A Classification for Multiple Mission Observation Concepts

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Abstract—Terms such as “sensorwebs,” “satellite trains,” and “constellations” are used to describe multiple mission observation concepts. This paper categorizes these concepts based upon how they observe. The observation aspects are: (1) the spatial distribution of the observations, (2) the degree of similarity of the observations, and (3) requirement for real-time observation coordination. The author proposes a taxonomy for these concepts based on names already proposed or in common use. Similar classifications could be based upon aspects such as communication or location. The author hopes this work will help advance the discussion and development of multiple mission observation capabilities.

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1. INTRODUCTION

The author recently completed a thesis in partial fulfillment of the requirements for the Degree of Master of Science in Engineering and Management from the Massachusetts Institute of Technology [1]. As part of this thesis, the author organized and described current and proposed Earth observation multi-mission concepts, using these to gain insight into future Earth observation system architecture options.

All observation missions, whether orbiting remote sensing spacecraft, airborne in situ sensors, or surface-based buoys and ground stations, must perform certain basic processes or functions. Attributes of these basic functions can be used to classify mission types.

- Missions observe by physically interacting with some aspect of the environment.
- Observations are useful only if there is some means for conveying the results of the physical interaction, ultimately to an end user.
- In support of the primary processes of sensing and conveying results, a mission must have some means (either active or passive), for navigating and guiding, determining and controlling its attitude, and for physically supporting the sensing capability (e.g., powering, heating/cooling, etc.).
- A mission must have some means of deploying to perform its primary processes, such as launching for space missions or deploying for earth-based missions.
- By some means, the mission must be monitored and controlled.
- The full mission life cycle requires capabilities to conceive, design, develop, and test the mission.
- Finally, sustaining the mission capability requires some means of decommissioning current missions at their end-of-life, and for developing new, improved, and replacement missions.

Numerous concepts have and continue to be developed and described for networks of distributed observation missions, using terms such as “sensorwebs,” “satellite trains,” and “constellations.” This paper includes a summary of papers that describe future multi-mission Earth observation concepts and describes a categorization of multiple mission observation concepts based upon three aspects of how multiple missions observe. These aspects are (1) the spatial distribution of the observations, (2) the degree of similarity of the observations, and (3) the degree of real-time coordination required for the observation. The author draws upon many concept names already proposed or in common use and proposes a complete set of concept names.

Other categorizations can be based upon the other crosscutting mission functions listed above. For example, sensorweb concepts could be classified based upon the network topologies and link type/data rate requirements returning the observation results, or upon similar link classifications for how the missions are controlled. Missions are often classified based upon how and where the

observation capability is deployed and located (e.g., orbital vs. airborne vs. fixed surface platforms). The NASA Earth Science Enterprise distinguishes between systematic missions that require long-term and sustained capability and exploratory missions that require shorter-duration process studies.

The above represent independent, crosscutting functions that all missions must perform. Some earlier discussions of sensorwebs have used blended categorizations based upon observation approach and communications approach. The author hopes that establishing criteria for categorization and recognizing that certain crosscutting functions form independent bases for categorization will help clarify future discussion of sensorweb concepts.

2. DISCUSSION OF RECENT "SENSORWEB" CONCEPTS

Current missions provide examples of many of the non-real-time coordination concepts. Earth remote sensing satellites and most Earth-based remote and in situ sensors currently operate independently by executing preprogrammed sequences that are periodically updated by ground-based operators and operations systems. Any coordination of observations between missions must be preprogrammed and rely upon absolute references, such as time, position, and/or pointing/geolocation. Responses to unexpected or unusual events typically require operator-in-the-loop adaptation by the ground operations system.

The real-time, autonomous coordination of observations is the focus of majority of current Earth science "sensorweb" concept work. The various "sensorweb" concepts that have been described in Earth Science Enterprise vision statements and IGARSS papers all share this attribute. In general, the Earth science oriented descriptions of sensorweb concepts tend to emphasize distributed, heterogeneous observations that are widely distributed in vantage (e.g., *in situ*, airborne, low Earth orbit, as well as high orbit and sentinel locations). These Earth science sensor web concepts interact autonomously in near real time to adapt observations strategies in response to rapidly evolving phenomena. On the other hand, the space science oriented descriptions of sensorweb concepts tend to emphasize homogeneous observations that are mostly *in situ*, such as might be deployed on the surface of Mars.

The following summarizes concepts from numerous reports and papers.

Ticker and Azzolini describe four of the types of distributed spacecraft architectures, global constellations, virtual platforms, precise formation flying, and sensorwebs. [2]

- They describe constellations as distributed in time and space, providing multiple similar observation spacecraft to increase (temporal and/or spatial) coverage.

