PRISMA satellite

Photo courtesy of Swedish Space Corporation (SSC) and Intespace

GNSS in Space

Part 2 Formation Flying Radio Frequency Techniques and Technology

The idea of flying two or more satellites in controlled formations with complementary sensors on board to execute scientific research missions will receive a lot of practical attention in the near future. Part 1 of this two-part series reviewed some of those missions and their objectives. In some cases, GNSS signals will be used to meet the high-precision positioning and orientation requirements for this application. Other, higher-orbit missions will employ RF-based techniques similar to those used to make GNSS carrier phase measurements. This second and final part of the series describes in greater detail the technologies and techniques used in this scientific research.

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In the November/December issue of *Inside GNSS,* the first part of this column described the upcoming scientific missions that fly two or more smaller satellites in close formation to create large spaceborne instruments. The final part of this series explains the GNSS techniques and technologies employed to achieve very accurate relative positioning and orientation of the spacecraft at lower altitudes as well as a similar approach used at higher altitudes for relative positioning by means of RF carrier phase measurement techniques.

FF Missions Metrology Requirements

Table 1 summarizes the needs of the formation flying (FF) missions in terms of metrology requirements. In general, all the proposed scientific missions discussed here have FF elements with closed-loop formation control in non-Keplerian orbits, typically at L2 (the second Lagrange Point about 1.5 million kilometers from the Earth) or HEO. They all have demanding accuracy requirements and are sufficiently consolidated.

The proposed EO missions are mostly in LEO orbit with less demanding navigation accuracy requirements in real time (very often the processing is done on the ground). At the moment, requirements for the EO FF missions are less well defined than the space science FF missions. PRISMA and CanX-4/5 are short-term missions with launches tentatively scheduled for 2009.

From the overview of the FF mission metrology requirements, we can identify four main development lines in the frame of spacecraft formation flying.

Earth Observation Missions. These missions, in LEO orbit, will respond to the demand for highly accurate Earth models on a global space and time scale. Two or more satellites of identical type and build are flown at close distances to synthesize three-dimensional baselines between the satellites that can be reconfigured during the mission lifetime.

The relative orbit control accuracy required for such formations is relatively coarse (~100 meters) and may drive the need for real-time onboard relative navigation accuracies at a 1–10 meter level. High precision (submillimeter) post-facto reconstruction of the three-dimensional relative motion may be needed for some missions.

Discussions about future gravity field satellite missions are underway to overcome the intrinsic limitations of gravimeters such as CHAMP (Challenging Minisatellite Payload), GRACE (Gravity Recovery and Climate Experiment), and GOCE (Global Ocean Circulation Experiment). The GRACE geodetic observables, for example, are inherently non-isotropic, as a result of the permanent along-track orientation of the laser link and its scalar character. To enhance the spectral content, future geodetic satellite missions (post-GRACE, post-GOCE) would make use of autonomous formation flying with multiple baselines.

Dual Spacecraft Telescopes. These instruments aim at spectral investigation of sources that are too faint for study with the current generation of observatories (e.g., Chandra, XMM-Newton). The typical mission profile seeks orbits with a low level of perturbations, stable thermal environment, lack of eclipses, and wide sky visibility.

In contrast to the unfavorable LEO environment, in this context, GEO, HEO, and Lagrange points of the Sun-Earth system offer optimum conditions. Typical separations aim at focal lengths of about 30–250 meters. Autonomous formation flying capabilities are driven by the telescope optical design and should allow uninterrupted science observations. This translates into combined attitude/orbit control systems with required navigation accuracies at (sub)centimeter level.

A clear constraint arises from the need to implement a navigation system at altitudes above the GNSS constellations. Provided that the GNSS receivers can acquire and track the very weak side lobes of the broadcast signals, real-world simulations have demonstrated centimeter-level relative navigation accuracies in LEO (~5 centimeters) and HEO at radial distances up to 17 times the Earth radius. Only self-contained relative (inter-satellite) navigation sensors (i.e., radio frequency and optical) can fulfil the requirements of autonomous formation flying at even higher altitudes.

Multi-Spacecraft Telescopes. The third type of application addresses the use of multiple spacecraft telescopes. Researchers have identified interferometry in the infrared and visible wavelength regions as the key technology to support new astrophysical discoveries and the direct search for terrestrial exoplanets.

To achieve that purpose, clusters of three or more units need to fly in -millimeter-precision-close formations with interspacecraft navigation accuracies at the submillimeter level. Only optical sensors and laser interferometers can provide the required formation flying metrology performances. RF metrology is needed for deployment and maneuver control.

