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AUTONOMOUS FORMATION FLYING AT DLR'S GERMAN SPACE OPERATIONS CENTER (GSOC)

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ABSTRACT

In the upcoming years, significant changes in the profile of satellite missions are expected as scientists and managers want to benefit from multi-satellite missions. Among others, distributed or virtual satellite platforms will create a completely new class of space missions, where not one single spacecraft or payload segment has to be operated but a formation or constellation of satellites. A "formation" designates multiple satellites in close proximity and is typically characterized by demanding guidance, navigation and control requirements. In comparison to perform these tasks by a ground control approach, on-board autonomy can guarantee superior performance with respect to control accuracies and cost efficiency.

A dedicated research and development program on "Autonomous Spacecraft Navigation and Formation Flying" was initiated at DLR/GSOC in 1998. Numerous contributions in the area of space-borne GPS receiver technology, precision relative navigation and autonomous orbit control of satellite formations as a prerequisite for spacecraft autonomy have been made. Practical experience in the operations of a two-satellite formation has been gained by the GRACE mission. Next, GSOC is supporting Swedish Space Cooperation (SSC) in the implementation of the PRISMA formation flying demonstration mission, where a fully autonomous, robust and precise formation flying of spacecraft will be conducted by experiment. Finally, the German TerraSAR-X/TanDEM-X radar satellites will be Europe's first space mission equipped and operated routinely with an autonomous formation flying system.

1. INTRODUCTION

1.1 Autonomous Formation Flying – Motivation and Future Challenge

Spacecraft formation flying is considered as both a new class and a future enabling technology for advanced scientific and commercial applications in space. The distribution of functions and payloads among fleets of coordinated smaller satellites offers the possibility to overcome the classical limitations of a monolithic system: First, the science return is enhanced through observations made with larger, configurable baselines. Second, a highly improved degree of redundancy within the space segment is guaranteed in the event of failures.

Satellites can be flown in a formation either by ground control or in autonomous spacecraft mode. In the first case guidance, navigation and control tasks are primarily performed on-ground with tight constraints in terms of ground-station visibility. This introduces severe limitations on the achievable control accuracies, and does not consent an optimum usage of on-board resources. On the contrary on-board autonomy guarantees superior performance and prompt response to contingencies. The continuously increasing demand of spatial and temporal resolution for aperture synthesis and the required imaging performances for novel missions can only be satisfied by space-borne autonomous formation flying systems. Furthermore, the costs of mission operations can be drastically reduced by a harmonic coordination of on-board and on-ground activities.

Despite evident technology needs and promising theoretical studies, nowadays autonomous formation flying is mostly confined to laboratory research. The reason for such a gap is that the benefits of satellites flying in formation come at a cost. The new systems architecture poses challenges in the areas of on-board sensing and actuation, high-level mission management and planning, as well as distributed fault detection, isolation and recovery.

However, previous mission failures and terminations decrease the level of confidence in multi-satellite systems. Examples include NASA's Demonstration of Autonomous Rendezvous Technology (DART) mission in 2005, which ended in an unintentional collision with the target satellite, and the U.S. Air Force TechSat-21 formation flying experiment in 2005, which was terminated due to technical issues "far more challenging than originally thought". This experience indicates clearly the necessity of precursor technology demonstration missions for autonomous rendezvous, proximity operations and formation flying.

Table 1. Development lines for satellite formation flying missions over the next decades.

Applications	SAR Interferometer and Gravimeter	Dual Spacecraft Telescope	Multi Spacecraft Telescope
Time line	2009	2017	2020
Orbit	Low Earth Orbit	High Earth Orbit (or Lagrange Point)	Lagrange Point (or High Earth Orbit)
Number of satellites	2-4	2	$\geq$3
Typical separation	50-1000 m	30-100 m	50-500 m
Orbit control accuracy	10-100 m	0.1-10 cm	~1 mm
Navigation accuracy	1-10 m (1 mm post-facto)	0.01-1 cm	1-100 μm
Examples	TanDEM-X, Cartwheel	XRO, SIMBOL-X	DARWIN, PEGASE, TPF

