# A New Taxonomy for Distributed Spacecraft Missions

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***Abstract*—Due to many technical and programmatic changes, distributed spacecraft missions (DSMs) and constellations are becoming more common, both in national space agencies as well as in industry and academia. These changes are the results of various driving factors, such as maturing technologies, minimizing costs, and new science requirements. But they are also made possible by the availability of easier and more frequent launches and the capability to handle increased requirements in terms of scalable mission operations and "big" data analytics on the ground and onboard. With the increase in this type of missions and with the need to connect and interrelate all the data that will be generated by these various missions as well as with the data acquired from ground and airborne sensors, there is a need to define more accurately all the terms used in relation to DSMs. This article presents a terminology including various definitions that describe DSMs and related concepts, their organization, physical configuration, and functional configuration, as well as a taxonomy from which DSMs can be designed.**

***Index Terms*—Distributed spacecraft mission (DSM), nomenclature, taxonomy, terminology.**

## I. Introduction

Although space- and ground-segment technologies have advanced significantly over the years, the evolution of our observing systems has been quite linear. We continue to use stove-piped spacecraft missions that collect more data and downlink it at ever faster bit rates, without applying potentially useful and timely information that may be available from other observing system assets or ground systems. This motivated Goddard's study of spacecraft constellations in 1999, NASA's "Earth Science Vision 2025" [1] in 1999–2002, as well as more recent internal studies at several NASA Centers. The cornerstone of the 2025 Vision was to improve prediction, specifically including daily and even hourly measurements. The Vision described a new paradigm in which holistic, integrated insight, foresight, and discovery replaced point monitoring and exploration.

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In order to reach this Vision, different new technologies were proposed including the exploration of new vantage points, such as L1 and L2 and Molniya orbits; real time, adaptive, remote, and *in situ* sensor swarms; and SensorWebs and on-demand virtual instruments. In particular, the concept of SensorWeb was extensively studied and was later the topic of several NASA Earth Science Technology Office (ESTO) solicitations and awards; for example, the weather prediction technology study to identify the science applications and technology improvements needed to aim for weather forecasts of 10–14 days in the 2025 timeframe. It was followed by the development of an "Architecture for Advanced Weather Prediction Technologies, in 2008, using a two-way interactive SensorWeb and modeling system" [2]. Other projects dealt with the application of SensorWebs to disaster management [3]–[5]. In the Earth Science Vision, a SensorWeb was seen as creating *On-Demand Virtual Instruments* in which *any user could dynamically reconfigure the SensorWeb or its components and mine the digital libraries/metadata warehouses to provide products that are uniquely tailored for the desired measurement.* It would provide *the ability to rapidly carry out scientific "experiments" without waiting for the selection, development, and launch of a new mission* [1]. Similarly described by Torres-Martinez *et al*. [6], the SensorWeb concept proposed by NASA defined *a virtual organization of multiple numbers and types of sensors combined into an intelligent "macroinstrument" in which information collected by any one sensor could be used by any other sensor in the web, as necessary, to accomplish a coordinated observing mission.*

Overall, SensorWebs were proposed to do the following:

1) acquire simultaneously multiple observation types;
2) use multiple vantage points and multiple resolutions simultaneously in a constellation or formation flying configuration;
3) use low-cost micro- and nanosatellites, e.g., utilizing sensorcraft with deployable apertures;
4) acquire overlapping measurements for calibration and validation;
5) utilize reprogrammable and reconfigurable sensor systems; and
6) increase the autonomy of space systems.

Another study performed by Barrett [7] identified two types of motivations for multiple spacecraft missions: First, *scientific motivation*, i.e., get better resolution to either isolate the signal when it is a microphenomenon or to cover the entire signal space when it is a fast or a macrophenomenon; and second, *engineering motivation*, i.e., provide extensibility, be able to add and/or replace sensors in the future, potentially incrementally, or provide redundancy using spares to respond to failures.

The main recommendation coming out of these studies was for NASA to have a strategy defining an incremental deployment of ground and space assets across a full range of sensor-web-capable earth science missions. This would necessitate the development of specific standards and capabilities to ensure scalability, homogeneity, and operability of such missions [6].

Another historical program of interest is the DARPA F6 Fractionated Spacecraft program [8]. F6 was started in 2008 with the goal of developing and demonstrating on orbit key capabilities for spacecraft fractionation. This was envisioned using a "cluster of wirelessly interconnected modules that could share their resources." The main goal was to demonstrate adaptability and survivability of space systems. The program relied on the development of open interface standards [9] that would ensure the sustainment and development of future fractionated systems and low-cost associated commercial hardware. Cellularized spacecraft, which is related to fractionated spacecraft, has been developed under the more recent DARPA Phoenix Program [10], [11], with the goal of changing the paradigm by which space systems are engineered, first designed, then developed, then built, and finally deployed. With that purpose, that program aims at reaching the terrestrial paradigm of "assemble, repair, upgrade, and reuse" [9]. This includes developing the following technologies: *advanced GEO space robotics*, including on-orbit assembly, repair, life extension, and refueling; *satlets*, i.e., small independent modules that incorporate essential satellite functionality but share data, power, and thermal management capabilities to provide a low-cost, modular satellite architecture; and *a standardized payload orbital delivery (POD) system*. The Phoenix concept could improve satellite usefulness and lifespan and could lower their development and deployment costs.

But, although the SensorWeb and many related distributed missions' concepts and technologies were extensively studied and matured before 2008, it is only recently that national space organizations, industry, and academia have been proposing and developing distributed spacecraft missions (DSMs)and constellations; some examples are the recent NASA-funded Cyclone Global Navigation Satellite System (CYGNSS) [12] and Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of SmallSats (TROPICS) [13] earth science missions, ESA QB50 [14] and Proba-3 [15], and new commercial ventures, such as Planet Labs [16], OneWeb [17], and Capella Space [18]. Additional information about missions and research performed between 2000 and 2017 can be found in [26] and [27].

Due to this renewed interest in distributed concepts, starting in 2013, NASA Goddard conducted several internal consecutive studies, during which the general concept of "DSMs" and its related terminology was defined. The main objectives of these studies have been first to summarize what has been explored and developed previously in the domain of distributed missions, what is the state-of-the-art, who are the main players, and what are the main challenges, and then to provide a preliminary characterization of the tradeoffs that link science return and mission architectures. The outcomes of the study included a full terminology, some preliminary mission taxonomies, a survey of past, current, and future DSMs, examples of potential Science applications, a list of technology challenges, and some preliminary results in developing DSMs' cost and risk analysis tools.

This article summarizes our results from terminology and taxonomy points of view, with the goal of facilitating the development of such future concepts (particularly when several organizations are involved), as well as the trade analysis and the actual design of future DSMs.

## II. Distributed Spacecraft Missions

*Main Definition:* A DSM is a mission that involves multiple spacecraft to achieve one or more common goals.

This general definition of a DSM, defined as the incept of our studies, purposefully, does not specify if the multiple spacecraft are launched together, achieve common goals by design or in an *ad hoc* fashion, or if the common goals are scientific. "Multiple" in this case refers to "two or more" and can refer to tethered or nontethered satellites, although very few tethered concepts have been proposed so far. The various levels of details that describe a DSM are embedded in the specific terms defined in Section IV. For example, a DSM can be defined from inception and we call it a "constellation," or it can become a DSM after the fact, in which case it is an "ad hoc" DSM or a "virtual" mission. For all the various types of DSMs, we do not assume the spacecraft to be of any specific sizes, i.e., the studies were not restricted to CubeSats or SmallSats (these sizes are defined in Section III), although lowering costs often involve choosing smaller spacecraft.