Long-Range and RdV Missions. The last type of application involves long-range and rendezvous (RdV) missions. These types of missions require an RF sensor technology, combined with the navigation algorithms of the GNC system, during the long-range phase while the satellites are far apart. The chaser vehicle must be able to detect, acquire, and track the relative position of the target spacecraft to close on, and then perform, the final approach and docking.

Examples are post-ATV (Crew Space Transportation System or CSTS), Next-Mars, and Mars Sample Return (MSR) missions. Long-range metrology used in HEO activities include the Magnetosphere Constellation (MagCON), Magnetospheric Multiscale (MMS), and Cross-Scale missions (all studies of the Earth's magnetosphere). These missions also require a capability for long-range operations across thousands of kilometers, which makes this type of FFRF technology very attractive.

	FF Mission Needs			Non-FF
	Earth Observation	Dual Spacecraft Telescope	Multi Spacecraft Telescope	Long-Range & RdV
Missions	PRISMA, GRACE, PostGOCE, postGRACE, TerraSAR/TanDEMX, NanoForm, SABRINA, Romulus	PROBA-3, GRL, Xeus, Simbol-X, MAX	Darwin, PEGASE, SPECS, TPF, New Millenium	NextMars, MSR, ATV, CSTS-ISS (LEO), CSTS-Expl (Moon), SMART-OLEV, MagCON, MMS, ALFA, MAXIM
Orbit	Low earth orbit (LEO)	High earth orbit, HEO (or Lagrange point)	Lagrange point (or HEO)	HEO, moon, Mars, LEO (ISS), GEO (OLEV)
Number of S/Cs	≥2	2	≥3	Long-range: ≥3 RdV: 2
Typical separation	100 m–1000 km	30–250m	10–1500m	Long-range: 100m–3000km
Navigation accuracy	1–10 m (1 mm post-facto)	0.01–1cm	1–100mm	10–100m
Technology	GNSS space receivers *(or integrated with RF ISD)*	RF metrology		RF long-range metrology *(integrated with GNSS Rx for LEO)*

TABLE 1 FF Metrology needs

The RF Metrology Subsystem

On FF missions, the FFRF subsystem is responsible for the relative positioning of two to four satellites. It generates relative position, velocity, and line-of-sight (LOS) data as inputs to a GNC subsystem for which it provides coarse measurements.

The overall FF metrology system has both coarse and fine modes. The coarse mode provides accuracy of one meter and 20 degrees for LOS with omnidirectional coverage in order to provide inputs for pointing the telescope, imaging sensor, or other instrumentation of the spacecraft's primary mission. For fine mode, the accuracy is expected to be one centimeter for distance and one degree for LOS measurement in a cone of a few degrees of aperture.

As the first element in the FF metrology system chain, the FFRF sensor provides initial relative positioning for the subsequent optical metrology subsystems that could be used if a higher accuracy is required (coarse optical lateral metrology, fine optical metrology, and fine longitudinal metrology).

A dedicated computer/RF terminal and up to four sets of antennas on each satellite in the constellation comprise the FFRF subsystem. A set of antennas can be either a triplet —one receiver/transmitter (Rx/Tx) master and two Rx slaves — or a single Rx/Tx antenna. The maximum number of triplets is two, and the total maximum number of antennas is eight.

The FFRF terminal operates with a dual-frequency S-band ranging signal, and each terminal transmits and receives signals to and from all the other satellites in a time division multiple access–based pattern. Ranging and angular measurements are extracted from received signals and used for computing relative position, velocity, and LOS. In addition to providing relative navigation measurements, the FFRF subsystem also provides an intersatellite data link (data ISL) as auxiliary functionality.

The FFRF equipment developed for PRISMA thanks to the European Space agency (ESA), CNES, and CDTI (Centro para el Desarrollo Tecnológico Industrial — Spain) is generic — flexible in terms of frequency plan, number of antennas, and antenna accommodations. The FFRF functionalities planed for PROBA3 that are not present on PRISMA include, for instance, an extended intersatellite range up to 100 kilometers instead of 30 kilometers and higher data rates for short intersatellite distances, thanks to a current ESA predevelopment made in cooperation with CNES.

Frequency Band. A study of International Telecommunications Union (ITU) regulation showed that the only portion of RF spectrum allowing FFRF operation (provided with reasonable transmitted power to comply with the omnidirectional coverage requirement) was the space-to-space communication band sharing the tracking, telemetry, and control (TTC) allocation in S-band (2025–2110 MHz and 2200–2290 MHz). The challenge is to find frequencies that are compatible with the platform TTC, which is also in S-band. To ensure compatibility with all future FF missions, the FFRF frequencies can be programmed during the manufacturing stage at several frequencies located in the TTC S-band. The TTC frequencies of missions like PRISMA, PROBA3, and Simbol-X are in S-band, but X-band could also be used for telemetry of certain missions, such as one at a Lagrange point, for instance.

