GNSS in Space Part 1

Formation Flying Radio Frequency Missions, Techniques, and Technology

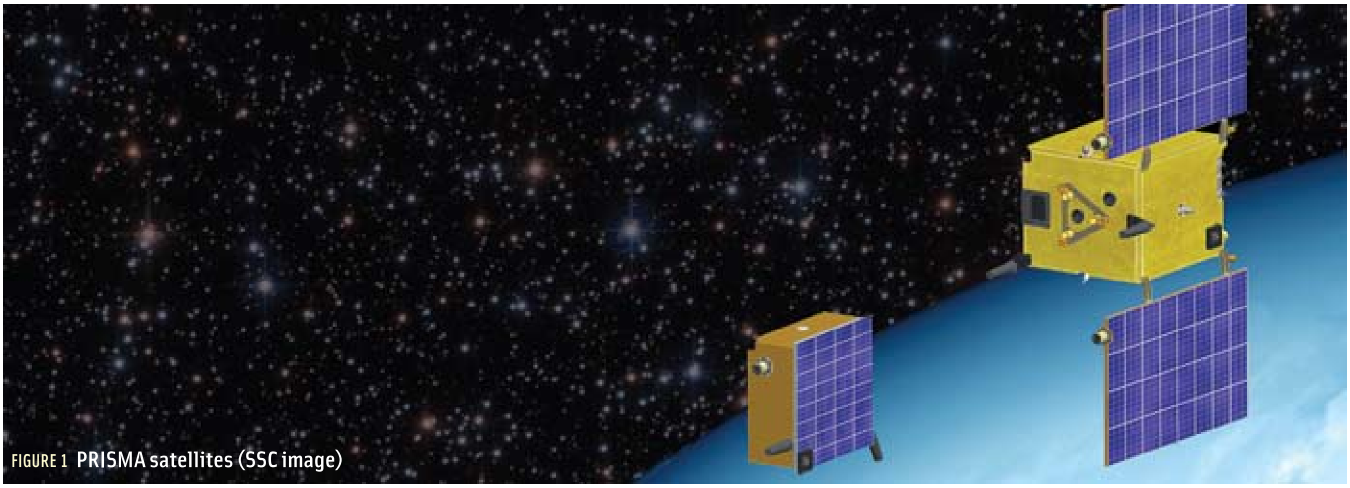

FIGURE 1 PRISMA satellites (SSC image)

Using two or more small satellites can sometimes be better than one, especially when trying to create a large spaceborne instrument for scientific research or experiments. But coordinating the alignment of the components of such instruments on separate space vehicles requires highly accurate orientation and positioning. Carrier phase GNSS can provide such precision for spacecraft operating below the altitude of GPS satellites, and GNSS-like techniques can be employed for spacecraft operating in higher orbits.

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Formation flying (FF) creates large spaceborne instruments by using several smaller satellites in close formation. The concept requires very accurate relative positioning and orientation of the spacecrafts, the complexity of which is largely outweighed by the enormous benefit of the extended instrument size compared to traditional one-satellite configurations.

The easiest way to perform formation flying with relative attitude and positioning in space is to use signals broadcast by GNSS satellites. Yet this ideal configuration, which could enable a relative positioning of better than one centimeter in certain cases, is limited to formation flying mission in low earth orbit (LEO).

Such low-altitude operations can exploit the full visibility of the GNSS constellations, which is needed to perform the integer carrier phase ambiguity resolution required to achieve centimeter-level accuracies. Use of GNSS is the easiest way because most LEO satellites are already provided with a GPS or GLONASS receiver for orbit and time determination.

Thanks to GNSS constellations, formation flying can be made at higher altitudes with a perigee of up to 25,000 kilometers, if GNSS receivers equipped with low acquisition and tracking thresholds are selected. Such receivers have tight coupling between the signal processing and the onboard orbital Kalman filter delivering pseudovelocity and pseudorange aiding to the open or closed delay locked loops and phase locked loops. Even in this case, however, the relative positioning accuracies can be degraded by up to a few meters, or even more sometimes, at a high-altitude orbital apogee.