As described in Section I, for the past 20 years, the concept of distributed observations has not been systematically traded when designing main stream missions, e.g., decadal survey missions, although it has been considered when it was the only solution capable to satisfy some given science requirements (e.g., in earth science for the GRACE mission or in heliophysics for the magnetospheric multiscale mission, MMS, designs). Nevertheless, this concept is being found again in more recent studies, such as in the 2017 Earth Science Decadal Survey [38] where ideas, such as "advanced cost-effective observation methodologies such as ad hoc and *distributed observations*," "given cost considerations, miniaturization using CubeSats, SmallSats, and *satellite constellations* could be an efficient pathway to technological development," and "rapid capture and delivery of synoptic data by space-borne assets following a disaster can directly mitigate the loss of life and infrastructure. These data can be obtained by rapidly *retasking existing satellites*, deploying new satellites dedicated to a specific measurement objective, or by deploying a *constellation* of future satellites that provide the temporal fidelity required," being proposed for science as well as for disaster monitoring. Similar ideas can also be found in heliophysics, and even planetary science and astrophysics. Additionally, some flagship missions, such as future Landsat missions are currently being redesigned considering this concept.

This gap of more than 10 years in a systematic interest given to a DSM is probably explained by the cost and, potentially, the complexity associated with such missions. The high costs that were estimated for a potential DSM were often the consequence of constellation designs based on repeating *n* times the design and the building of one spacecraft, therefore leading to costs being *n* times the cost of a monolithic mission; this is explained not only by the mission design itself but also by cost models that have been designed for monolithic missions and do not take into account cost savings associated with economies of scale and with risk minimization when dealing with a DSM. On the other hand, it is true that building a distributed mission adds to the complexity of the mission, not only in the development phase, but also in the operational phase, and this complexity translates into additional costs and risk to the mission.

Therefore, it is only now that new technologies and capabilities, such as SmallSats, CubeSats, hosted payloads, instrument miniaturization, onboard computing, better space communications, and ground systems automation, have appeared and became mature, that a DSM seems to be feasible for a reasonable and potentially lower cost and risk than monolithic missions.

At the same time that these new technologies have been developed, a new economic environment is developing, with lower or flat space budgets, a greater international competition, and a steady growth of the private sector in space ventures. As stated in a series of articles published in Space News by Wertz [39], space needs to be reinvented, and having a mix of traditional, large programs with some much lower cost, more rapid, more responsive programs is a way to respond to this new environment. Among the more responsive programs, distributed and disaggregated assets offer solutions that significantly reduce risk. In particular, as we heard in many of the science interviews that we conducted, apart from science goals that can only be attained with a DSM, distributed missions are usually motivated by several goals, among which, increasing data resolution in one or several dimensions (e.g., temporal, spatial, or spectral), decreasing launch costs, increasing data bandwidths, as well as ensuring data continuity and intermission validation and complementarity.

Therefore, our goal in developing the proposed terminology and taxonomy was to capture these science goals and turn them into trades that will be used to design the future DSMs; the characteristics defined in the remainder of this article represent a preliminary characterization of the tradeoffs that link science return and mission architectures.

An example of the utility of this characterization is illustrated by our design of the Trade-space Analysis Tool for Constellations (TAT-C) [25], which provides a framework to facilitate DSM prephase A investigations and optimize DSM designs with respect to *a priori* science goals. TAT-C was designed based on these principles with the following:

1) TAT-C inputs that include: *mission concept* (e.g., area of interest, mission duration, and launch options); *satellite specifications* (e.g., existing satellites, altitude/inclination ranges, specific orbit needs, and communication bands); *payload specifications* (e.g., concept of operations, number and the type of instruments, mass, volume, and optical characteristics); and *constraints* on the range of output values; and
2) TAT-C science outputs that include: all *metrics* computed for each architecture (e.g., average of spatial and temporal metrics); *spatial information* (e.g., spatial resolution, swath overlap percentage, occultation positions, and coverage); *temporal information* (e.g., revisit, access, and repeat times); *angular information* (e.g., view zenith, solar illumination); and *radiometric information* (e.g., signal-to-noise fall-off).

This terminology and taxonomy allowed us to clarify the variables that were essential to trade when designing DSM concepts.

The remainder of this article is organized in the following way. A nomenclature of spacecraft size and mass is given in Section III. The full DSM terminology taxonomy is described in Section IV and a preliminary use of this taxonomy for DSM design is given in Section V.

TABLE I
2013 Classification From NASA STMD [24]

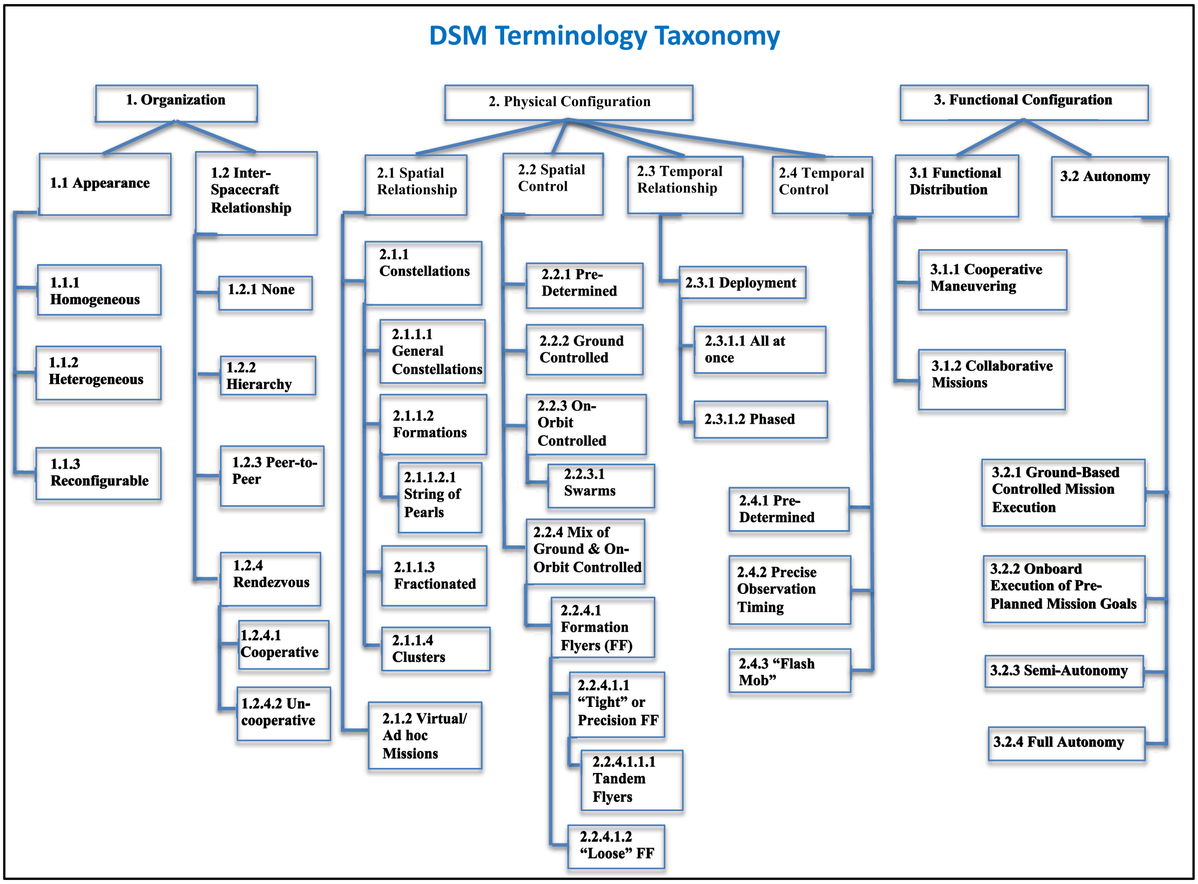
| Satellite Class | Mass |
|---|---|
| Femtosatellite | 0.001-0.01 kg (or 1-10 g) |
| Picosatellite | 0.01-1 kg |
| Nanosatellite | 1-10 kg |
| Microsatellite | 10-100 kg |
| Minisatellite | 100-180 kg |