For the PRISMA mission, Thales Alenia Space–France (TAS-F) performed a thorough study to reduce the risk of disturbance between the FFRF and the TTC subsystems. The result is a frequency plan that takes into account the following constraints and hypotheses:

- maximize the frequency separation between the telecommand (TC) band and S2 and between the telemetry (TM) band and S1.
- maximize the RF distance between FFRF and deep space research (DSR) bandwidth (2290–2300 MHz).
- provide a reasonable FFRF interfrequency separation to optimize the integer ambiguity resolution (IAR) functionality.

Intermodulation (IM) products between FFRF S1 and S2 and TM could result from TM signal leaking into the switch of the FFRF RF module; these IM products will not fall into the TC band.

For PRISMA, this led to a frequency plan in which FFRF frequencies are located in the upper part of TM and TC bands: S1 = 2275 MHz and S2 = 2105 MHz. TM frequency is 2214 MHz, while TC frequency is equal to 2035 MHz. This frequency plan guarantees sufficient separation between S2 and TC. Moreover, the signal at S2 has reduced power compared to S1, which limits further interference with TC.

Carrier frequency	S1 : 2275 MHz (in TM band)		S2 : 2105 MHz (in TC band)
Modulation	QPSK		BPSK
Channel	I (ranging signal)	Q (data signal)	I (ranging signal)
Ranging code	C/A (same as GPS)	-	C/A (same as GPS)
Average data rate	-	7.2 or 16.8 kb/s	-

TABLE 2 FFRF signal characteristics

Signal Characteristics. Measurements are made thanks to signals based on GPS technology. Using multi-antenna bases (triplets) and TDMA sequencing, each terminal transmits and receives a GPS C/A-code navigation signal modulated on two S-band carrier frequencies. A data link is provided on the first frequency with data bits modulated in quadrature of the navigation signal.

Table 2 outlines the full set of FFRF signal characteristics.

Measurement Principle and Factors

To allow the determination of relative position and relative speed, the FFRF subsystem provides the following fine-mode information every second:

- intersatellite scalar distance (specified precision = one centimeter)
- intersatellite velocity with a precision of a few millimeters
- azimuth and elevation of line of sight between two satellites (specified accuracy = one degree)
- azimuth and elevation variations
- clock bias between the two satellites.

Every terminal is equipped with both a transmitter and a receiver; so, each satellite is able to make ranging and LOS measurements with every other satellite. First, the system makes coarse measurements using the ranging signal from the C/A code and then performs fine measurements with centimeter accuracy using carrier phase measurements.

The dual-frequency S-band configuration allows the system to perform carrier ambiguity resolution using a wide-lane technique, while two-way measurements account for the relative clock drift of the platforms. LOS measurements are made by measuring the carrier phase difference between the

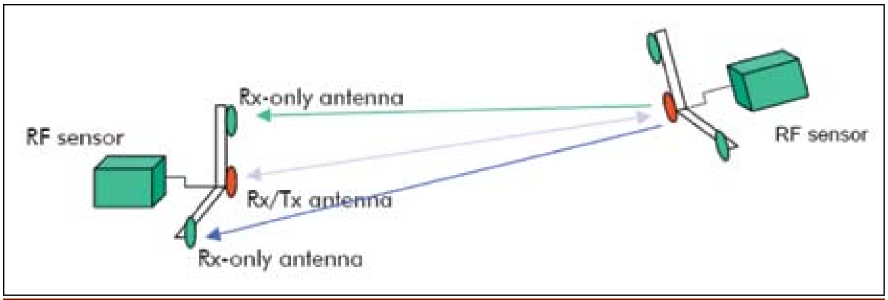


FIGURE 1 Two-satellite FFRF S/S configuration

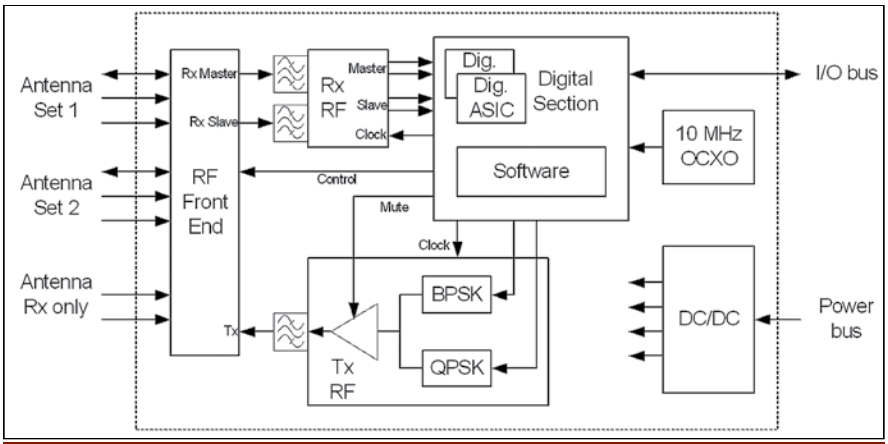


FIGURE 2 FFRF terminal block diagram (generic case)