- They describe virtual platforms as nearly co-located in time and space, providing multiple distinct observations of the same location (e.g., to increase spectral coverage).
- They describe precise formation flying as a special case requiring precise knowledge or control of position.
- Finally, they describe Sensorwebs as having multiple vantage points, multiple sensor types, and using data fusion for real-time, autonomous measurement coordination. Ticker and Azzolini define sensorwebs (for the purpose of their study) as both distributed in orbit/vantage and complementary in observation type, stating that sensorwebs are "an architecture that utilizes multiple vantage points and a mixture of sensor types to achieve synergistic observations of the Earth."

Figure 1 from Ticker and Azzolini depicts the relationships or transformations between these four architectures.

Figure 1: Notional Architecture Transformations (Ticker and Azzolini)

Ticker and Azzolini's classification of distributed spacecraft architectures views the distinction between Global Constellations and Virtual Platforms as the coordination of observations, the distinction between Virtual Platforms and Precise Formation Flying as the addition of precision metrology, and the unique attribute of Sensorwebs as the aspect of data fusion. In describing the characteristics of a Sensorweb, they state, "Data fusion and real-time measurement coordination and communication across platforms and systems create a leveraged system of systems." Similar heterogeneous and distributed sensorweb concept are discussed in numerous vision and strategic plan documents. [3]

Kramer describes a number of multi-satellite observation concepts, particularly in section 1.3.3, "Cooperative Distributed Systems, Satellite Formations." [4] Kramer introduces the term "parasitic" in a discussion of multi-static sensing in which the passive receiving spacecraft use cartwheel orbits (originally proposed by CNES) and are "independent" of the transmitter function.

Several papers presented at the IEEE 2001 International Geoscience and Remote Sensing Symposium (IGARSS

2001) provide further, and in some cases slightly contradictory discussions of the sensorweb concept.

Crisp et al describes an integrated web of surface, air, and in-space sensors that are coordinated by an advanced, semi-autonomous network. [5] This network would link the systems to each other, provide a seamless interface with data processing, and enable the system to rapidly assimilate, evaluate, and disseminate data and results. The sensorweb would include an enhanced space-based communications architecture to provide near real time access to data from all vantage points, continuously transmitting data at high communications bandwidth. This concept would require significant advances in spacecraft autonomy that enable the system to react autonomously in response to simple, goal-oriented commands. The paper describes the application of this sensorweb concept to a system to rapidly recognize, analyze, and disseminate information about natural hazards.

Peri, Hartley, and Duda describe a sensorweb approach that involves a large numbers of similar or identical frequency-agile instruments. [6] These hyperspectral remote sensing instruments would normally operate in lower resolution monitoring modes that would use techniques such as spectral band aggregation, spatial averaging, data selection, and compression to reduce the monitoring data rate. However, the system would be capable of autonomous event detection and real-time adaptive operation. When an event is detected, the system would adapt in real-time to higher resolution probing modes.

This is a hybrid sensorweb concept in which the hardware is capable of similar observations from distributed orbits and vantages, but might autonomously elect to obtain complementary subsets of observations in order to reduce data rates or user information overload.

Prescott, Smith, and Moe describe a sensorweb concept in which all instruments are independently controlled either directly by ground command (for example, giving an investigator direct command authority over an instrument), or autonomously by the integrated sensor-web system itself. [7] The instruments would be networked into an organic measurement system, with each satellite able to act autonomously to significant events by making adjustments such as increasing precision and coverage where needed. This closely integrated constellation would normally act autonomously in controlling instruments and spacecraft, but be able to respond immediately to the commands of the user. The real-time information systems would support on-board processing and intelligent sensor control, high data rate transmission and network control, intelligent platform control, and information production, distribution and storage.

The concept of the user having the ability to exercise real-time control over the system, while adding complexity, is comparable to the user input being the highest-level event

trigger that alters the response of the system. Therefore the analysis in this paper does not treat this as a unique driver.

Lemmerman, et al, describes a distributed, heterogeneous, adaptive, cooperating macro-instrument concept, coordinating efforts between multiple numbers and types of orbital and terrestrial sensing platforms, both fixed and mobile. [8] In this concept, information is shared and used across the system. Each element communicates within its local neighborhood, distributing information to the whole. The architecture would allow obsolete or damaged elements to be replaced with minimal impact. The web could be expanded over time as resources and budgets allow, using the same techniques as networks on Earth. The paper summarizes the major technical challenges in software (protocols, information security, and network reliability) and hardware (miniaturized and agile hardware elements). The space elements in the network face additional challenges unique to the space environment, including infrequent contacts, asymmetric links, high time delays, and increased bit error rates. The sub-space (or Earth-based) portion of the sensor web could leverage existing and evolving terrestrial Internet protocols, such as mobile ad hoc networking.