## III. Small Satellite Nomenclature

Because DSMs are often designed and flown using small satellites as individual elements to make the system cost feasible, this section attempts to provide a nomenclature of what is a “small” spacecraft. The term “SmallSat” has been used with various meanings, and some of these discrepancies have been captured in 2010, as they relate to European missions [19]. A formal small satellite classification was first performed in 1991 by Sweeting [20], and then refined by Kramer *et al.* in 2008 [21]. In 2004, Konecny [22] extended the range of minisatellites from 100 to 1000 kg, abolishing the medium satellite class. The new classification was then reviewed by Xue *et al*. in 2008 [23]. Another definition is given in the FY13 SmallSat Technology Partnerships solicitation from the NASA Space Technology Mission Directorate (STMD) [24]: “Small spacecraft, for the purpose of this notice, are defined as those with a mass of 180 kg or less and capable of being launched into space as an auxiliary or secondary payload.” In this last nomenclature, minisatellites start at 100 kg but the upper mass is limited to 180 kg instead of 500 kg, and the threshold between femto- and picosatellites is slightly different. Nag *et al.* [40] discussed small satellite classes in detail, with examples from international missions, and its impact on cost and risk.

For the purpose of our study and the remainder of this article, we will adopt the nomenclature shown in Table I, utilizing the general term of *SmallSats for spacecraft of less than 180 kg* and *minisatellites for spacecraft of mass in the range of 100–180 kg*. Note that CubeSats usually fall in the nano- to microsatellite range.

TABLE II
DSMs TERMINOLOGY TAXONOMY




## IV. DSM TERMINOLOGY TAXONOMY

Generally, a *taxonomy* can be defined as the description, identification, nomenclature, and classification of a group of things or concepts. Although the main terms related to DSMs have been defined in the past, for example in [7], [26], and [29], many other terms have not been defined or not defined consistently.

Additionally, the meaning of some of these terms has also evolved with new technologies being developed, e.g., CubeSats, and it is important to define them, being grouped together under the same umbrella and for the purpose of collaborative mission design, development, and operations.

*Main definition:* A DSM is a mission that involves multiple spacecraft to achieve one or more common goals.

This general definition of DSM (given in Section II and repeated above), purposefully, does not specify if the multiple spacecraft are launched together, achieve common goals by design, or in an *ad hoc* fashion (i.e., application-driven), or if the common goals are scientific. These different levels of details are embedded in the following definitions.

In order to derive this terminology, various DSM characteristics were considered and their different instantiations were classified in the taxonomy described in Table II.

All the terms shown in this taxonomy and that need to be defined accurately are described in the remainder of this section; note that the terms are listed according to Table II, with each box referred to as "TAB." The three main characteristics that have been considered are: TAB 1) Organization; TAB 2) Physical Configuration; and TAB 3) Functional Organization. Under these three main TABs, a DSM can be defined by a certain number of characteristics.

***Under TAB 1***, "Organization," two characteristics define a DSM, "Appearance" and "Inter-Spacecraft Relationship."

### TAB 1.1 Appearance

Under this TAB, three different types of appearance have been defined for all types of DSMs that will be defined in TAB 2.1. These are "Homogeneous," "Heterogeneous," and "Reconfigurable."

#### *TAB 1.1.1 Homogeneous Constellation or Formation*

A DSM whose member spacecraft employ functionally identical bus, payload, and operational characteristics (e.g., MMS and Iridium).

#### *TAB 1.1.2 Heterogeneous Constellation or Formation or Fractionated Spacecraft*

A DSM whose member spacecraft employ a different bus, payload, or operational characteristics. Note that a fractionated spacecraft is always heterogeneous.

***TAB 1.1.3 Reconfigurable Constellation or Formation or Fractionated Spacecraft***

A DSM that possesses the ability to change one or more intrinsic characteristics while on orbit. Some of these characteristics may include any or all of the following changes: orbit, attitude, relative spacing, observing activity coordination with other spacecraft, number of spacecraft, and other TBD characteristics.

Iridium is an example of a nonreconfigurable, but homogeneous constellation. MMS is reconfigurable and homogeneous and F6 would have been a reconfigurable and heterogeneous mission.

**TAB 1.2 Inter-Spacecraft Relationships**

***TAB 1.2.1 None***

This describes a DSM with no or no specific interspacecraft relationships.

***TAB 1.2.2 Hierarchical Relationship***

A constellation system in which one (called mothership) or several of the distributed spacecraft has a higher degree of capability and serves as the central focal point for the constellation communication, control, and command, and/or general coordinator of all constellation activities.

***TAB 1.2.3 Peer-to-Peer Relationship***

A system in which all the distributed spacecraft can interact with every other with equivalent control, capabilities, and responsibilities, assuming that appropriate communication and a predetermined routing protocol between nodes (e.g., disruption-tolerant networking for low earth orbit (LEO) constellations [28]).

***TAB 1.2.4 Rendezvous Mission***

A rendezvous mission is a mission in which two spacecraft perform an orbital maneuver such that they approach each other at a very close distance and come to within actual or visual contact.

**TAB 1.2.4.1 Cooperative Rendezvous Missions**

A cooperative rendezvous mission is a mission in which two spacecraft cooperate with each other to achieve a rendezvous maneuver. The two spacecraft arrive at the same orbit and approach at a very close distance, in a cooperative manner; this can be followed or not followed by docking during which the two spacecraft come into contact. One example is the rendezvous and docking performed between a spacecraft (or a space shuttle) and the International Space Station.

**TAB 1.2.4.2 Uncooperative Rendezvous Missions**

This is a mission performing a type of space maneuver during which one spacecraft under known control arrives at the same orbit and approaches at a very close distance of another uncontrolled spacecraft or space object; this can be followed or not followed by docking or landing. This is the case, for example, when one spacecraft is servicing another nonfunctioning satellite or a spacecraft tumbling out of control (e.g., DARPA Phoenix Satellite Servicing). Another example is a rendezvous mission between a spacecraft and a natural object such as an asteroid (e.g., OSIRIS-REx mission).

***Under TAB 2***, **"Physical Configuration,"** four characteristics define a DSM, "Spatial Relationship," "Spatial Control," "Temporal Relationship," and "Temporal Control."

**TAB 2.1 Spatial Relationship**

Under "Spatial Relationship," the two main types of DSM are the general type called "Constellations" and "Virtual or *Ad Hoc* Missions." In other words, a Constellation is the most general term defining a DSM. Then, under a Constellation, some specific types can be defined, e.g., "Formations," "Fractionated," and "Clusters." Note that some DSMs may comprise one or more of the listed relationships. For example, multiangular observations may be done by clusters and the temporal resolution could be improved by a constellation of clusters (also called "clustellation"). In fact, this mix and match of different types of DSMs to make a coalition is possible under the proposed taxonomy.