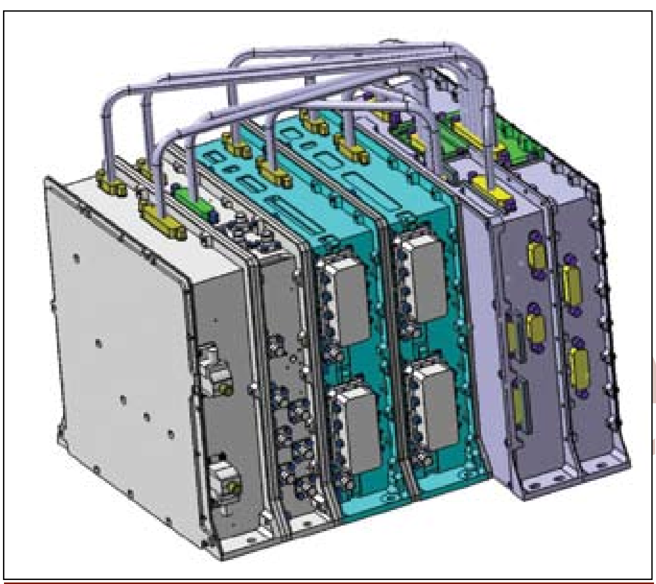


FIGURE 3 FFRF box preliminary design (TAS-F)

master and slave antennas on the triplet antenna base. Attitude, though, comes from an external attitude sensor, such as a star tracker.

On PRISMA, the Target satellite has only three Rx/Tx antennas on different facets to ensure full space coverage. Thus, the Main satellite, which is the only one equipped with a full antenna triplet, will perform the position-velocity-time (PVT) algorithms to determine the precise positioning of the Target satellite.

For formations with more than two satellites, a centralized PVT algorithm uses all the measurements made by all the satellites to give the relative position of each satellite. See Figure 1.

Ambiguity Resolution. Carrier phase, used for LOS and distance computation, is measured modulus 2 pi. Thus, an integer number of cycles remains unknown and must be solved to reach nominal precision. This operation is performed by the IAR function that is responsible for solving both LOS and distance phase ambiguities.

In this scenario, retained precise knowledge of LOS is necessary to correctly solve the ambiguity on distance. Thus, IAR has to be performed first on LOS, then on distance. IAR on LOS requires a satellite rotation around antenna direction of about 40 degrees magnitude, with the rotation characteristic provided to the network processor unit software. This rotation helps to mitigate the multipath error bias.

The IAR on distance is done in two steps. First, the system forms a carrier widelane and removes its ambiguity using code measurement smoothed over time. Then, in a second step, the carrier ambiguity on S1 is removed using the filtered widelane measurement. The sensitivity of the latter step to multipath is critical and requires multipath calibration

Multipath Errors. A significant source of errors on the LOS and distance measurements comes from signal multipaths created by the satellite structure surrounding FFRF antennas. These errors can reach several centimeters on phase measurements—resulting in a significant degradation of FFRF precision and potentially causing the carrier ambiguity resolution to fail. Indeed, when forming the carrier phase widelane, the carrier multipath error is amplified. The IAR can be successful only if the carrier phase error can be reduced to a few millimeters on both frequencies. Currently, a calibration method of multipath errors in an anechoic chamber is under study at CNES. The new method maps multipath errors in function of LOS to provide calibration tables for in-flight correction.

Terminal Architecture

The FFRP terminal's architecture is largely based on results of an ESA Technology Research Program study and CNES architecture studies. It reuses some of the components and software from a 12-channel, L1 spaceborne GPS receiver.