As a result of these GNSS accuracy limitations, a dedicated formation flying radio frequency (RF) technique is needed that is accurate and equipped with omnidirectional features emerged for high and very high altitude orbital missions. But the use of GNSS-like signals and techniques appears to still be advantageous, because they allow cost effective accurate measurements, thanks to the widespread use of GNSS techniques, even for spacecraft navigation and synchronization.

The first part of this two-part column will describe the PRISMA, PROBA-3, and Simbol-X missions and provide an overview of other future FF missions. Part 2 will discuss those missions' positioning, orientation, and metrological requirements, focusing on the formation flying RF (FFRF) techniques and instrumentation.

Institutional Roles

Mastery of formation flying is an area of priority for the French Space Agency (Centre National d'Etudes Spatiales or CNES) and the European Space Agency (ESA) and is driving the agencies' long-term investment in the development of associated technologies and skills in cooperation with other European partners. The goal of this continuous effort is to prepare for future FF missions of which the CNES Simbol-X project and ESA's PROBA-3, Darwin, and Xeus projects are representative examples.

Mainly within this European framework, CNES and ESA have collaborated and contributed through R&D activities to the preliminary design and implementation of a new sensor for coarse metrology—the (FFRF) metrology subsystem. This RF-based sensor, for which breadboard development was initiated by ESA in 2001, is based partly on existing spaceborne GPS technology.

Proposed by CNES in an early version in 1991 for the Hermes space plane project, the FFRF equipment was initially designed and developed by a private manufacturer. ESA and CNES officially selected the FFRF equipment as a coarse metrology sensor, FFRF being mandatory for first-stage formation acquisition on all future European non-LEO formation flying missions.

This FFRF generic technology developed by ESA, CNES and CDTI will be validated onboard the PRISMA Swedish mission, and around 2012 it will be used for PROBA-3, an ESA mission demonstrating FF capabilities and making scientific observations. In 2013, it will be onboard Simbol-X, a multilateral CNES mission implementing an X-ray telescope of two satellites.

The PRISMA Mission

To validate FFRF in flight, CNES will participate in the experimental PRISMA mission, a technology test bed for formation flying and rendezvous (RdV) of two LEO microsatellites undertaken by the Swedish National Space Board (SNSB). As the first European mission to demonstrate FF, PRISMA is an invaluable opportunity for CNES to acquire valuable FF experience as early as 2009.

The French contribution to PRISMA—Formation Flying In-Orbit Ranging Demonstration (FFIORD) —consists of implementing the FFRF subsystem on the two PRISMA satellites as a passenger experiment. The FFRF procurement is a partnership between CNES and Spain's Centre for the Development of Industrial Technology (CDTI).

In addition to in-orbit validation of the sensor, FFIORD will include closed-loop operations with FFRF, thus allowing genuine autonomous formation flying scenarios and associated guidance, navigation and control (GNC) algorithms to be tested in real-life conditions.

The PRISMA satellites have arrived from Sweden to the test facilities in Toulouse, France. Testing in the vaccuum-solar chamber took place in late November 2008. Launch of PRISMA is expected during the summer 2009 as a secondary payload into a sun-synchronous LEO orbit of about 700 kilometers.

Expected duration of the mission is approximately eight months. All flight operations will be controlled by the Swedish Space Corporation (SSC) via the Kiruna ground station.

The mission will consist of two spacecraft, shown in **Figure 1**: the Main spacecraft of 140 kilograms with full three-axis reaction wheel–based attitude control and three-axis delta-V capability, and a second simplified Target spacecraft of 40 kilograms with coarse three-axis attitude control, based on magnetometers, sun sensors, and magnetic torquers. Various sensors, depending on the experiment and the satellite distance, will measure the relative positions of the space vehicles, using the following:

- Differential GPS. The DGPS system provided by DLR (German Aerospace Center) is the primary relative positioning measurement system on PRISMA (made possible by the LEO nature of this mission). Experiments will mainly be carried out for inter-satellite distances greater than 30 meters. The system is based on a fully redundant set of 12-channel, single-frequency Phoenix GPS receivers developed by DLR and antennas on each spacecraft.
- Visual-based sensor (VBS). Based on a star tracker used in many microsatellite missions, this sensor provided by the Technical University of Denmark (DTU) will be used to identify the Target spacecraft as a nonstellar object at distances up to 500 kilometers and to track Target down to very close range, typically 10 meters

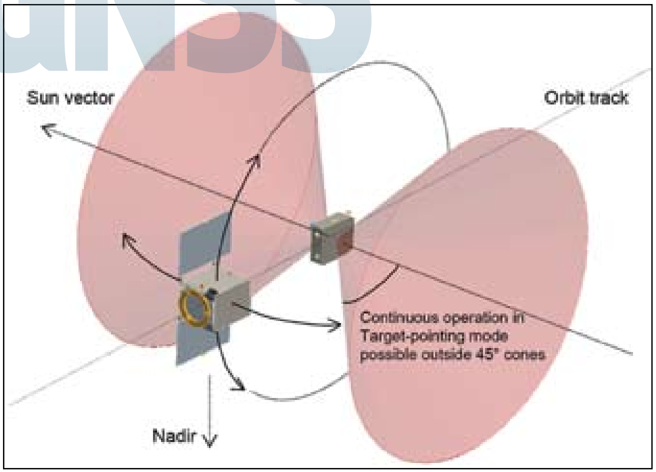


FIGURE 2 Main motion around target

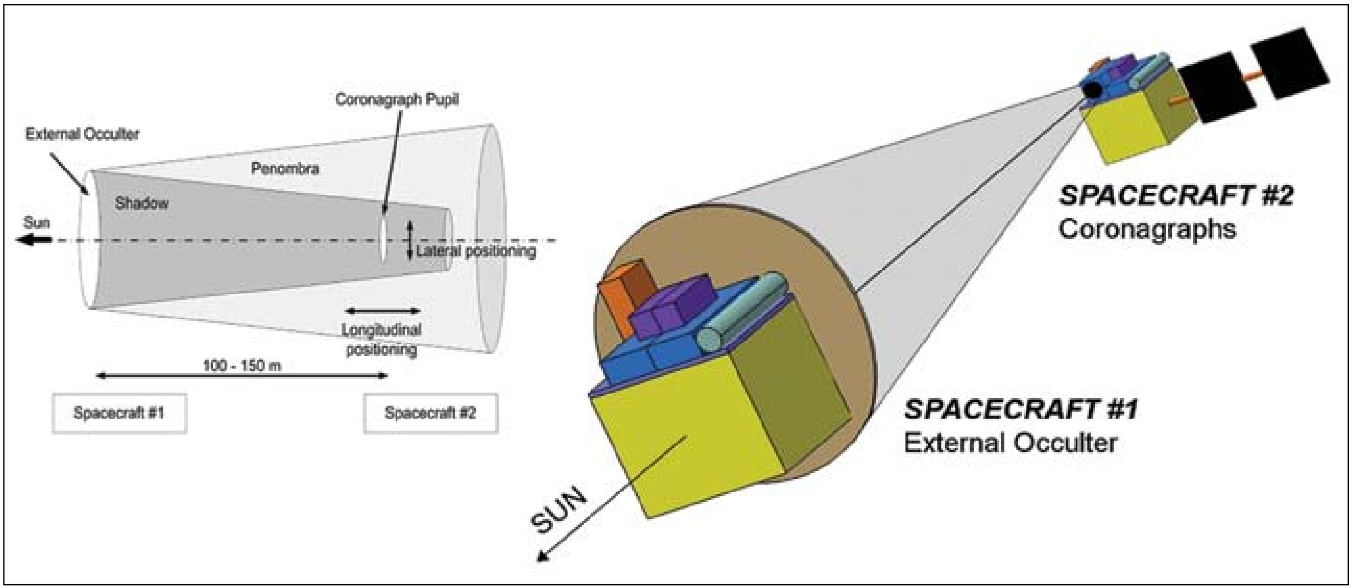


FIGURE 3 Illustration of PROBA-3 formation flying

during a sequence of autonomously scheduled approach maneuvers.