***TAB 2.1.1 Constellation***

A reference to a space mission that, beginning with its inception, is composed of two or more spacecraft that are placed into specific orbit(s) for the purpose of serving a common objective (e.g., MMS or Iridium).

**TAB 2.1.1.1 General Constellation**

This refers to the most general type of constellations and might have various attributes; for example, a constellation maybe called *uniform* when the spacecraft are uniformly distributed in multiple orbital planes and uniformly distributed in each orbital plane. The "Walker Delta" constellation (GPS, Galileo) and "Walker Star" constellation (Iridium) are examples of uniform constellations.

***TAB 2.1.1.2 Formation***

Two or more spacecraft that conduct a mission such that the relative distances and three-dimensional spatial relationships (i.e., distances and angular relationships between all spacecraft) are tightly controlled (usually through direct sensing) by one spacecraft of at least one other spacecraft state (e.g., GRACE and PRISMA).

A special case of Formations is a String of Pearls Formation defined in the following manner.

***TAB 2.1.1.2.1 String of Pearls***

A String of Pearls orbital configuration is a type of formation flying in which all the spacecraft are flying in the same orbit separated in the along-track direction by fixed distances (e.g., Terra, SAC-C, EO1, and Landsat-7).

***TAB 2.1.1.3 Fractionated Spacecraft***

A fractionated spacecraft is a satellite architecture where the functional capabilities of a conventional monolithic spacecraft are distributed across multiple modules that are not structurally connected and that interact through wireless links. These modules are capable of sharing their resources and utilizing resources found elsewhere in the cluster. Unlike general constellations and formations, the modules of a fractionated spacecraft are always largely heterogeneous and perform distinct functions corresponding, for instance, to the various subsystem elements of a traditional satellite (e.g., DARPA F6 System)

***TAB 2.1.1.4 Cluster***

A collection of spacecraft that is not uniformly distributed over a particular spatial region, in contrast to a Walker constellation, e.g., clusters aggregate in certain orbital regions (e.g., MMS and COSMIC). A cluster may be, subjectively, considered "tight" or "loose" depending on the relative proximity of the member spacecraft.

***TAB 2.1.2 Virtual or "Ad Hoc" Mission***

A virtual mission is a DSM that exploits observations made from multiple missions that were designed independently, but the output can be considered in a coordinated fashion as if they were acquired from a single mission. A virtual mission exploits the coordinated positions and the complementary of the observations to add value to each of the individual measurements. An example of such a virtual mission is the A-Train. The original A-Train DSM included the Aqua, Aura, and PARASOL satellites that were later joined by the CloudSat, CALIPSO, GCOM-W1, and OCO-2 satellites. PARASOL has now ceased operations, whereas CloudSat/CALIPSO have lowered their orbit and also left A-Train (see https://atrain.nasa.gov/ for more information).

**TAB 2.2 Spatial Control**

Under spatial control, missions' characteristics are defined in terms of the end results as well as how this particular type of spatial control has been obtained.

***TAB 2.2.1 Pre-Determined***

This describes missions that do not have any specific spatial control, except the one predetermined before launch. This is often the case of low-budget CubeSat missions.

***TAB 2.2.2 Ground Controlled***

This type of constellation is spatially controlled from the ground. An example is the MMS mission.

***TAB 2.2.3 On-Orbit Controlled***

This type of constellation is spatially controlled in orbit with some level of autonomy (described in TAB 3.2). A special case of this type of constellation is a *swarm,* described below.

**TAB 2.2.3.1 Swarm**

A reference to a space mission that is composed of a high number of micro- or nanospacecraft that serve a common objective and that are uncontrolled or loosely coordinated from the ground but with some sort of onboard autonomous control.

***TAB 2.2.4 Mix of Ground and On-Orbit Controlled***

**TAB 2.2.4.1 Formation Flyers (FFs)**

FFs were defined in TAB 2.1.1.1; FF can either be controlled from the ground or controlled onboard or a combination of both. In this TAB, the specific spatial control patterns associated with FF are defined.

**TAB 2.2.4.1.1 "Tight" or Precision Formation Flying**

This represents a subjective characteristic referring to the preciseness required of a particular formation. There does not appear to be any particular set of objective metrology standards regarding the degree of precision and is determined entirely by the application; such applications can be distributed "virtual" aperture, often associated with applications, such as interferometry or distributed spacecraft optics, for which a very precise formation is required. The terms "tight" and "precision" are sometimes used with different meanings depending on the degree of precision that is required. PRISMA and PROBA-3 are examples of Precision Formation Flying.

**TAB 2.2.4.1.1.1 Tandem Flyers**

Tandem Flyers represent a specific case of Precision FF. These are two or more spacecraft that follow one another in the same orbital plane (e.g., GRACE and GRAIL). It represents a special case of precision formation flying, with lesser requirements on control, owing to two spacecraft in the same orbit.

**TAB 2.2.4.1.2 "Loose" Formation Flying**

This represents a subjective description of a smaller degree of precision and accuracy needed to be maintained between the spacecraft that comprise the FF. The degree of precision required in a loose FF is not as strict as the one required by a Precision FF.

**TAB 2.3 Temporal Relationship**

This TAB mainly considers the temporal deployment of the multiple spacecraft in the constellation.

***TAB 2.3.1 Deployment***

Deployment includes two main different types of temporal deployment, "All at Once" and "Phased."

**TAB 2.3.1.1 All At Once Deployment**

In this type of mission, all constellation spacecraft are launched at the same time. They can be deployed from the same or different launchers as long as they become operational at the same time. This is the case of missions such as MMS, GRACE, and CYGNSS.

**TAB 2.3.1.2 Phased Deployment**

A phased deployment of a constellation is often employed for very large constellations or for megaconstellations. In this case, individual or groups of spacecraft are launched incrementally by design. This deployment strategy is also used for heterogeneous constellations with spacecraft launch in different orbits or at different altitudes. Examples of such constellations are QB50 or the Planet Labs series of spacecraft.

A special case of phased deployment is an *accretionary or incremental deployment by reaction*. This is the case when new spacecraft are placed into specific orbits based on evolutionary mission circumstances. This was the case of the *ad hoc* DSM A-Train for which CloudSat, CALIPSO, GCOM-W1, and OCO-2 were added to the A-Train to achieve additional requirements based on the observations made by the first satellites.

**TAB 2.4 Temporal Control**

Just as for Spatial Control, Temporal Control considers both the end result and the means by which the DSM temporal control is obtained.

***TAB 2.4.1 Pre-Determined***

This term characterizes missions for which the measurement acquisition is predetermined, and no specific temporal control is required after launch.

***TAB 2.4.2 Precise Observation Timing***

Precise observation timing is required when the DSM mission goals require measurements to be very precisely intercorrelated; the position and the orientation of each spacecraft and their payloads need to be closely controlled to optimize the measurement acquisition. This is usually something designed as part of the overall mission. CYGNSS is an example of a DSM demonstrating precise observation timing.

***TAB 2.4.3 "Flash Mob"***

The "flash mob" concept is also related to intercorrelated measurements but corresponds to a more agile DSM, e.g., a swarm, that reacts in real time to transient or real-time events and phenomena. There has been proposed heliophysics mission concepts but no actual missions exhibiting this type of behavior.

***Under TAB 3***, the **"Functional Configuration"** of DSMs or constellations is being considered. This covers the mechanisms by which specific functionalities are being achieved.