The following hardware sections comprise the terminal (see the block diagram in Figure 2 and box design in Figure 3):

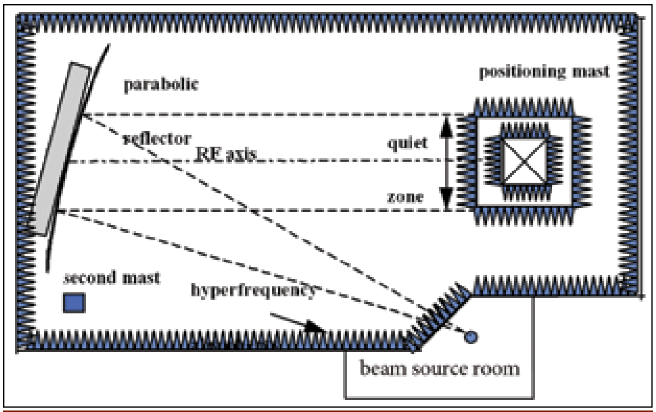


FIGURE 4 CNES compact range configuration, anechoic chamber

- RF front-end (RFE), which makes the switch between the eight antennas on one side and the Tx signal, the master Rx signal and the slave Rx signal on the other side
- transmitter RF module, which generates the dual-frequency signal to be transmitted by the Rx/Tx antennas
- RF receiver (Rx) module, which performs the frequency conversion and digitization of the dual-frequency received signal (There are two Rx modules, one for the master signal, one for the slave signal.)
- digital (or processing) section, which acquires and tracks signals, produces ranging and angular measurements, computes relative position/velocity/line of sight, synchronizes with TDMA sequence, controls the transmitter section, and generates Tx baseband signals
- 10.00 megahertz oven controlled crystal oscillator (OCXO), which provides the reference clock of the terminal. (There is currently an open trade-off between the OCXO, already used for the 12-channel, L1 spaceborne GPS receiver and the OCXO that is currently being qualified.)
- Power supply section: provides secondary supply voltages from satellite power bus

All the modules are then stacked together, except RF filters (Rx and Tx), which can be separate.

In the PRISMA case, there are two configurations for the FFRF terminal — one for the Main spacecraft and one for the Target. On the Main craft, the FFRF terminal connects to a unique triplet antenna set. As a consequence, at module levels, differences with the generic case are limited to front end. On the Target, the FFRF terminal connects to three, single Rx/Tx antenna sets. As a consequence, at module levels, differences with the generic case occur:

- in the front-end
- in the Rx RF module, where only one receiver chain is present (master Rx signal only)
- in the digital processing module, where only one digital ASIC is needed, because only a master Rx signal is processed.

Data Link (ISL). The FFRF subsystem includes an intersatellite data link capable of transferring data to or from any visible satellite in the formation. Two kinds of data are exchanged:

- navigation ISL: For positioning, the RF sensor works on a cooperative basis, meaning that RF signals are transmitted and received to and from each vehicle to measure distance and line of sight. Each sensor calculates the results of these measurements, then the sensors exchange the navigation data to allow PVT computation for each vehicle.
- transparent ISL for the on-board computer (OBC): The RF sensor allows data to be transferred in a transparent manner between the OBC of each satellite. For all FF missions, this data exchange link is necessary to transfer TC and TM between master and slave satellites for command and control purposes. This OBC ISL operates with a dual-bit rate of either 4 or 12 kilobytes.

Multipath Calibration

Signal reflections caused by the satellite structure surrounding FFRF antennas will be the major source of error on FFRF LOS and distance measurements. These multipath errors can reach several centimeters on phase measurements—resulting in a significant degradation of precision.

To reduce multipath effects, CNES has set up a method of multipath-error calibration in an anechoic chamber. (See Figure 4.) This method is inspired by previous work done at CNES to improve attitude determination by GPS. The multipath calibration method is depicted in the following section.

Stanford University and NASA have also performed accurate multipath calibrations for GPS attitude determination applications.

T. Grelier and associates performed the first measurement campaign at CNES in 2006, and those results can be found in their publication listed in the Additional Resources section at the end of this article.

CNES performed a second multipath measurement and calibration campaign in 2007, and those results are presented here. For this campaign, the set-up was different than the previous one, and it represents the final calibration that will provide error correction tables to be used in 2009 prior to PRISMA's launch.

Calibration Principle. A wave front originating from a given direction with respect to the satellite will always reflect and diffract off the various surfaces of the spacecraft in exactly the same way. Given such a repeatability of the wave front scattering, we can calibrate multipath errors as a function of the LOS signal by premeasuring these errors. The calibration system makes multipath error maps depicting carrier phase and interferometric phase residual errors as a function of the azimuth and elevation of the signal.

Experimental Set-Up. Measurements were made in the CNES anechoic chamber to avoid the creation of external multipath to the mock-up satellite and to create space-like conditions.

For this experiment, two radioelectrical mock-ups of PRISMA satellites were built (see accompanying photos). The design called for three antennas to be mounted on the Main craft on the

PRISMA radioelectrical mock-ups with S-band helix antennas in CNES anechoic chamber (2007 campaign)

same face, allowing distance and phase interferometric measurements. The Target had only one antenna, allowing distance measurement.