In addition to these IGARSS papers, a number of other papers describe slightly different concepts of sensorwebs. In particular, Delin outlines "the potential of the Sensor Web concept" and describes, "How the Jet Propulsion Laboratory Sensor Webs Project ... uses a set of criteria in evaluating Sensor Web applications." [9] The observations used as examples in this paper tend to be similar but not always identical. An example is a distributed network of less accurate sensors to provide earlier detection with occasional high accuracy sensors to provide calibrated observations. The emphasis in this concept and definition of a sensor web is not on differentiation between sensor types, but on the sharing and use of data among "pods" in the sensor web, providing real-time interaction and adaptive sensing strategies.

3. PROPOSED MULTIPLE MISSION OBSERVATION CLASSIFICATION

In examining and trying to understand these related but slightly different multi-mission observation concepts, the author recognized that the blending of classifications based upon observation approach with those based upon location or communication approach added complexity. To simplify the analysis the author identified three attributes that could be used as a basis for classification based solely upon the observation approach. The three attributes are:

1. *Position/Vantage*: Whether either the observed locations or the observation vantage points are:
 - *Distributed*: widely distributed in space, typically with global coverage.

- *Aligned*: generally aligned, typically with the precision available through standard methods, as in the current Terra/Landsat-7/EO-1/SAC-C satellite train.
 - *Precise*: using precise control or knowledge beyond that generally available, requiring additional hardware or unusual operating procedures, as is needed to recover the gravity signal from the GRACE mission. Ticker and Azzolini use the term Precision Formation Flying, and make a distinction between Virtual Platforms and Precision Formation Flying. [10] This recognizes that some mission concepts require knowledge and/or control of the relative positioning of satellites to accuracies that exceed by several orders of magnitude what is possible with GPS and other standard techniques.
2. *Observation Type*: Whether the types of observations are:
- *Complementary*: using different instrumentation, as in infrared observations that complement visible observations, or cloud contamination measurements to complement land surface observations.
 - *Similar*: using the same or related instrumentation to obtain similar observations, as in global coverage with multiple copies of the same instrument, as in stereo imagery, or as are the microwave links between the two spacecraft in the GRACE mission.
3. *Coordination*: The degree to which the coordination of the observations is:
- *Scheduled*: pre-scheduled with the operator-in-the-loop, as is the common practice today.
 - *Autonomous*: performed autonomously and in real-time, as in the descriptions of the sensorweb concepts.
- Note that this last attribute does not consider the form of the command and communications system that allows autonomous coordination. The coordination system could involve direct links between missions, but could also be implemented through an autonomously acting ground-based system. The key distinction is the autonomous and near real-time nature of the coordination, not the nature of the network used to achieve the coordination.
- The following table uses these attributes to classify multiple satellite observation concepts, cites examples, and proposes names for each type of concept, building upon concept names that are already in use.

Table 1: Three-Attribute Classification of Multiple Satellite Observation Concepts with Proposed Concept Names and Examples

Proposed Concept Name	Classification Factors			Examples
	Location/Vantage	Observation Type	Coordination	
Stand-Alone Missions	Distributed	Complementary	Scheduled	UARS, TRMM, etc.
Satellite Train	Aligned	Complementary	Scheduled	Aqua/Aura Train
Precision Satellite Train	Precise	Complementary	Scheduled	
Global Constellation	Distributed	Similar	Scheduled	GPM, Iridium
Multi-View Formation	Aligned	Similar	Scheduled	"Parasitic" Cartwheel
Precision Formation	Precise	Similar	Scheduled	GRACE
Multi-Measurement Sensorweb	Distributed	Complementary	Autonomous	ESE Vision Sensorweb
Virtual Platform	Aligned	Complementary	Autonomous	
Precision Virtual Platform	Precise	Complementary	Autonomous	
Super-Instrument Sensorweb	Distributed	Similar	Autonomous	JPL Sensorweb
Multi-View Virtual Truss	Aligned	Similar	Autonomous	
Precision Virtual Truss	Precise	Similar	Autonomous	Optical Interferometry

4. DISCUSSION OF PROPOSED CLASSIFICATION

The following text discusses these concepts, the rationale behind the proposed concept name, and provides some examples.