**TAB 3.1 Functional Distribution**

Under Functional Configuration, this first TAB looks at functionality distribution between spacecraft. The two following TABs give some examples of such types of distribution although these do not represent an exhaustive list of potential configurations.

***TAB 3.1.1 Cooperative Maneuvering***

Missions with spacecraft that have functionalities are compatible to be used together to create a virtual DSM.

***TAB 3.1.2 Collaborative Missions***

These are missions that are designed to create coordinated observations. Among those are missions with reconfigurability or targeting capabilities. A special case is missions that can create a "virtual instrument," but also DSMs that react to a transient event or phenomenon.

**TAB 3.2 Autonomy**

The general concept of "Autonomy" has been recently defined by the NASA Autonomous Systems Capability Leadership Team [30] and this is the definition that we will adopt in this article: "Autonomy is the ability of a system to achieve goals while operating independently of external control." Here, a system can refer to either a monolithic or a highly complex distributed system. Autonomy is not equivalent to artificial intelligence (AI), but may use AI to achieve the specified goals; autonomy is also not equivalent to "automation," which is the automatically controlled operation of a system but is not "self-directed." Therefore, a system may be automated without being autonomous and autonomy may rely on automation for some of the tasks required to achieve its goals.

Autonomy involves many functions, including plan validation, planner/scheduler [28], [32], diagnostics, state estimation, onboard processing, and onboard decision making; each of these functions can be performed by humans or by software. "Autonomy" implies a system's capability for realizing "self-governance" and "self-direction," as well as "self-management." Autonomy is self-governance and self-directive in the sense that it requires the delegation of responsibility to the system to meet its prescribed operational goals. The self-management aspect provides for the self-configuring, self-healing, self-optimizing, and self-protecting properties required for a fully autonomous system.

As described in [35], a space system may have four levels of mission execution autonomy (according to the ECSS-E-ST-70C standard), spanning from [low] ground-based, preplanned control to [high] goal-oriented, onboard mission replanning. It may have two levels of data management autonomy and two levels of FDIR autonomy as well. In TAB 3.2, we adopted these four basic levels of Autonomy as they relate to DSMs.

Many other characteristics could describe the term "autonomy," but they are not limited to the concept of DSM and therefore are not included in this taxonomy.

***TAB 3.2.1 Ground-Based Controlled Mission Execution***

In this case, the DSM execution is entirely performed under ground control, with no onboard autonomy. There is real-time control from the ground for nominal operations and it may only include some execution of time-tagged commands for safety issues.

***TAB 3.2.2 Onboard Execution of Pre-Planned Mission Goals***

The DSM includes onboard execution of preplanned, ground-defined, mission operations. Again, there is real-time control from the ground for nominal operations and it may only include some execution of time-tagged commands for safety issues.

***TAB 3.2.3 Semi-Autonomy***

A semiautonomous DSM represents a combination of system autonomy and ground control. It includes onboard execution of adaptive mission operations, particularly event-based autonomous operations and execution of onboard operations' control procedures.

***TAB 3.2.4 Full Autonomy***

In order to achieve and maintain full autonomy (i.e., execution of goal-oriented mission operations onboard including goal-oriented mission replanning), the DSM needs the following enabling properties: it needs to be self-aware of the internal capabilities and state of the managed component; it needs to be self-situated in the sense that it is aware of its environment and context; and, finally, it needs to be able to monitor and adjust itself through the use of such things as sensors, effectors, and control loops.

A special case of autonomous DSM is an *intelligent and collaborative constellation (ICC)*: this is a specific type of constellation that uses onboard intelligence to perceive its environment and takes actions that maximizes its chances of success in creating coordinated observations. An ICC can also potentially learn from its experiences. To achieve these capabilities, an ICC involves the combination of real-time data understanding,