The 2006 campaign used a FFRF breadboard, developed in 2004 under a joint ESA and CNES contract. This breadboard three terminals with an integrated 12-channel L1 receiver. The terminals differed from FFRF in that signal transmission occurred in L-band and single frequency, instead of S-band and dual frequency.

This first campaign provided preliminary information about the multipath magnitude that could occur on PRISMA satellites. However, no information was available for S-band multipath magnitude, and more important, the campaign failed to provide information on the magnitude of the widelane multipath magnitude information, which is critical for IAR. So, a new measurement campaign was necessary.

As no FFRF equipment or breadboard was available in S-band, FFRF was replaced by a network analyzer (NA). The previous campaign had shown that differences between phase measurements made by FFRF and a network analyzer were negligible.

Moreover, in this second experiment, L-band patch antennas were replaced by S-band helix antennas, the same ones that will be used on PRISMA satellites (see accompanying photos of the radioelectrical mock-ups in anechoic chamber). Multipaths measured on the mock-ups should be representative of what will occur for PRISMA.

Final calibration in 2009 will use engineering models of FFRF and the S-band helix antennas mounted on new radioelectrical mock-ups of both satellites.

Calibration Process. To perform error mappings, the anechoic chamber was used in its normal configuration. A network analyzer was connected to an S-band horn antenna located in the beam source room and to the S-band Saab antennas on the mock-ups (either Main or Target) fixed to the positioning mast.

This configuration simulated far-field conditions because the parabolic reflector created a perfect plane wave. Successive mappings of Main and Target spacecraft were made.

Error mappings took place through continuous measurements, which consist of scanning the meridians (fixed azimuth, elevation: from -90 to +90 degrees) with a given step in azimuth angles (two degrees). A very low (one degree per second) rotation velocity of the positioning mast to avoid dynamic stress errors.

Each successive position taken by the positioning mast recorded carrier phase and interferometric phase measurements. A postprocessing tool was used to compute the expected measurements (from the positioning mast positions) and then obtain the residual errors by subtracting the expected phase from NA phase measurements. Complete error maps were achieved in eight hours.

Next, multipath mapping took place, consisting of mapping the carrier phase errors and two of the interferometric phase errors for the Main craft and a carrier phase error map of the Target craft. (Only carrier phase error mapping was done for the Target craft because it makes only absolute phase measurements — which could be differentiated — but not direct interferometric measurements.)

Calibration Method Assessment. To evaluate the efficiency of the calibration method, a second configuration was used with the Main craft mounted on the positioning mast while the Target is fixed on a second mast added in a corner of the anechoic chamber (see accompanying photo).

Measurements were performed for different positions of the first mast. Then residual errors were computed and compared to the residual errors taken from satellite multipath mappings.

For carrier phase measurements the applied correction consists of the sum of both Target and Main carrier phase corrections. Subtracting corrections from errors produced a calculation of the residual error after multipath corrections. The efficiency in terms of percentage of correction is then computed.

Measurement Results. Following are the key results of the calibration campaigns of 2006 and 2007:

- Multipath errors on carrier phase measurements can reach several centimeters. Statistically, multipath error increases with elevation of received signal (elevation is the angle between antenna boresight and signal direction of arrival).

- The standard deviation of multipath error residual is half that of initial multipath error, that is, multipath calibration enables the reduction of error by 50 percent.
- Modification of the multi-layer insulation (MLI) configuration (which could happen because of launch vibrations) changes the multipath geometry configuration, thus reducing the performance of multipath calibration. Indeed, measurements performed before and after modification of MLI showed that differences in multipath errors of up to five millimeters can occur between measurements. So, multipath correction tables created through calibration campaigns on the ground will probably not be fully representative of an in-flight situation.

We concluded that, because of potentially large values of multipath errors for high elevations and reduced performance of multipath correction, the integer ambiguity resolution process will have to be performed using reduced values of elevation (LOS measurement cone elevation less than 20 degrees). Alignment in such a cone could be made using the FFRF coarse mode.

Future Trends

As we have seen, a high number of developments made for FFIORD will be directly reusable for other FF missions.

