FORMATION FLYING – THE FUTURE OF REMOTE SENSING FROM SPACE

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ABSTRACT

Over the next two decades a revolution is likely to occur in how remote sensing of Earth, other planets or bodies, and a range of phenomena in the universe is performed from space. In particular, current launch vehicle fairing volume and mass constraints will continue to restrict the size of monolithic telescope apertures which can be launched to little or no greater size than that of the Hubble Space Telescope, the largest aperture currently flying in space. Systems under formulation today, such as the James Webb Space Telescope will be able to increase aperture size and, hence, imaging resolution, by deploying segmented optics. However, this approach is limited as well, by our ability to control such segments to optical tolerances over long distances with highly uncertain structural dynamics connecting them. Consequently, for orders of magnitude improved resolution as required for imaging black holes, imaging planets, or performing asteroseismology, the only viable approach will be to fly a collection of spacecraft in formation to synthesize a virtual segmented telescope or interferometer with very large baselines. This paper provides some basic definitions in the area of formation flying, describes some of the strategic science missions planned in the National Aeronautics and Space Administration, and identifies some of the critical technologies needed to enable some of the most challenging space missions ever conceived which have realistic hopes of flying.

1. BACKGROUND

Formation Flying (FF) is critical to enable order of magnitude (and greater) improvements in resolution and coverage achievable from scientific remote sensing platforms. Size limitations on launch vehicle fairings leave formation flying as the only option to assimilate coherent large apertures or large sample collection areas in space. Note that we are not necessarily referring to the replacement of single large spacecraft, such as the Hubble Space Telescope (HST) or the James Webb Space Telescope (JWST) with clusters of micro- or nano-spacecraft, but rather we are enabling capabilities that would never be achievable by single large spacecraft. In cases of precision formation flying for high resolution imaging or interferometry, the "member" spacecraft are constrained to be no smaller than required to support an optical element of approximately one meter, based on signal-to-noise and other requirements estimated for the Stellar Imager (SI) mission and commonly accepted for other mission concepts as well.

1.1 Definition

Formation Flying is a subset of a more general category that we will classify as *distributed space systems* (DSS).

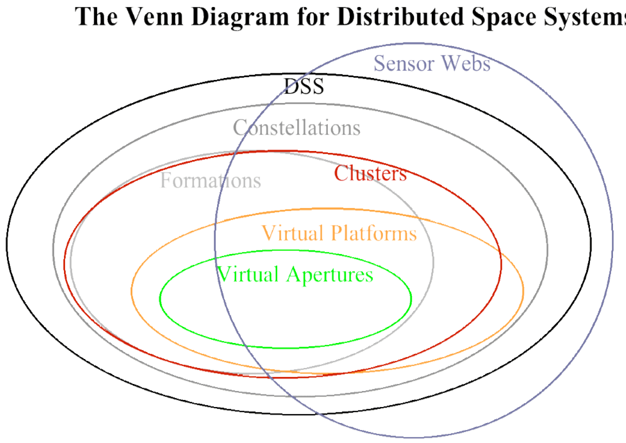

Figure 1. Relationship of common terms associated with formation flying

Fig. 1 shows a relationship among a number of common terms used relative to distributed spacecraft and formation flying, including the concept for sensor webs, which may involve many non-space elements.

Across the Formation Flying community there exists a wide range of definitions for formation flying and related terms, each set generally geared towards its own purpose. We will consider a couple of representative definitions that are generally consistent with most elements of the community. The most distinct differences in definition occur between the science (or instrument/sensor) community and the engineering (or technology) community, where for science the interest is in the collection of data, and for engineering the concern is how to collect the data that meet specifications for quality.

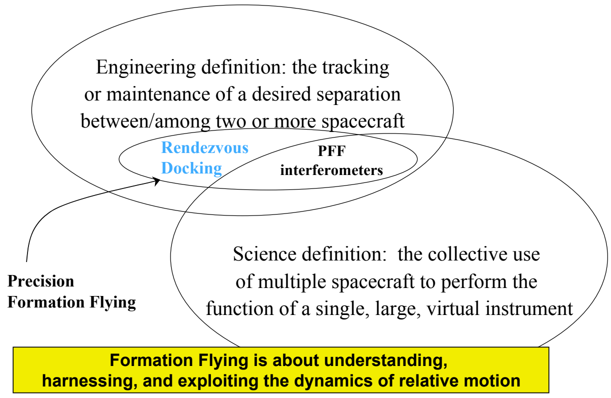

Figure 2. Science vs Engineering Definitions for Formation Flying

Fig. 2 portrays the relationship between the science and engineering definitions, including where they overlap and how "precision" formation flying (PFF) and Rendezvous and Docking fit into the picture. The engineering definition is convenient to employ for the purposes of developing technology plans because missions in that class can have related bins of technologies (at various performance levels), while missions that meet the science definition may have no related technologies at all. The technology bins will be discussed in more detail later in the paper.