TABLE III

FEW EXAMPLES OF CURRENT OR PAST DSM MISSIONS AND THEIR CHARACTERISTICS AS IDENTIFIED IN TABLE II

| DSM Name | Mission Goal | Coverage Goal | Category and Status | Spatial Relationship | DSM Appearance | Spatial Control | Temporal Relationship, esp. Deployment | Autonomy | Number of S/C | Spacecraft Size | Orbit(s) Selection | Launch Date | Main & Partner Organization(s) | Website |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CYGNSS Cyclone Global Navigation Satellite System** | Wind measurement using perturbation of GPS signals | Multipoint measurements | Earth Science / Operational | Constellation | Homogenous | Loose Formation; no spacecraft interaction | All at once with a dispenser | None | 8 | 20 kg | 500 km; 35° inclination | 2016 | University of Michigan SWRI | http://aoss-research.engin.umich.edu/missions/cygnss/ |
| **COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate)** | Weather soundings via GPS signal occultations | Many soundings | Earth science & Heliophysics / Operational | Constellation | Homogenous | Pre-determined Constellation; no spacecraft interaction | All at once | None | 6 | 70 kg | 500 km; 72° | 2019 | NOAA, Taiwan, AF, JPL | http://www.cosmic.ucar.edu/index.html |
| **Jilin** | High-resolution optical remote sensing satellites for commercial use | Capture views of any point on Earth every 30 minutes | Earth Commercial / Operational | Constellation | Heterogeneous: different instruments | Pre-determined Constellation; no spacecraft interaction | Phased; multiple s/c on multiple launches | None | 10 (60 by 2020 and 138 by 2030) | 95 kg | 525 to 655 km orbits | 2015-current | Chang Guang Satellite Technology Co, China | https://spaceflightnow.com/2019/01/22/chinas-long-march-11-rocket-lofts-earth-imaging-and-tech-demo-satellites/ |
| **Planet Labs Doves** | Earth High resolution imaging | Image the whole world everyday | Earth Commercial / Operational | Constellation | Homogenous | Pre-determined Constellation; no spacecraft interaction | Phased; multiple as secondaries | None | 175 | 5 kg (3U cubesats) | variety of orbits | 2014-2018 | Planet | https://www.planet.com |
| **Disaster Monitoring Constellation for International Imaging (DMCii)** | Multipoint earth observations | Provide emergency Earth imaging for disaster relief under the International Charter for Space and Major Disasters | Earth Monitoring/ Operational | Constellation | Homogeneous | Pre-determined Constellation; no spacecraft interaction | Phased with customers' needs; multiple launches | Semi-autonomous | 8 | 120 kg | Sun-Synchronous | 2002-2013 | Surrey Satellite Technology Ltd (SSTL) with Algerian, Nigerian, Turkish, British and Chinese governments | http://www.dmcii.com/ |
| **Iridium** | Global Coverage for phone calls | Global coverage | Communications/ Operational | Formation | Homogenous | Loose Formation with inter-spacecraft comms | Phased/ Incremental by design and reaction; multiple launches with dispensers | Semi autonomous | 66 plus spares | 680 kg | 781 km 86.4° | 1997-1998 | Iridium | http://www.iridium.com/default.aspx |
| **TDRSS Tracking and Data Relay Satellite System** | Near complete coverage of low earth orbit for communications | Near full coverage of low earth orbit | Communications / Operational | Constellation | Homogenous (three generations) | Pre-determined Constellation; no spacecraft interaction | Phased/ Incremental by design and reaction; multiple individual launches | Semi autonomous | 8 | 2100 kg (3rd generation) | Geo | 1988-2013 | NASA Goddard | http://tdrs.gsfc.nasa.gov/ |
| **Beidou** | Positioning | Global coverage | Global Positioning / Operational | Constellation | Homogeneous | No spacecraft interaction | Phased; multiple launches | None | 40 | 280 kg | 21,550 km 55° plus Geo | 2012-2018 | China | http://spaceflight101.com/spacecraft/beidou-3/ |
| **Galileo** | Positioning | Global coverage | Global Positioning / Operational | Constellation | Homogeneous | Pre-determined Constellation; no spacecraft interaction | Phased; multiple launches | None | 26 | 850 kg | 23,230 km 55° | 2011-2017 | Europe | http://spaceflight101.com/spacecraft/galileo/ |
| **GPS Global Positioning System** | Positioning | Global coverage | Positioning | Constellation | Homoegeneous (although several generations) | Pre-determined Constellation; no spacecraft interaction | Phased/Incremental by design; one launch per spacecraft | Semi-autonomous | 32 | 2030 kg | 20,200 km; 55° | 1989-2012 | USAF | http://spaceflight101.com/spacecraft/gps-block-iif/ |
| **MMS Magnetospheric Multiscales** | Three dimensional measurements of magnetosphere | Three dimensional measurements | Heliophysics / Operational | Formation | Homogenous | Cluster; no spacecraft interaction | All at once; single launch | Semi autonomous | 4 | 1250 kg | Variety of elliptical orbits | 2014 | NASA Goddard; SWRI | http://mms.gsfc.nasa.gov |
| **QB50** | Investigating the thermosphere and tech demos | Multipoint thermosphere measurements | Heliophysics/tech demo | Constellation | Some common, some different - built by many different groups | Pre-determined Constellation; no spacecraft interaction | Phased; 3 launches | Semi autonomous | 36 | 2-3 kg<br>2 and 3 U | 320 km 79° | 2017 | European Union and others | https://www.qb50.eu |
| **ST-5 (Space Technology 5)** | tech demonstration and multipoint magnetosphere measurements | Point Measurements and Tech demo | Heliophysics/ Tech Demo | Constellation | Homogenous spacecraft and most instruments - some instruments unique to one s/c | Cluster; no spacecraft interaction | All at once; single launch with dispenser | Included Autonomous experiment for ~ 1 week | 3 | 26 kg | 300 x 4500 elliptical inclined orbit | 2006 | NASA Goddard; SWRI | http://nmp.jpl.nasa.gov/st5/index.html |
| **GRACE Gravity Recovery and Climate Experiment** | Earth gravity measurement (including ice sheet masses) | Relative positions | Earth Science / Operational | Formation | Homogenous | Tandem flyers; inter-spacecraft ranging | All at once; single launch | Semi autonomous | 2 | 487 kg | 428 km 89° | 2002 | JPL | http://www.csr.utexas.edu/grace/ |
| **TanDEM-X** | Earth Digital elevation model | Formation Flying | Earth Science / Operational | Formation | Homogenous (some differences but functionally common) | Formation Flying; inter-spacecraft comms | Two launches | Semi autonomous | 2 | 1335 kg | 514 km, 97.4° | 2010 | Germany | http://www.dlr.de/eo/en/desktopdefault.aspx/tabid-5727/10086_read-21046/ |
| **Proba-3** | Virtual Telescope and tech demo | Virtual Telescope | Tech Demo & Heliophysics / Operational | Formation | Heterogeneous - Occulter and solar coronagraph | Precision Formation Flying; Precise Correlated Measurements and Control for virtual telescope | All at once; single launch | Semi autonomous | 2 | 340 kg<br>200 kg | elliptical orbit | Late 2020 | ESA | http://www.esa.int/Our_Activities/Technology/Proba_Missions/About_Proba-3 |
| **Optical Communications and Sensor Demonstration (OCSD)** | Demonstrate optical comm and formation flying with cubesats | Tech demo | Technology / Operational | Formation | Homogenous | Formation Flying; proximity ops & station keeping (7 meters apart) | All at once; single launch | Semi autonomous | 2 | Cubesats 2.5 kg | 550 circular >34° | 2017 | Aerospace | http://www.nasa.gov/directorates/spacetech/small_spacecraft/ocsd_project.html#.UxPFaFw8dyk |
| **Cubesat Proximity Operations Demonstration (CPOD)** | Demonstrate rendezvous, proximity operations and docking | Tech demo | Technology / Development? | Formation | Homogenous | Formation Flying | All at once; single launch | Autonomous and semi autonomous | 2 | Cubesats 4 kg | | 2019 | Tyvak Nano-Satellite Systems | http://www.nasa.gov/directorates/spacetech/small_spacecraft/cpod_project.html#.UxPIwFw8dyk |
| **PRISMA** | Formation Flying tech demo | Tech demo | Technology / Past | Formation | Heterogeneous | Precision Formation Flying; Inter-spacecraft ranging & comms | All at once; single launch | None | 2 | 50 kg<br>150 kg | 725 km sun sync | 2010 | Sweden | http://www.lsespace.com/about-prisma.aspx |
| **TOPEX/ Poseidon/ Jason** | Ocean altimetry | Coverage over long lengths of time | Earth Science / Operational | Virtual/Ad Hoc | Topex and Jason are very different; Jason's are similar but not identical | Not applicable | Phased/ Incremental by design; multiple launches | Semi autonomous | 4 | 505 kg | 1336 km 66° | 1992<br>2001<br>2008<br>2015 | NOAA; JPL; CNE; EUMETSAT | http://sealevel.jpl.nasa.gov |

TABLE IV
DSM TAXONOMY FROM [7] FOR HELIOPHYSICS MISSIONS

| Orbits | Phenomenon Location |
|---|---|
| Low Earth | All spheres |
| Elliptical | Magneto & Iono Spheres |
| Beyond Moon | Helio & Celestial Spheres |
| Lissajous | Celestial Sphere |
| Co-Earth (Drift Away) | Helio & Celestial Spheres |

| Aggregations | Motivation (Scientific or Engineering) |
|---|---|
| Cluster | Isolate Signal |
| String of Pearls | Isolate Signal or Engineering |
| Constellation | Cover Large Signal Space |

situational awareness, problem solving, planning and learning from experience, all of them combined with communications, and cooperation between the multiple spacecraft, in order to take full advantage of various sensors distributed on multiple platforms.

Table III shows a few of current and past DSMs and their characteristics as identified in Table II. Of course, Table III is not exhaustive; there are many more such missions in the U.S. and in the world, and only a few representative missions have been listed in Table III, mainly from the earth science and communications domains (with a few heliophysics and global positioning missions), to illustrate the definitions that were proposed in this section.

## V. Designing Earth Science Missions Using the Distributed Spacecraft Mission Taxonomy

As the general characteristics of a DSM have been defined and categorized in the taxonomy defined in Section IV, this section investigates how these concepts can be utilized to design future earth science missions. This design can be informed by other factors, such as those described in two previous taxonomies [7], [26]. In 2001, Barrett [7] characterized distributed missions (in the heliophysics domain) in terms of the phenomena that needed to be observed and of the information that needed to be gathered. They first categorized DSMs by the type of phenomena to be measured, for example, *slow/predictable* or *fast/intermittent phenomena*, occurring on a microscale (few points) or on a macroscale (many/all points). This is equivalent to characterizing the missions in terms of the mission science goals, i.e., the information that needs to be collected, with a signal space (e.g., spatial, angular, and temporal resolution), a symbol space (e.g., spectral and radiometric resolution), and a behavior (e.g., global coverage and revisit times). When dealing with multiple platform missions, an orbit and aggregation taxonomy is required in addition to the information taxonomy. Each orbit corresponds to a different phenomenon location and each different type of aggregation corresponds to a different motivation. Table IV summarizes the considerations from [7] for a selected number of examples, particularly in the heliophysics domain.