For CNES, one important FF mission within a medium time frame is the Simbol-X mission — an astrophysical X-band observatory (covering a continuous energy range from 0.5–70 keV) to be launched in 2013 in a HEO orbit. The CNES mission, which is a cooperative effort with Italy and Germany and France, will consist of two satellites (one *Mirror* and one *Detector*) in close formation:

- intersatellite distance = 30 meters
- lateral relative position requirement = 1 centimeter
- longitudinal relative position requirement = 10 centimeters

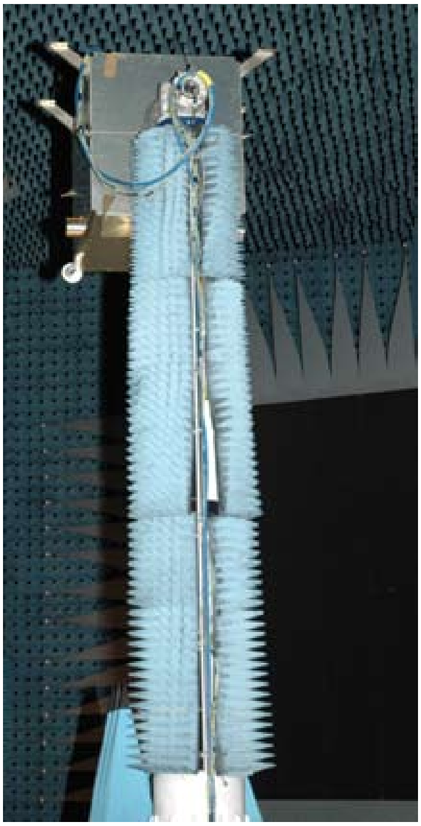
In this formation, the Mirror will be the master satellite, and the Detector will act as the slave. Dependent on accurate formation control, Simbol-X will carry the FFRF sensor as a main coarse and fine metrology subsystem, which will be fully redundant. Both GNC/formation flight management and FFRF developments and validation performed through the FFIORD experiment will therefore be directly reusable for Simbol-X.

Moreover, ESA's FFRF R&D plan includes the current development of a dynamic FFRF test bench, using true hardware equipment and a dynamic multipath and propagation channel generator. This hardware is associated with GNC algorithms embedded within LEON boards. The dynamic avionics test bench aims at simulating the behaviors of two spacecraft flying in formation.

The RF-conducted network is made up of three dynamic phase shifters providing a 30-centimeter range capability on the line-of-sight and on the distance, plus static attenuators. The phase shifters are controlled in coherency with the environment thanks to a Dspace box in charge of propagating the relative states of the satellites.

The FFRF R&D plan of ESA also includes the upgrade of the FFIORD third Engineering Model (EM) to extend its flight domain up to a distance as long as 100 kilometers between the spacecraft without increasing the transmitted power. This third EM will also include increased data rates (up to about 100 kilobytes per second), which could be used for short distances between the spacecraft. CNES is participating in these ESA activities.

CNES is also studying the possibility of performing line-of-sight IAR without any maneuvering of the spacecraft, as well as the possibility of improving the distance IAR thanks to the simultaneous use of four or, more probably, five dual-frequency S-band antennas and to improved IAR algorithms. CNES will also contribute to the evolution of the ESA FFRF test bench with the adaptation of the bench to the S-band FFRF engineering model and with the introduction of dynamic multipath. Finally, CNES will predevelop a multipath –10-decibel attenuating MLI, with the help of the Commissariat à l'Energie Atomique (CEA).



Configuration with two satellites in anechoic chamber (2006 CNES campaign)

Some of these R&D efforts might benefit the Simbol-X and PROBA-3 projects. In the long term, for post-PROBA-3/Simbol-X missions, we envisage miniaturization of the FFRF technology and some simplified designs for future missions. One such mission could be the return of samples from the planet Mars, requiring FFRF for the recovery of the canister containing the samples.

In low earth orbit, the future of formation flying, including controlled approaches and rendezvous between manned spacecraft, relies mainly on multistandard GNSS receivers, in L1/E1/B1-BOC, or L5/E5a, or E5b/L3/B2 combinations, for instance. The use of several interoperable constellations provides more robustness and more accuracy, especially for spacecraft with GNSS antennas not pointed toward the zenith, that is, those craft lacking visibility of GNSS satellites when a single GNSS constellation is used.

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 early 2009, an autonomous RFFF sensor shall be flying onboard the PRISMA satellites. This sensor will use GPS-like signals in S-band. Later, in 2012, the ESA PROBA-3 and CNES Simbol-X spacecraft will demonstrate the technology in scientific missions in HEO orbit.

However, to achieve the required accuracy, IAR on carrier phase will be needed. For this to succeed, multipath errors will have to be mitigated by calibrating the multipath on the ground to make in-flight corrections.