- The RF metrology subsystem. Designed to handle first stage omnidirectional RF metrology, the FFRF provided by CNES will mainly function at intersatellite distances from 3 meters to 30 kilometers.

PRISMA Goals

The primary goals for PRISMA are technology demonstrations and maneuver experiments (see Figure 2) examining GNC and sensor technology for a family of future missions that will use RdV and/or FF. The main demonstrations are as follows:

- GNC maneuvering experiments with a high level of autonomy: autonomous formation flying, homing and rendezvous, proximity operations, and final approach and recede operation. The experiments are run mainly by SSC with important contributions from DLR.
- GPS-based navigation system experiment from DLR, which will evaluate real-time differential GPS as a sensor for autonomous formation flying
- evaluation of the VBS as a multirange, range-tracking and RdV sensor
- demonstration flight test of the FFRF subsystem in open- and closed-loop configuration.

Further, the mission also has some secondary goals mainly oriented toward testing of new technologies appropriate for future small-satellite missions. These include 1) in-flight testing of high performance green propellant (HPGP) and cold gas microthruster propulsion systems, 2) onboard software development with MATLAB/Simulink and autocode generation, and 3) validation of new ground support equipment with multi-satellite support capability.

PROBA-3: The Next Step

The ESA PROBA-3 mission is foremost an FF demonstration mission and secondly am FF scientific mission. The first objective is to validate the GNC system, relative position and pointing determination systems (RF, and coarse and fine optical), and actuators. This mission will also validate formation acquisition, maneuvering, and collision avoidance algorithms as well as test different operational scenarios and formation flying architectures.

The second objective is to observe the solar corona, a luminous plasma ”atmosphere” that surrounds the sun. The total light output from the solar corona is less than one-millionth of that radiated by the disk of the sun. This enormous disparity in apparent brightness gives rise to the need to use an “occulter” to block light coming from the solar disk so as to be able to observe the corona better. (See Figure 3.)

PROBA-3 comprises two independent, three-axis stabilized spacecrafts flying close to each other with the ability to accurately control the attitude and separation of the two spacecraft in a closed loop. The spacecrafts will fly in a high earth orbit (HEO) divided between periods of accurate formation flying, when payload observations will be possible, and periods of free flight.

The length of the formation control period will result from a trade-off analysis involving the amount of fuel needed to maintain the orbits when in formation. The formation control part (around the apogee) will be used to demonstrate formation flying for astronomical and scientific missions as well as to observe the solar corona.

During the perigee (portion of orbit nearest to the Earth), the spacecraft will revert to normal, gravitationally determined orbits to reduce fuel consumption, with the thrusters then being used only for collision avoidance. The perigee pass will also demonstrate formation flying configurations required for LEO earth observation missions.

PROBA-3 Guidance & Control

The relative positions of the two spacecraft are determined by the S-band RF metrology subsystem, which functions for separations between five meters and eight kilometers, with an accuracy of centimeters. Increased accuracy for separations up to 500 meters will be

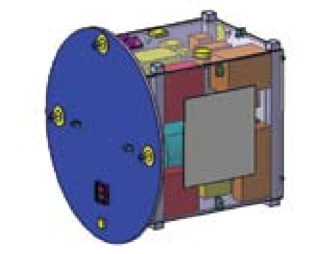


FIGURE 4 The PROBA-3 occulter spacecraft

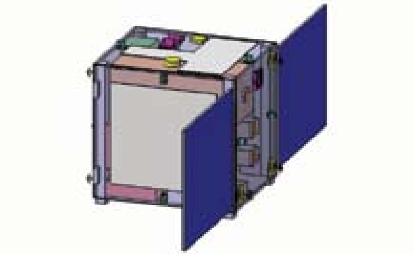


FIGURE 5 The PROBA-3 coronagraph spacecraft

obtained using optical laser techniques having both coarse and fine sensors to refine the relative position measurements.