Stand-Alone Missions: Until recently, and with a few exceptions, most of the satellites in operation have unique sets of instruments and observation capabilities, and are in distinct orbits. This is what is referred to as the *Stand-Alone Missions* in the above table. The observations are *complementary* in that they provide distinctly different data about the Earth system, the positions or vantages are *distributed*, and ground operators *pre-schedule* any coordination between missions.

Satellite Trains: In contrast, separated, multi-mission observations that are *aligned* or co-located in position or vantage can provide simultaneous or near-simultaneous observations of the same location, or provide simultaneous or near-simultaneous contiguous observations of adjacent areas. A recent trend in NASA Earth science missions is to fly missions with distinct but *complementary* observing capabilities in *Satellite Trains*. For these current missions, coordination between observations is *pre-scheduled* through the ground system. Current and planned near-term satellite trains include:

- The currently operating train containing Terra, LandSat-7, EO-1, and SAC-C.
- Jason-1 and Topex/Poseidon, flying 1 minute apart for cross-calibration.
- The planned "A-Train" (Aqua & Aura Train), with Aqua, CALIPSO, PARASOL, CloudSat, and Aura observing the same location in a span of about 6 minutes.

Distinct observations of the same location can extend spectral coverage by using sensors that cover different regions of the spectrum. This can provide overlapping observations for later data fusion by the information system. They can also support cross-calibration of methods for consistency, legacy, and continuity requirements, or cross-calibration of replacement measurements, including new approaches for system upgrades/new technology observations. To a certain extent, it is a matter of definition as to how similar or different a replacement has to be in order to be considered *similar* or *complementary*. For example, the New Millennium Program (NMP) First Earth Observing mission (EO-1) is flying innovative technologies for the next generation of land cover and land cover change instruments. EO-1 is currently flying in a *Satellite Train* with LandSat-7 in order to demonstrate compatibility between the old and new technologies and to address data continuity and legacy concerns.

Precision Satellite Trains: A *Precision Satellite Train* would be a set of multiple missions acquiring *complementary* observations with distinct instrument sets,

requiring *precise* metrology, but only requiring *pre-scheduled* or operator-in-the-loop coordination between the spacecraft. The author is not aware of any mission concept that would call for such an arrangement.

Global Constellation: *Similar* observations using separated missions that are *distributed* in position or vantage can be used to provide greater spatial and temporal coverage. Multiple missions that are distributed in location and timing can reduce the time between satellite observations or cover wide areas with distributed *in situ* sensors. If they only require *pre-scheduled*, operator-in-the-loop coordination between satellites, these are referred to as *Global Constellations*. This is consistent with the sense in which the term *Constellation* is used in the book *Space Mission Analysis and Design*. [11] If the similar observations are distributed, cross-calibrations may occur whenever coverage overlaps.

If we consider a constellation as two or more satellites obtaining similar measurements in different or distributed orbits, a very early example of a satellite constellation are the Polar Orbiting Environmental Satellites (POES), with one Sun-synchronous satellite in a morning orbit and one in an afternoon orbit. Similarly, the Geostationary Orbiting Environmental Satellites (GOES) qualify, with operational satellites at two longitudes, and International agreements to obtain comparable observations from International satellites at additional longitudes. Large constellations are currently in use to provide communications coverage, such as the Iridium constellation, with 66 active satellites and 7 on-orbit spares.

Multi-View Formation: This is a proposed term, not in the literature. *Multi-view Formations* would have *aligned* observations for viewing nearly the same location. They would involve *similar* or related instruments. Operators on the ground would *schedule* and program any required coordination.

One use of *Multi-view Formations* might be to observe the same areas for cross-calibration of sensors. Cross-calibration is often needed for consistency, legacy, and continuity requirements when replacing an observation capability with a replacement or an upgraded/new technology capability. Another use could be similar observations made from similar, but not the same orientation, such as stereo observations, phase-angle observations, polarization observations, and active bistatic or multistatic observations, such as interferometric synthetic aperture radar, that can be performed without direct satellite-to-satellite coordination.

Precision Formation: This is another proposed term that builds upon the concept of a formation. A *Precision Formation* would require *precise* metrology, although almost certainly only for after-the-fact determination, because there would only be *pre-scheduled* coordination

between the satellites. The observation type would be *similar*.

For example, the currently flying Gravity Recovery and Climate Experiment (GRACE) mission requires extremely accurate knowledge after-the-fact of the separation between the spacecraft. However, the measurement does not depend upon controlling the spacecraft separation, which is allowed to drift within broad limits.

