review and provide recommendations to governments regarding the state of knowledge of the science of climate change, the risks associated with human-induced climate change, the social and economic impacts of climate change and possible response strategies. In 1992 the United Nations Framework Convention on Cli-

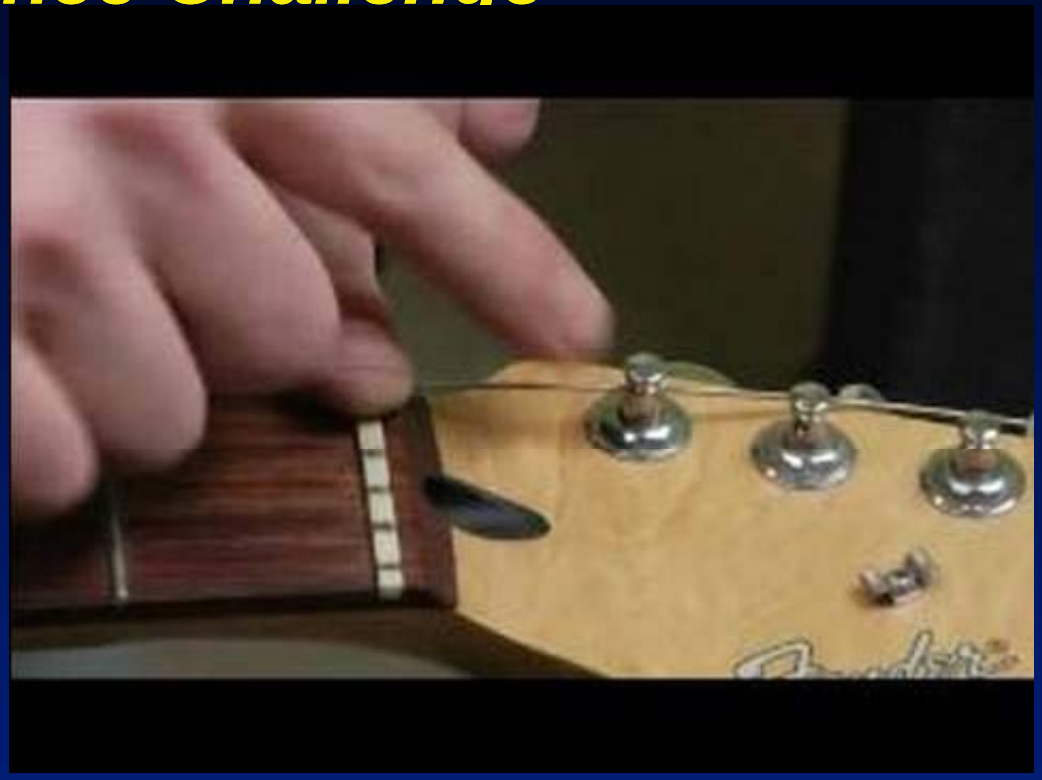
[1] Examples of key surface-based networks contributing to climate observations include, but are not limited to, the GCOS Upper Air Network (GUAN) and GCOS Reference Upper Air Network (GRUAN), the Argo Ocean Buoy Network, the AErosol RObotic NETwork (AERONET), and WMO's Global Atmosphere Watch (GAW) and Regional Basic Climatological Network (RBCN).

Credit -CEOS publication

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)*