In 2017, Selva *et al.* [26] also provided a taxonomy of "DSM concepts demonstrated in flight or proposed, based on morphological analysis"; although the paper does not describe a precise taxonomy and terminology such as the one described in Section IV and Table II, it provides a comprehensive assessment of DSM concepts and technologies and some conclusions about the current barriers to DSM implementation. In particular, it considers the maturity of key enabling technologies: subsystem level technologies, such as high-precision attitude determination and control, high-precision thrusting, high-bandwidth communications, high throughput onboard data processing; as well as some other higher system-level capabilities. These novel technologies and capabilities need to be considered when designing a DSM.

Examples of some other specific trades that need to be considered when characterizing distributed missions and that are not included in the previous taxonomy are the manufacturing approach of the multiple spacecraft, the launch options and opportunities, the deployment time, the operational complexity on the ground and on orbit, the cost, the risks associated with development schedule, mission costs, and the on-orbit operations, just to name a few.

The sensitivities associated with each DSM characteristic represent the tradeoffs that will need to be considered when designing the distributed mission, which are, for example:

- *The mass of each spacecraft* will be chosen as a function of the manufacturing capabilities, the launch options (and costs), and the size of the sensors. Some mass categories are: $<1$ kg, $<10$ kg, $<500$ kg, $<5000$ kg, and $>5000$ kg. The number of spacecraft (e.g., 2–10, 10–50, or $>50$) will bring trades in terms of manufacturing approaches and ground complexity.
- *The spacecraft variability* corresponds to the spacecraft being all identical/homogeneous or heterogeneous either through different instruments, different buses, or with fractionated spacecraft.
- *Launches can be approached* through multiple launches, hosted payloads, rideshares, or dispensers.
- *On-orbit plans* include mothership and slaves model, swarm, formation, constellation, or *ad hoc*.
- *Spacecraft interactions* can be modeled as independent, ground coordinated, cross communicating, or fractionated.
- *The coverage goal* considers temporal coverage, spatial coverage, repeatable tracks, and redundancy.
- *The orbit selection* is a function of the type of information to collect but also of the launch options that are available. These can be LEO inclined, LEO polar, geosynchronous, or other.

Based on the mission science goals, and the other trades considerations described earlier in this section, the taxonomy defined in Section IV can be utilized to design future earth science missions. Assuming that the mission is either monolithic or distributed and that distributed missions fall into one of four main categories, i.e., constellations, formation flying, fractionated, or *ad hoc*/virtual missions, the following attributes are traded to design the mission: *appearance and functionality, spatial relationship of the DSM, interspacecraft relationship and functional configuration, spatial control, temporal deployment, temporal control, autonomy, number of spacecraft, spacecraft*

TABLE V
DESIGNING DISTRIBUTED SPACECRAFT MISSIONS

<table>
<tr><th colspan="21">DISTRIBUTED SPACECRAFT MISSIONS TRADES</th></tr>
<tr><th></th><th rowspan="2">MONOLITHIC</th><th colspan="19">DISTRIBUTED</th></tr>
<tr><th>MAIN DSM TYPES</th><th colspan="6">GENERAL CONSTELLATION</th><th colspan="5">FORMATION FLYING</th><th colspan="4">FRACTIONATED</th><th colspan="4">VIRTUAL/AD HOC MISSION</th></tr>
<tr><td rowspan="2">Appearance</td><td rowspan="2">Homogeneous</td><td colspan="3" rowspan="2">Homogeneous</td><td colspan="3">Heterogeneous</td><td colspan="2" rowspan="2">Homogeneous</td><td colspan="3">Heterogeneous</td><td colspan="4">Heterogeneous</td><td colspan="4">Heterogeneous</td></tr>
<tr><td>Instrument</td><td>Bus</td><td>Both</td><td>Instrument</td><td>Bus</td><td>Both</td><td colspan="4">Instrument and Bus</td><td colspan="4">Instrument and Bus</td></tr>
<tr><td rowspan="2">Inter-Spacecraft Relationship</td><td rowspan="2">N/A</td><td colspan="2" rowspan="2">None</td><td rowspan="2">Hierachical</td><td rowspan="2">Peer-to-Peer</td><td colspan="2">Rendezvous</td><td rowspan="2">None</td><td colspan="2" rowspan="2">Hierarchical</td><td colspan="2" rowspan="2">Peer-to-Peer</td><td colspan="2" rowspan="2">Hierarchical</td><td colspan="2" rowspan="2">Peer-to-Peer</td><td colspan="2" rowspan="2">None</td><td colspan="2" rowspan="2">Peer-to-Peer</td></tr>
<tr><td>Cooperative</td><td>Non-Cooperative</td></tr>
<tr><td>Spatial Control</td><td>Ground and On-Orbit</td><td>Pre-Determined/ Passive</td><td colspan="2">Ground</td><td>On-Orbit/Swarm</td><td colspan="2">Mix of Ground and On-Orbit</td><td colspan="2">Ground</td><td>On-Orbit/Swarm</td><td colspan="2">Mix of Ground and On-Orbit</td><td colspan="2">On-Orbit/Swarm</td><td colspan="2">Mix of Ground and On-Orbit</td><td>Ground</td><td colspan="2">On-Orbit/Swarm</td><td>Mix of Ground and On-Orbit</td></tr>
<tr><td rowspan="2">Temporal Relationship/ Deployment</td><td rowspan="2">All at once</td><td colspan="3" rowspan="2">All at Once</td><td colspan="3">Phased/Incremental</td><td colspan="5" rowspan="2">All at Once</td><td colspan="4" rowspan="2">All at Once</td><td colspan="4" rowspan="2">Phased/Accretionary</td></tr>
<tr><td>By Design</td><td colspan="2">By Reaction</td></tr>
<tr><td>Temporal Control</td><td>N/A</td><td colspan="2">Pre-determined and/or Loose/Ad Hoc Correlated Measurements</td><td colspan="2">Precise Observation Timing</td><td colspan="2">"Flash Mob"</td><td colspan="5">Precise Observation Timing</td><td colspan="4">Precise Observation Timing</td><td colspan="4">Pre-determined and/or Loose/Ad Hoc Correlated Measurements</td></tr>
<tr><td>Autonomy</td><td>None or Semi-Autonomous</td><td colspan="2">None/Ground-based control or onboard execution of pre-planned mission goals</td><td colspan="2">Semi-Autonomy</td><td colspan="2">Fully Autonomy</td><td>None/Ground-based control or onboard execution of pre-planned mission goals</td><td colspan="2">Semi-Autonomy</td><td colspan="2">Fully Autonomy</td><td>None/Ground-based control or onboard execution of pre-planned mission goals</td><td colspan="2">Semi-Autonomy</td><td>Full Autonomy</td><td colspan="2">None/Ground-based control or onboard execution of pre-planned mission goals</td><td colspan="2">Semi-Autonomy</td></tr>
<tr><td>Number of Spacecraft</td><td>1</td><td colspan="2">[2-10]</td><td colspan="2">[10-50]</td><td colspan="2">> 50</td><td colspan="5">[2-10]</td><td colspan="4">[2-10]</td><td colspan="2">[2-10]</td><td colspan="2">[10-50]</td></tr>
<tr><td>Spacecraft Mass (kg)</td><td>Variable Size and Mass</td><td>< 1</td><td colspan="2">[1-10]</td><td>[10-500]</td><td>[500-5000]</td><td>> 5000</td><td colspan="2">[1-10]</td><td>[10-500]</td><td>[500-5000]</td><td>> 5000</td><td colspan="2">[10-500]</td><td>[500-5000]</td><td>> 5000</td><td colspan="4">Variable Size and Mass</td></tr>
<tr><td>Launch Approach</td><td>Single</td><td colspan="3">One Launch</td><td colspan="3">Multiple Launches</td><td colspan="2">One Launch</td><td colspan="3">Multiple Launches</td><td colspan="4">One Launch</td><td colspan="4">Independent and Multiple Launches</td></tr>
<tr><td rowspan="2">Launcher Approach</td><td rowspan="2">Dedicated</td><td colspan="2" rowspan="2">Dispenser</td><td colspan="4">Multiple Launches</td><td rowspan="2">Dispenser</td><td colspan="4">Multiple Launches</td><td colspan="4" rowspan="2">Dispenser</td><td colspan="4" rowspan="2">Variable/Mission dependent</td></tr>
<tr><td>Dedicated</td><td>Rideshare</td><td>Hosted Payloads</td><td>Combination</td><td>Dedicated</td><td>Rideshare</td><td>Hosted Payloads</td><td>Combination</td></tr>
</table>