Multi-Measurement Sensorweb: To make a distinction between sensorwebs that have multiple, similar nodes from sensorwebs made up of many distinct observation capabilities, the term *Multi-Measurement Sensorweb* is proposed. These would be globally *distributed* missions carrying distinct and *complementary* instrument sets that are connected into a sensorweb through real-time links that allow the system to respond *autonomously* to events detected throughout the system. Multi-measurement sensorwebs might use sentinel and monitoring observations to trigger other observations, such as:

- A geostationary clouds monitor that notifies LEO land imaging instruments when areas of interest are clear.
- In situ volcano stations to trigger low Earth orbit satellites to change observation modes to better observe plume evolution.
- Geostationary total lightning monitors that trigger higher time-resolution modes in ground-based cloud-to-ground lightning observations when thunderstorms with tornado potential are detected.

Virtual Platforms: Ticker and Azzolini define virtual platforms as “a system employing two or more spacecraft flying in formation and registered as if the observations were made and coordinated as a single spacecraft.” The registration would require that *Virtual Platforms* have *autonomous*, real-time coordination between the spacecraft. Generally speaking a real platform would carry distinct, *complementary* instruments that would be *aligned* on the platform, and this is carried over to the virtual platform concept.

For example, the satellites in the “A Train” (Aqua, CALIPSO, PARASOL, CloudSat, and Aura) do not have the ability to communicate with each other. Because each points to within a fairly loose dead-band based upon absolute coordinates, there will be times when the observations are not completely aligned. If they were able to communicate directly, the more agile spacecraft could control to the relative pointing of the least agile spacecraft, increasing the degree of alignment and co-coverage without significantly affecting the attitude control design.

Precision Virtual Platforms: The *Precision Virtual Platform* concept would build upon the platform as a carrier of diverse or *complementary* instruments, with *virtual* signifying *autonomous* coordination. The term *precision*

implies the use of precise metrology. I am not aware of any measurements requiring this approach.

Super-Instrument Sensorweb: As mentioned above, much of the sensorweb work done in support of space science is based on *distributed* but *similar* observations with *autonomous* real-time coordination. For example, the JPL Sensorweb Project has as a demonstration a small, distributed network of identical miniature weather stations that operate autonomously and can be accessed over the Internet.

Multi-View Virtual Truss: The term *truss* is proposed for virtual structures that carry similar instruments, such as the boom or truss that held the second antenna for the Shuttle Radar Topography Mission (SRTM). A *Multi-View Virtual Truss* would potentially serve the same function as the real truss for SRTM. In the case of SRTM, the truss allowed the two receiving radar antennas to observe the same region at the same time, building an interferometric data set that provided topographic measurements. SRTM is an example of *similar* measurements that were *aligned*, and that required real-time, *autonomous* coordination using a real truss. Future interferometric synthetic aperture radar observations may rely upon separated spacecraft, connected as a virtual truss.

Precision Virtual Truss: This thesis proposes the term *Precision Virtual Truss* for *similar* observations that require *precise* and *autonomous* control of the spacecraft location. The examples cited by Ticker and Azzolini that fit this category are gravity field observations and optical interferometers. In the gravity observations the “signal” from variations in the gravity field is *manifested in very small* variations in the separation between co-orbiting spacecraft. While the current GRACE mission only requires after-the-fact knowledge, future missions concepts require active control. As another example, optical interferometers require position control to a fraction of the wavelength of the light being observed. Current concepts use this technique for outward-looking astronomy missions and not for Earth observation.

Hybrid Cases: There are clear examples of current or near-term assets that fit more than one of these categories. For example, the “A-Train” includes the Aqua, CALIPSO, PARASOL, CloudSat, and Aura missions. Because there is no real-time coordination between satellites, these are an example of a *Satellite Train*. However, the MODIS instrument will be flying on both Aqua and Terra. From the point of view of the measurements that use the MODIS instrument, Aqua and Terra are *Global Constellation* members. Similarly, there is an on-going effort to place GPS sounding instruments on flights of opportunity, and several instruments are currently operating. Even though each of the satellites hosting a GPS instrument is quite different, from the point of view of the GPS sounding

measurement, these satellites form a GPS *Global Constellation*.

5. SUMMARY

In summary, this paper discusses a small set of essential or "crosscutting" functions that all observation missions must perform. These apply whether the mission is space-based, sub-orbital, or ground-based. These functions can be used as a basis to classify various multiple mission observation concepts. This paper develops and proposes a classification of multiple mission observation concepts based upon how they observe. The author hopes that clearer criteria for categorizing concepts and cleaner definitions and distinctions between various multiple mission observation approaches will clarify the discussion and advance the development of multiple mission observation concepts such as "sensorwebs," "satellite trains," and "constellations."

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