1.2 Technology Impacts

There are a number of strategic missions in various stages of formulation for NASA that are enabled entirely by formation flying technology. Based on our engineering definition, formation flying consists of the fuel-constrained design of formation geometry to meet science requirements and the measurement and control of relative vehicle states implemented through inter-spacecraft communication links to maintain that geometry. Such technology will enable distributed magnetospheric science, planet finding, black hole imaging, stellar imaging, planet imaging, and life-finding mission concepts. At the system-level, there has been no space demonstration of formation flying with control implemented through the spacecraft crosslinks, although many of the technologies have been demonstrated at the breadboard or brassboard level. While there are a range of highly advanced and precise component technologies required to enable many future formation flying missions, the space demonstration of communication-in-the-loop, closed-loop formation flying, even at moderate performance levels (centimeter – meter class relative measurement and control) is one of the most critical stepping stones to progress both technically and politically in the development of these ambitious future missions. Henceforth, under NASA's New Millennium Program, a precision formation flying (PFF) space system validation concept is competing against four other technology concept areas for just such a demonstration mission, which would fly in the 2008-2009 time frame [1].

2. FORMATION FLYING OVERVIEW

From the perspective of our engineering definition, FF involves the control of relative distances or geometric configuration between spacecraft. Very simply, it's the understanding, harnessing, and exploitation of the dynamics of relative motion. FF is fundamentally comprised of formation design, relative measurements between spacecraft, inter-satellite communications, and formation control. Additionally, FF missions frequently drive requirements for advanced guidance, navigation, and control algorithms and actuators and modeling and simulation capabilities beyond those needed by single spacecraft missions.

2.1 The Elements of Formation Flying

As described above, there are four elements that are unique to the formation flying problem: formation design, relative navigation, intersatellite communication, and formation control. These are described as follows.

Formation design

Formation design is the collective guidance problem for the desired geometry as a function of time as dictated by the science needs of the mission. The dynamics of relative motion as applied to formation design continue to be a major research area. The problem is not only the specification of where the spacecraft needs to be as a function of time but also how to do this in the most fuel-efficient manner, since differential effects between spacecraft and small errors in initialization can be very costly in fuel. Concisely, formation design is the science and art of designing the desired relative motion of the vehicles to best meet science requirements without prohibitive fuel consumption.

Relative Navigation

Relative navigation (relnav) is the estimation of relative positions based on the measurements between adjacent spacecraft. It includes the sensors, metrology systems, and wavefront error sensing systems and algorithms needed to determine relative position and attitude, either for direct science purposes or for feedback control. The overall measurements in this area represent combined performance of loose (low-precision and/or low bandwidth) ranging systems and precision metrology so as to meet overall science requirements on knowledge of relative positions. The relnav requirements can be driven directly by science requirements (e.g., based on a dynamic range limitation for post-processing) or possibly indirectly through other engineering requirements. In particular, formation control requirements may drive the relnav requirements more stringently than direct science requirements will. A common rule-of-thumb is to require relnav to be 10 times more precise than control. In order to validate the flight-readiness of relnav technologies, ground performance simulations must be performed with the sensors in the loop and a high fidelity channel simulator. Relative navigation is constrained by technology, but component-level demonstrations of ranging systems have shown more than sufficient performance. However, the required level of performance has not been demonstrated in a relevant environment. Furthermore, relnav technologies have not been demonstrated in continuous, closed-loop operations at high precision for significant durations of time. Such demonstrations will be key predecessors to realizing some of the challenging missions that are forthcoming.