TABLE VI
DESIGNING DISTRIBUTED SPACECRAFT MISSIONS—EXAMPLES FOR FOUR MAIN CATEGORIES OF DISTRIBUTED MISSIONS

<table>
<tr><th colspan="21">DISTRIBUTED SPACECRAFT MISSIONS TRADES - EXAMPLES</th></tr>
<tr><th></th><th rowspan="2">MONOLITHIC (Ex: Landsat)</th><th colspan="19">DISTRIBUTED</th></tr>
<tr><th>MAIN DSM TYPES</th><th colspan="6">GENERAL CONSTELLATION - Example: ST-5 ("Cluster")</th><th colspan="5">FORMATION FLYING - Example: GRACE ("String of Pearls")</th><th colspan="4">FRACTIONATED - Example: DARPA SYSTEM F6 ("Cluster")</th><th colspan="4">VIRTUAL/AD HOC MISSION - Example: A-TRAIN ("String of Pearls")</th></tr>
<tr><td rowspan="2">Appearance</td><td rowspan="2">Homogeneous</td><td colspan="3" rowspan="2">Homogeneous</td><td colspan="3">Heterogeneous</td><td colspan="2" rowspan="2">Homogeneous</td><td colspan="3">Heterogeneous</td><td colspan="4">Heterogeneous</td><td colspan="4">Heterogeneous</td></tr>
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<tr><td>Autonomy</td><td>None or Semi-Autonomous</td><td colspan="2">None/Ground-based control or onboard execution of pre-planned mission goals</td><td colspan="2">Semi-Autonomy</td><td colspan="2">Fully Autonomy</td><td>None/Ground-based control or onboard execution of pre-planned mission goals</td><td colspan="2">Semi-Autonomy</td><td colspan="2">Fully Autonomy</td><td>None/Ground-based control or onboard exectuion of pre-planned mission goals</td><td colspan="2">Semi-Autonomy</td><td>Full Autonomy</td><td colspan="2">None/Ground-based control or onboard execution of pre-planned mission goals</td><td colspan="2">Semi-Autonomy</td></tr>
<tr><td>Number of Spacecraft</td><td>1</td><td colspan="2">[2-10]</td><td colspan="2">[10-50]</td><td colspan="2">> 50</td><td colspan="5">[2-10]</td><td colspan="4">[2-10]</td><td colspan="2">[2-10]</td><td colspan="2">[10-50]</td></tr>
<tr><td>Spacecraft Mass (kg)</td><td>Variable Size and Mass</td><td>< 1</td><td colspan="2">[1-10]</td><td>[10-500] (26 kg)</td><td>[500-5000]</td><td>> 5000</td><td colspan="2">[1-10]</td><td>[10-500]</td><td>[500-5000]</td><td>> 5000</td><td colspan="2">[10-500]</td><td>[500-5000]</td><td>> 5000</td><td colspan="4">Variable Size and Mass</td></tr>
<tr><td>Launch Approach</td><td>Single</td><td colspan="3">One Launch</td><td colspan="3">Multiple Launches</td><td colspan="2">One Launch</td><td colspan="3">Multiple Launches</td><td colspan="4">One Launch</td><td colspan="4">Independent and Multiple Launches</td></tr>
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</table>

*mass, launch approach, and launcher approach*. Table V summarizes this design process, with the mission categories shown on the horizontal axis and the mission attributes shown on the vertical axis. Orbital parameters are not considered here to stay general but should be included for specific science domains. Each characteristic may have several values, but its range depends on the mission category. For example, a constellation may have a homogeneous or a heterogeneous appearance and functionality, but a fractionated mission can only be heterogeneous. Similarly, a constellation can be temporally deployed all at once or incrementally (by design or by reaction). To illustrate this design process, Table VI shows specific values for one monolithic mission (Landsat-7) and four reference DSMs, corresponding to the four types of DSM categories: ST-5 for general Constellation (shown in light green), GRACE for Formation Flying (shown in light blue), F6 for Fractionated (shown in light yellow), and the A-Train for Ad hoc/Virtual mission (shown in purple).

As described in Section II, the taxonomy defined in Section IV and the design process highlighted in this section have already been used to design TAT-C [25]. TAT-C is a prephase A mission design tool that facilitates DSM prephase A investigations and optimizes DSM designs with respect to *a priori* science goals. TAT-C, through a modular architecture including a knowledge base, a cost and risk module, an orbit and coverage module, an instrument module, a launch module, and carefully designed trade-space search iterator and user interface enables to quickly assess, visualize and validate a very large number of potential DSM constellation architectures in response to input and output science requirements.

## VI. CONCLUSION

This article has presented various concepts related to the design of DSMs, first by introducing the definitions of various terms defining the various characteristics of a DSM, then relating these characteristics to the choices or sensitivities that need to be considered when designing such missions. Based on these considerations, a DSM taxonomy has been proposed; this taxonomy has already been utilized in developing a trade-space tool for designing constellations. Over time and with the development of future DSM and related capabilities, this taxonomy will be refined.

For example, another concept, which is important in relation to DSM is the concept of *SensorWeb* [33], [34]. Although a SensorWeb does not fit the current DSM taxonomy, it is a concept that will be useful to trade when designing future earth science missions. According to [36], “A SensorWeb is a distributed system of sensing nodes (space, air, or ground) that are interconnected by a communications fabric and they function as a single, highly coordinated, virtual instrument. It semi- or -autonomously detects and dynamically reacts to events, measurements, and other information from constituent sensing nodes and from external nodes (e.g., predictive models) by modifying its observing state, so as to optimize mission information return.” The concept of SensorWeb is now being considered in earth science for new observing strategies (NOS) [37] in which the concepts of DSMs and SensorWebs will be traded to optimize the acquisition of measurements, such as those defined in the 2017–2027 Earth Science Decadal Survey [38]. By extending the DSM concepts to SensorWebs, NOS will take advantage of multisensor nodes producing measurements integrated from multiple vantage points and in multiple dimensions (spatial, spectral, temporal, and radiometric) to provide a unified picture of earth science physical processes or natural phenomena.

## Acknowledgment

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