The combined system is expected to achieve a relative positioning accuracy of about 100 micrometers over a separation range of 25–500 meters. Multiple thrusters, using either cold gas or ion technology, will be used to maintain the required relative positions.

Both spacecraft will carry GPS receivers to provide timing synchronization and relative navigation during perigee passage. GPS signals can be used at least 25,000 kilometers from Earth — and even more if carrier-to-noise spectral density (C/N_0) threshold reduction techniques are used. So, the signals should be useful for at least one-third of the proposed orbit and possibly all of it. Each spacecraft will employ a star tracker for absolute attitude determination.

Concerning the observation of the solar corona, the FF control system allows the use of a two-component space system with the external occulter on one spacecraft (**Figure 4**) and the optical instrument on the other spacecraft (**Figure 5**) at approximately 100–150 meters apart. The stability of the formation is linked to the requirement of keeping the optical pupil plane in the shadow of the occulter.

Lateral positioning accuracy is about ±2.5millimeters and longitudinal is about ±250 millimeters. The absolute attitude of the satellite hosting the external occulter is required to be about ±40 arcseconds. With the proposed PROBA-3 arrangement, accurate measurements will likely be possible from 1.05–3.2 solar radii.

Future FF Missions Overview

A remarkably large number of formation-flying and rendevouz missions are planned over the next 10 years or so by European and other nations or groups of nations. **Tables 1–3** summarize these missions as well as the probability of their being realized by 2020.

Table 4 provides a classification of the FF missions with respect to the objectives of the mission (space science, earth observation, and technology demonstrations).

Conclusion

GNSS constellations are the most practical way to perform RF formation flying in LEO, and autonomous two-way transmission of GNSS-like S-band signals is a better way to perform FFRF in HEO or within the Lagrange points. PRISMA is a unique opportunity in Europe, both technically and programmatically, to validate under real conditions the basic feature of any non-LEO future FF mission—the RF-based autonomous metrology, using GPS-C/A-like signals and techniques.

By mid-2009, an autonomous RFFF sensor shall be flying onboard the PRISMA satellites. This sensor will use GPS-like signals in S-band. Later,

Mission	Orbit	Launch Date	Number of Spacecraft	Baseline	Main Field	Agency
PRISMA	LEO	2009	2	FF: 100m–10km RdV: 10km -> 0	FF/RdV technology demonstration	SSC/DLR/CNES/CDTI
TerraSAR-X and TanDEM-X	LEO	2007/09	2	150m–10km	Earth's digital model (DEM) and SAR interferometry	DLR/Astrium
PROBA-3	HEO (24 h)	2012	2 (1 occulter and 1 observer)	Demo: 25m–250m Corona: 100m–150m RdV: 10km -> 0	FF/RdV (solar corona) technology demonstration	ESA
NanoForm*	LEO	2013	5 (1 mother and 4 children)	200m	EO (SAR)	ASI
SABRINA*	LEO	2012	2	100s m–100s km	EO (SAR)	ASI
Simbol-X	HEO (4 days)	2013	2 (1 mirror and 1 detector)	20m	X-ray telescope	ASI/CNES
Xeus	L2	2019	2 (1 mirror and 1 detector)	35m	X-ray telescope	ESA
Darwin	L2	2020+	4 (3 telescopes, 1 beam combiner)	10–1300m	Space IR interferometer	ESA
PEGASE	L2	2017	3 (2 telescopes, 1 beam combiner)	50m–500m	Infrared interferometer	CNES
MAX	HEO or L2	2015+	2 (1 mirror and 1 detector)	80 (90m)	Gamma-ray telescope	CNES
GRL	L2	2020+	2 (1 mirror and 1 detector)	500	Gamma-ray telescope	ESA
Romulus	LEO	2020+	4 in sequence	18m–21m–30m	Military. Synth.aperture for high image resolution	CNES/ONERA

* NanoForm and SABRINA are missions in competition. Only one will be selected after phase A