Inter-satellite Communications
The inter-satellite communication system is the data bus of the formation. More so than in other data buses, robustness and continuity are essential. The primary areas of development are mass, power and cost reduction, and integration of communications and ranging functions. This area includes hardware (transceivers or transponders), algorithms and network architectures, and software. Substantial work is still needed in developing requirements for communication bandwidth and time synchronization and transfer for precision formation control performance [2]. Since the formation control laws are implemented through this system, a lack of integrity in the system will be a showstopper.

Formation Control
Formation control is responsible for rejecting disturbances, maintaining formation stability, and commanding the formation. Specifically, this involves the application of forces and moments required to regulate and/or track desired formation geometry. Formation control includes the actuators, other components and algorithms, together with autonomy and higher-level command and control. The formation control function is heavily dependent on new technology. It is truly a system-level problem, depending critically on performance of the inter-satellite communications, the relative navigation, and the formation design. Formation control is the principal driver for concepts such as six degree of freedom spacecraft control and closed-loop orbit control.

Using such general expressions as defined above, we can divide and conquer the critical subsystem-level challenges unique to the formation flying problem while, at the same time, we acknowledge that there may be multi-stage sensing, actuation, and communication which cannot be easily divided among their individual stages. For example, a key element of precision metrology will be the handoff between a coarse and fine measurement stage. The challenges of this handoff will not be adequately addressed if the metrology were not an element of an overall relative navigation process.

2.2 Distributed Spacecraft Missions and Concepts

Depending on the science needs, the engineering requirements for formation flying can vary substantially. The current state of the art in space (where separations have been controlled) is the EO-1 Landsat-7 formation flying demonstration [3]. This represents the loosest, and least collaborative form of formation flying, implemented through the ground (not through a cross-link). Magnetospheric measurements, such as those proposed to be performed by the Magnetospheric Multi-Scale (MMS) mission typically require loose formation flying in another sense [4]. In this formation flying mission, it is only important to control the geometry of the formation (in this case to form a tetrahedron) at the apogee point of the orbit. This is also the case for the Solar Imaging Radio Array (SIRA) mission, where loose control of spacing between spacecraft is required and all spacecraft must be maintained within a spherical region. Both of these would be classified as loose formations because there is much flexibility in controlling inter-spacecraft distances and the controls need be applied only once or twice an orbit or even only every several orbits. They are indeed formation flying because the relative positions must be controlled.

Distributed interferometry missions, on the other hand, require precise and continuous control, though at various levels of precision. Some examples are the Terrestrial Planet Finder Interferometer (TPF-I) [5], DARWIN [6], the Micro-Arcsecond X-ray Imaging Mission (MAXIM) [7], Stellar Imager (SI) [8], and the Submillimeter Probe of the Evolution of the Cosmic Structure (SPECS) [9], each based on distributed interferometry concepts. In these missions the controls required are precise and continuous, although at various levels of precision. For Michelson interferometer concepts with few spacecraft (less than 10), such as TPF-I or SPECS, in the longer wavelengths, inter-satellite path lengths can be trimmed using delay lines or even through post-processing correction or heterodyne approaches. Fizeau interferometer concepts such as MAXIM or Stellar Imager frequently have more spacecraft and shorter wavelengths (e.g., X-Ray) that make the pathlength control problem much more difficult than at the longer wavelengths. Likewise the Fizeau concepts do not have the flexibility for correcting gross errors through post-processing. Michelson concepts employing path delay lines may have precise relative position/orientation knowledge requirements with looser (but still precise) formation control requirements than Fizeau concepts. Hence, the metrology architectures can differ significantly between Michelson and Fizeau formations. Substantial trades are still required to reasonably assess the feasibility of path delay lines for various mission types. There is still much debate about the use path delay lines for the formation flying problem and trades continue in the TPF-I and DARWIN concepts. When pathlength control devices are employed, the spacecraft control requirements are driven by the dynamic range of the delay lines and/or post-processing capabilities. Alternatively Fizeau concepts with a substantial number of spacecraft have control requirements that are directly driven by a wavefront error requirement for the synthetic aperture. Other approaches for path delay and adaptive optics may be applicable at some wavelengths, but details are still not fully developed and the dynamic range will be limited. Fizeau concepts will virtually always require highly precise control. In either case, whether delay lines are employed or not, the relative measurement requirement which is driven by the control requirement is, as a rule of thumb, 10 times more precise than the control requirement (assuming that there is not a direct science requirement for the measurement that is more stringent). The spacecraft control and optical path control make up a nested set of control loops and must be analyzed as a coupled system.