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)**, Solna, Sweden, 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-France,** Toulouse, France, as the prime contractor on both the subsystem and FFRF terminal level. In turn, TAS-F is relying on the following subcontractors:

- **Thales Alenia Space España** (TAS-E, Madrid, Spain) for development of the RF modules of the FFRF terminal (RF front end, RF transmitter section, RF receiver section), which incorporate a digital technology and software coming from the TAS TOPSTAR 3000 spaceborne GPS receiver.
- **GMV** (Madrid, Spain) for development of the navigation software, including implementation of PVT algorithms
- **Thales Avionics** (France) for development of the FFRF terminal signal processing software
- **Saab Space** (Göteborg, Sweden) for the S-band helix antennas
- an OXCO from **TES Electronic Systems,** of Bruz, France, is currently being qualified; an OXCO from **Composants Quartz et Electronique (Temex)**, Mougins, France is also being used.

Additional Resources

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

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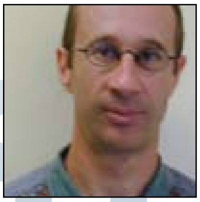
Authors

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 radio-navigation 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).

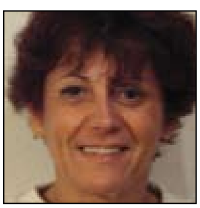


Eric Péragin is a TMTC expert in the CNES Transmission Techniques and Signal Processing Department having worked in this area for about 20 years. He designed the high performance Rx/Tx used on board the Myriade microsatellite family, also used for the intersatellite link of cometarian probes Rosetta (ESA/CNES/DLR) and Deep Impact (NASA). He was involved in the Martian Data Relay equipment 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 responsible of the intersatellite link of ROSETTA and RF expert for the FFRF equipment of PRISMA. He is also in charged of predevelopment activity for CNES's next generation of high performance TMTC susystems in S- and X-band for small platforms.

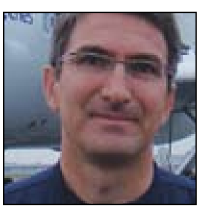
Laurent Lestarquit is a navigation signal expert at the CNES Transmission Technique and Signal

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 ALTBOC 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.



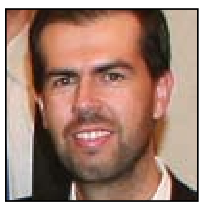
Jean-Luc Issler is in charge of the Transmission Techniques and Signal Processing Department at CNES. He is involved in the development of several types of GNSS, FFRF, and TMTC equipment in Europe for space or ground users. He is a French delegate to the GALILEO Signal Task Force. Issler received in 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.

Jean-Baptiste Thevenet was a doctoral and postdoctoral researcher in numerical optimization at ONERA and CNES for five years. He has been a navigation system engineer at Thales Alenia Space since early 2006, mostly in charge of system aspects for FFRF subsystems.

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 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 rendezvous and docking and on GPS and radio frequency-related technologies. He is actively involved in the FFRF metrology development and use for missions such as DARWIN, Mars Sample Return, PRISMA, and PROBA3. IG

REGIME CHANGE *continued from page 27*

Relations with China overall will pose a sizable and complex challenge to the new U.S. president. The security issues associated with GNSS technology make this a particular prickly subject. And the lack of transparency in China's Compass program, its effective control by the People's Liberation Army (China's defense establishment), and unexpected events such as China's January 2007 anti-satellite test (ASAT) have combined to limit face-to-face talks on the subject.

The constraints on bilateral approaches to China have made the success of the ICG thus far all the more important and noteworthy. Although the most recent ICG meeting in Pasadena, California, in early December marked the return of a more cautious mode, it probably reflected a desire to digest and sort out the surprising advances made in the previous meeting in Bangalore, India.

How far this internationalist impulse might carry GPS is yet to be determined. On the one hand, it might go as far as the joint secretariat established for the COSPAR/SARSAT with voluntary contributions to handle paperwork (glossary, terms of reference) and exchange information on system operations. On the other, it could remain a series of arm's length relationships that manage to reduce the inevitable conflicts that arise among systems operating in a common physical and technological space.

A New Regime

Overall, GPS is in a good place, with a sound foundation from the past eight years of work. But much of the current policy is designed for old situations and problems.

Management and advocacy of the system is divided in all ways: civil, military and within agencies. Markets and applications are exploding, underscoring the system's status as a critical infrastructure — as does the geopolitical situation. And competition from other GNSS providers is growing.

This is all a good thing — a critical infrastructure on solid footing, but a little behind the times, with competitors goading the U.S. leadership (so, it's not a good time to relax).

What is needed now is a new, strong advocate, a GPS/PNT champion who can connect the dots and make sure the Obama administration knows what's at stake.

The situation is a little like that at the beginning of the biblical Exodus story: "Now a new king arose over Egypt, who did not know Joseph."

Somebody's got to go tell the King. IG