TABLE 1. Overview of the European FF missions [Probability of mission launch in medium term (<2020) 🟩 High; 🟨 Medium; 🟥 Low]

Mission	Orbit	Launch Date	Number of Spacecraft	Baseline	Main Field	Agency
SMART-OLEV	GEO	2012	2 (OLEV & GEO S/C)	10s km -> 0	Commercial service for GEO life extension	OSS (Sw)
NextMarx	Mars	2015	2 (600 kg target and 50 kg chaser)	3000km -> 0	Demonstration of autonomous rendezvous	ESA
MSR	Mars	2020+	2 (obiter and sample container)	3000km ->0	Mars exploration. Autonomous long-range RdV	ESA
CSTS	LEO	2015+	2 (CSTS-ISS)	1000km -> 0	Manned mission. RdV&D with ISS. ATV/Soyuz type	ESA/RRSC/JAXA
	Moon	2020+	5	1000km -> 0	Manned mission to the Moon. Assembly and docking in LEO	ESA/Russia/JAXA

TABLE 2. Overview of the European rendezvous missions [Probability of mission launch in medium term (<2020) 🟩 High; 🟨 Medium; 🟫 Low]

Mission	Orbit	Launch Date	Number of S/Cs	Baseline	Main Field	Agency
MagCON	HEO perigee:1RE apogee: 7–27 RE	2020	30+	Mean inter-spacecraft separation of ~2 RE	Science. magnetosphere	NASA (USA)
MMS	HEO perigee:1.2 RE apogee: 12 RE	2013	4 in tetrahedron	10 km at apogee	Science. magnetosphere	NASA
SPECS	?	2015	3	100m–1 km	Sub-mm telescope	NASA
ALFA	Retrograde 106 km from the earth	?	16	Circular array 100km max diameter	Imaging interferometry	NASA
TPF	L2	2015	4 or 5 (3 or 4 telescopes, 1 beam combiner)	100m–1000m	IR interferometry	NASA
New Millennium	Earth-trailing heliocentric	?	2 (1 combiner and 1 collector)	50m–1000m	FF and technology demonstration	NASA
MAXIM	L2?	2020	33 (mirror formation); 1 detector	500km-2000 km	X-ray telescope	NASA
CAN-X4/5	LEO	2008	2 (< 5 kg)	< 5000 m	FF and technology demonstration	CSA (Canada)
JC2sat	LEO		2 (20 kg)		FF and technology demonstration	CSA/JAXA (Japan)

TABLE 3. Overview of the non-European FF missions [Probability of mission launch in medium term (<2020) 🟩 High; 🟨 Medium; 🟫 Low]

in 2012, the ESA PROBA-3 and CNES Simbol-X spacecrafts will demonstrate the technology in scientific missions in HEO orbit.

Manufacturers

PRISMA is a Swedish National Space Board (SNSB) mission, undertaken as a multilateral project with additional contributions from CNES, the German DLR, and the Danish DTU. The prime contractor is the **Swedish Space Corporation (SSC)**, responsible for design, integration, and operation of the space and ground segments, as well as implementation of in-orbit experiments involving autonomous formation flying, homing and rendezvous, and three dimensional proximity operations. It employs Phoenix GPS receivers developed by DLR that incorporates the GP4020 chip from **Zarlink Semiconductors,** Ottawa, Ontario, Canada.

The FFRF subsystem development is currently in phase C/D, with **Thales Alenia Space-F** as the prime contractor on both the subsystem and FFRF terminal level. FFRF terminals incorporate components and software of the TAS-F TOPSTAR 3000 spaceborne GPS receiver.