In parallel to formation flying missions and concepts, there are many missions that have many of the qualities of formation flying missions but lack the full system-level formation flying aspect defined above. The GRACE mission employs a metrology system to measure, on-board, the changes in range between spacecraft to a very precise level. Absolute range is not required on-board and the relative spacing between spacecraft is not controlled (as that would null the science). This, in fact, is the case for gravity science missions in general, as their science depends on measurements of the change in range between spacecraft. The Laser Interferometer Space Antenna (LISA) [10] mission is a current example of a mission in formulation where the spacecraft separations are not controlled, but highly precise measurements are taken. In spite of this, substantial formation design work is required to ensure the properly bounded relative motion behavior over the long term. The LISA mission does have a very interesting formation flying problem internal to each of the spacecraft. Each spacecraft and its two internal proof-masses (all in different orbits) must fly in very precise formation using capacitive measurements for feedback and electrostatic controls combined with micro-Newton-level thrusters and an articulation mechanism. Finally, the New Millennium Program ST-5 mission will prove out concepts of three-spacecraft formation design as well as some key micro-spacecraft technologies relevant to formation flying missions.

2.3 Formation Flying Capability Progression

FF enables synchronous measurements over large regions of the magnetosphere, synchronous bidirectional reflectance distribution function collection, unlimited resolution synthetic aperture radar collection capability, interferometry at microwave through gamma ray wavelengths, and μas (micro-arcsecond) or better image resolution, to name a few examples. While there are many component and subsystem technologies involved, the system-level performance can be summarized as pertinent to scientific objectives in terms of the relative position/orientation estimation and control. The following shows the scientific progression with formation control capability (may be met by direct control of spacecraft (s/c) positions, path or aperture control devices, or a combination of both):

- 2011 – loose formations, 4 s/c – magnetospheric science (MMS)
- 2019 – cm s/c position control, 5 s/c – Planet finding (TPF-I)
- 2022 – μm s/c position control, 8 s/c – black hole imaging in X-Ray (MAXIM)
- 2025 – nm control, 30 s/c – stellar imaging, asteroseismology (SI)
- 2030+ – <nm control, 30+ s/c – planet imaging/life-finding (Planet Imager, Life Finder)

3. FORMATION FLYING TECHNOLOGIES

3.1 Technology trends and trades

In the FF area, the integration of mature component technologies can tend to bring the components back to much lower technology readiness levels (TRLs) at the system level, so it is inevitable that much of the system-level development and validation work must be treated as a research effort. Much of the validation work at this level, generally in testbeds, is yet to be done, to verify that all of the formation flying components and algorithms work together to provide the required performance. At the more focused technology level, the biggest technology gap is in the formation line-of-sight (LOS) control problem. Revolutionary technological advances will be required to achieve the sub-μas level required in 10-15 years. Point-to-point ranging systems are continuing as an evolutionary development from those employed on long-boom systems, such as the Space Interferometry Mission (SIM). These must be expanded into system-level metrology solutions for Michelson and Fizeau interferometry architectures with sub-nm level requirements in such FF settings. A prototype metrology system for Michelson concepts has been developed under the context of the Starlight testbed at the Jet Propulsion Lab (JPL) that provides sub-cm range capability and sub-arcminute bearing measurement [11]. This sensor development effort, as well as a parallel effort focused on Fizeau applications (which will result in a unique architecture) must continue their development and transition, as well as to begin integration with some of the more precise point-to-point systems. There are many other relevant technologies being developed inside and outside of the space community. Common trades are between the use of optical vs. RF metrology systems, based on measurement precision required, power available, and spacecraft pointing capabilities. Substantial growth is required in wavefront sensing methods applied to FF distributed instruments, extending from approaches in development for connected apertures in support of JWST. Table 1 shows a more detailed breakout of current, fiscal year (FY) 08-projected, and future performance capabilities for the elements within this area.