In turn, TAS-F is relying on the following subcontractors:

- **Thales Alenia Space España** (TAS-E, Spain) for development of the RF modules of the FFRF terminal (RF front end, RF transmitter section, RF receiver section)
- **GMV** (Spain) for development of the navigation software, including implementation of PVT algorithms
- **Thales Avionics** (France) for development of the FFRF terminal signal processing software

Additional Resources

[1] Bourga, C., et al., "Autonomous Formation Flying RF Ranging Subsystem," *Proceedings of ION GNSS 2003,* Portland, Oregon, USA, September 2003

[2] Cledassou, R., Ferrando, P., "Simbol-X: An Hard X-Ray Formation Flying Mission," Focusing Telescope in Nuclear Astrophysics Gamma Wave Workshop, Bonifacio, France, September 2005

[3] Garcia-Rodríguez, A., *Formation Flight (FF) Radio-Frequency (RF) Metrology.* ESA/ESTEC Technology Dossier, Issue 1.2, Noordwijk, the Netherlands July 2008

[4] Godet, J. et al., "Improving Attitude Determination of Satellites," Internationnal Workshop on Aerospace Applications of the GPS, Breckenridge, Colorado, USA, February 2000

[5] Harr, J., et al., "The FFIORD Experiment: CNES' RF Metrology Validation and Formation Flying

Demonstration on PRISMA," 3rd International Symposium on Formation Flying, Missions and Technologies, Noordwijk, Netherlands, April 2008

[6] Issler, J., et al., "Lessons Learned from the Use of GPS in Space; Application to the Orbital use of GALILEO," *Proceedings of ION GNSS 2008,* September 2008

[7] Lestarquit, L., et al., "Autonomous Formation Flying RF Sensor Development for the PRISMA Mission," *Proceedings of ION GNSS 2006,* Fort-Worth, Texas, USA, September 2006

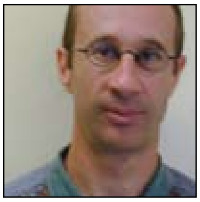
[8] Persson, S. et al., *PRISMA: An Autonomous Formation Flying Mission,* Small Satellite Systems and Service Symposium, Chia Laguna, Sardinia, Italy, September 2006

[9] PROBA-3 <http://www.esa.int/techresosurces/index.html>

Authors

Thomas Grelier has been a navigation engineer in the Transmission Techniques and Signal Processing Department at CNES since December 2004. He graduated from the French engineering school Supelec and received an M.S. in electrical and computer engineering from Georgia Tech (USA). Galileo signal processing is one of two main areas of research. He analyzed GIOVE-A, GPS IIR-M, Beidou-1 S-band, and modernized GLONASS signals. Grelier has also developed various Galileo #5 ALTBOC tracking techniques and analyzed their theoretical performances. Thomas Grelier is also technical responsible of the FFRF equipment of the PRISMA satellites.

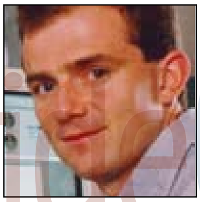
Alberto Garcia-Rodríguez is a radionavigation systems engineer of the European Space Agency. He is involved since 2000 in activities related to GNSS space receivers, GNSS applications and Formation Flying. He worked previously at GMV (Spain) performing GNSS system studies for the EGNOS and Galileo projects. He has a degree in Telecommunications Engineering from the Universidad Politécnica de Madrid (T.U. Madrid).



Eric Péragin is a TMTC expert in the CNES Transmission Techniques and Signal Processing Department having worked in this area for about 20 years. He designed the high performance Rx/Tx used on board the Myriade microsatellite family, also used for the intersatellite link of cometarian probes Rosetta (ESA/CNES/DLR) and Deep Impact (NASA). He was involved in the Martian Data Relay equipements supplied by CNES for Mars 96 Russian probe, and the U.S. probes Mars Observer and Mars Global Surveyor. He integrated a GPS receiver on the HETE1 spacecraft of MIT and NASA. He is now responsible for a set of predevelopments regarding CNES next-generation high performance TMTC in S and/or X band for the Rosetta intersatellite link and is the RF expert for the FFRF equipment of PRISMA.

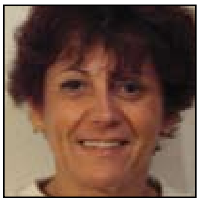
Formation Flying					
Space Science		Earth Observation		Technology Demonstration	
Physics	Astronomy	Aperture Synthesis	Distributed Instruments	Universities Blimp TestBed, CAN-X4/5	Agencies New Millenium, PROBA-3, PRISMA, TS/TD-X
Earth Cluster, Crosscale MMS, MagCon	Optical interferometry Darwin, TPF Pegase, Labeyrie	Optical interferometry TBD	Splitted Payloads EO-1, Cloudset		
Solar ASPICS/PROBA-3	Radio Interferemetry SPECS, ALFA	Distributed Microwave Radars/ Sounders Romulus, Cartwheel Techsat 21, GEO sounder			
Fundamental physics LISA	X-Ray telescopes Simbol X, MAXIM XEUS	Gradiometer Baselines GRACE Post-GRACE/GOCE			
	Gamma-Ray Telescope MAX, GRL				

TABLE 4. **Formation flying missions classification**

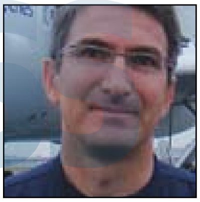


Laurent Lestarquit is a navigation signal expert at the CNES Transmission Technique and Signal Processing Department (TT). He was a member of the Galileo Signal Task Force and contributed to the definition of the Galileo signal and provided support to the 2004 US-EU agreement on GPS and Galileo. He invented the constant envelope four-code ALT-BOC modulation.

Jon Harr works at CNES in the "Etudes de l'Univers" project department. He is currently responsible for coordinating the CNES participation on the PRISMA mission, as project manager for the FFIORD experiment. He has background as a radio and remote sensing engineer, with several years of experience as specialist on radar altimetry and TTC systems onboard CNES small satellite missions such as Jason, Demeter, and Parasol.



Dominique Seguela is in the CNES R&D department. She is responsible for several R&D areas, including onboard-ground processing and hardware, and formation flying, and supervises the CNES mission group of PRISMA. She was involved in system and satellite activities for the SPOT spacecraft family.



Jean-Luc Issler is in charge of the Transmission Techniques and Signal Processing Department at CNES. He is involved in the development of several types of GNSS, FFRF, and TMTC equipment in Europe for space or ground users. He is a French delegate to the GALILEO Signal Task Force. Issler received in 2004 the Astronautic Prize of the AAAF (French aeronautical and space association), and in 2008 the EADS Prize of science and engineering delivered by the French Academy of Sciences, mainly for his technical work on Galileo signals and spaceborne GNSS equipment.

Christophe Ensenat graduated from "E.N.S.E.E.H.T" Toulouse with an engineering degree in electronics. He serves now at Thales Alenia Space, Toulouse, as equipment project manager, within the

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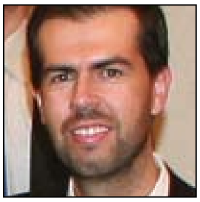
digital section of the Industrial Unit. His area of expertise includes the digital units of radar altimeters, GPS receivers, and RF sensors.

Nicolas Wilhelm has been working on GNSS space equipment at Thales Alenia Space for more then 10 years. He has been responsible for the development of the TOPSTAR 3000 space receiver in late 1990s and involved in formation flying RF studies and development with ESA and CNES since preliminary studies in 2002.

Ana Maria Badiola is the technical responsible for the RF modules of the FFRF terminal at Thales Alenia Space España. She has participated in development of the FFRF terminal modules since 2004, including preliminary studies, phase B, and the current phase C/D of the terminal. She has a wide experience in S-band transponders (for LEO applications of the PROTEUS satellite platform, ATV and Galileo) and X/C/Ku-band telemetry transmitters as technical responsible and RF design engineer.



Pablo Colmenarejo works for more than 10 years for GMV (Spain), where he is responsible of the GNC Division. With an Aeronautical Engineering academic background, he has developed most of his professional experience in projects related to Formation Flying and Rendez-vous&Docking and on GPS and Radio Frequency related technologies. He is actively involved in the FFRF metrology development and use for missions like DARWIN, Mars Sample Return, PRISMA and PROBA3. IG