3.2 State of Technology

Formation flying technology development dates back at least to some of the earliest works on analysis of orbital rendezvous in 1960 [12] from Clohessy and Wiltshire. Since that time many programs have driven the development of key elements of the formation flying problem, either under the context of a formation flying concept or under other auspices. Within the past 10 years, NASA and others in the space community began to integrate many of these component technologies into mission concepts and ground-based demonstrations. The formulation of these concepts and demonstrations and subsequent testbed evaluations have given rise to the formation flying technology "holes" and major challenges. While technology demonstration mission concepts such as the former TechSat 21 [13] and Starlight [11] have highlighted the extreme system-level challenges involved, the results of such development efforts as well as requirements analyses of future mission concepts have brought about some key technology areas that require substantial investment over the next decade. These include the following:

1. *Precision relative navigation and metrology in all orbital and deep space regimes*. What combinations of existing sensor technologies can be used and what new technologies need to be developed? See Figure 3, which depicts the problem by orbital regime, considering such sensors as Global Positioning System (GPS), Magnetometers (MAG), Celestial Navigation (CEL, CELNAV), Inertial Navigation Systems (INS), and radio frequency (RF) or optical ranging systems.

2. *Formation line-of-sight measurement and control* [9]. Imaging at μas resolution, requires alignment of the boresight of the formation to μas accuracy in order to place the image on the detector.

3. *Continuous six degree of freedom formation control implemented through intersatellite crosslinks*. Requirements for control at orders of magnitude finer precision than any s/c controlled today will necessitate propulsion systems with continuously varying levels of thrust, unlike impulsive systems currently in operation.

4. *Relative motion analysis and formation design in libration point regimes* [14]. Most precision formation flying missions are targeted for libration point orbital regimes. Critical factors are the differential gravitational effects and other disturbances near libration points on fuel consumption and on the precision of control available.

5. *Analysis of the effect of variable distance communication delays on multi-spacecraft formation control performance*. Given a large formation of spacecraft, with highly precise relative control requirements, how will the variable distances between spacecraft (as is the cases in many concepts) affect closed-loop control performance, when implemented through crosslinks?

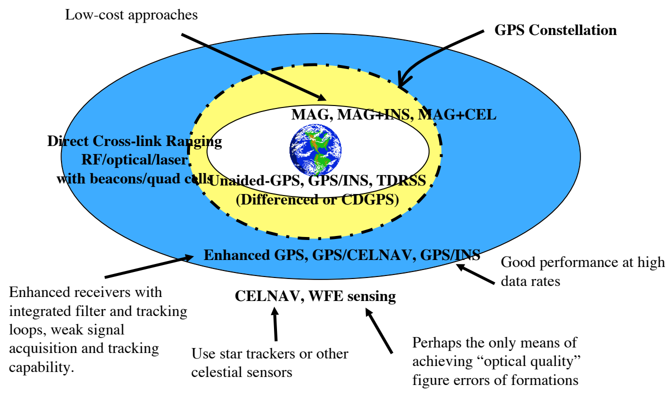

Figure 3. Relative Navigation – the big picture

4. SUMMARY

Because of fundamental limitations in launch vehicle fairing size, in concert with the challenges of precision control of large structures, formation flying will be the only means to enable vast improvements in angular resolution for future space-based telescopes and interferometers. Substantial technology development and systems engineering work has laid the ground work for realistic projections that these challenging formation flying missions will fly successfully.

5. ACKNOWLEDGMENTS

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Table 1. Current and Projected Technology Requirements

	Figure of Merit			
Required Capability	Now	FY08	Long-term	Current TRL, FY08 performance
Number of Satellites (affects measurement, control, communications, and operations)	2 S/C, non-collaborative (LS-7/EO-1)	4 desired 2 minimum	>30	constellations, 9 Formations, 6
Measure relative position	2 cm postprocessed (over 20,000 km measurement to GPS transmitter)	< 2 cm on-board, real-time	< 1 nm on-board	2 cm: 6 < 1 cm: 4
Measure S/C-S/C bearing angles (combination of relative attitude & 3 axis position)	N/A	1 am	1 mas	4
Control relative position through comm. link	Rendezvous/Docking, < 1m short range	10 cm	3 nm	4
Control S/C-S/C bearing angle	N/A	5 am	10 mas	2
Formation line-of-sight Control	N/A	No short-term	100 nas	1
Inter-S/C Communication Rate	300 Mbps TDRSS	10-1,000 Kbps < 20 W, 20 kg	3-10 Mbps	6
Autonomous collision avoidance	N	Y	Y	4
Precision of time synchronization	3 ns GPS, on-board real-time	< 1 □s	1 ps	9