1.2 Applications and Development Lines

Three main development lines can be identified in the frame of spacecraft formation flying. As shown in Table 1 the mission concepts are characterized by an increasing level of complexity, mainly dictated by the payload metrology and actuation needs. Synthetic Aperture Radar (SAR) interferometers and gravimeters are placed at the beginning of the time scale and are natural precursors of the more advanced virtual telescopes. The objective of these Low Earth Orbit (LEO) instruments is to respond to the demand of highly accurate Digital Elevation Models (DEM) and Earth's gravity models on a global space and time scale. Two or more satellites of identical type and construction are flown at typical separations of a few kilometers to synthesize three-dimensional baselines that can be reconfigured during the mission lifetime. The relative orbit control accuracy required for such formations is relatively low (~100 m) and drives the need for real-time on-board relative navigation accuracies at the meter level. A specific challenge for these kinds of missions is the need of high precision (sub-) millimeter post-facto reconstruction of the three-dimensional relative motion. A key example of a dual spacecraft SAR interferometer with such formation metrology requirements is given by the German TanDEM-X mission. Two identical spacecraft, namely TerraSAR-X (launched in June 2007) and TanDEM-X (launch expected two years later in 2009) fly in a precisely controlled formation to build a radar interferometer with typical baselines of ~1 km. This allows a much higher resolution than achieved in the X-SAR/SRTM Shuttle Topography mission and thus enters a new generation of DEMs with unrivaled accuracy.

At the same time, future gravity field satellite missions are being discussed to overcome the intrinsic limitations of gravimeters like CHAMP, GRACE and GOCE. The GRACE geodetic observables, for example, are inherently non-isotropic, due to the permanent along-track orientation of the laser link and to its scalar character. In order to enhance the spectral content, future geodetic satellite missions would like to make use of autonomous formation flying concepts with multiple baselines (i.e. Cartwheel concepts).

For LEO formation flying applications, the usage of Global Navigation Satellite Systems (GNSS) poses an attractive alternative to other relative navigation sensors (e.g. optical metrology or radar) in terms of accuracy, robustness, flexibility, and acquisition cost. With the continuous advancement in microelectronic engineering, the size and power consumption of GNSS receivers will further reduce, which makes them a perfect candidate for operation in micro-satellite and nano-satellite buses. GNSS systems provide highly accurate timing information for on-board time synchronization, enable simultaneous measurements from spacecraft within a formation and offer the required level of accuracy in the context of carrier-phase differential GNSS (CDGNSS) techniques.

Dual spacecraft telescopes represent the second relevant class of future formation flying applications. These instruments aim at the detailed spectral investigation of sources which are too faint for study with the current generation of observatories (e.g. Chandra, XMM-Newton). The typical mission profile seeks orbits characterized by 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 optimum conditions are offered by Geostationary Orbits (GEO), Highly Elliptical Orbits (HEO) and Halo orbits around the libration points of the Sun-Earth system. Distributed telescopes are composite spacecraft composed of a detector and a mirror unit flying as a formation during science operations. Typical separations aim at focal lengths of the order of 30-100 m. Autonomous formation flying capabilities are driven by the telescope optical design and should allow un-interrupted science observations. This translates into combined attitude & orbit control systems with required navigation accuracies at (sub-) centimeter level. The technological gap that exists between remote sensing LEO formations and outer space distributed telescopes is evident. It is not only given by the envisaged three-order-of-magnitude improvement of the required metrology and actuation needs, but is mainly caused by the necessity of implementing 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 GEO (~5 cm) and HEO (~30 cm) at radial distances up to 17 $R_{\oplus}$. Only self-contained relative (inter-satellite) navigation sensors (i.e. radio frequency and optical) can fulfill the requirements of autonomous formation flying at even higher altitudes.

The X-Ray Observatory (XRO), also known as XEUS (X-Ray Evolving-Universe Spectroscopy), is a relevant example of a dual spacecraft telescope. One of the main science goals of XRO is to investigate the high-red-shift universe. The current mission scenario is based on a Halo orbit around L2 and a composite spacecraft with a focal length of 35 m. The detector satellite is designed to support the payload units and track the focus point of the mirror satellite as to maintain it at the instrument focal plane. The launch of both units as a single stack is planned at the end of 2017, with nominal operations extending until the end of 2022.

Table 2. Formation flying metrology technologies and related inter-satellite navigation accuracies.

Metrology technology	Navigation accuracy	Comments
GNSS	m - cm	Limited to orbit altitude < GEO Primarily suited for LEO
Radio frequency	m - cm	Same measurement and technology principles as GNSS
Optical sensors	mm - µm	-
Laser metrology	µm - nm	-

The ultimate accuracy in terms of formation flying metrology and actuation is required for the successful deployment and operations of the third set of applications depicted in Table 1. Interferometry in the infrared and visible wavelength regions has been identified as the key technology to new astrophysical discoveries and to the direct search for terrestrial exoplanets. To that purpose, clusters of three or more units need to fly in millimeter precision close formations with inter-satellite navigation accuracies at the sub-millimeter level. As shown in Table 2, only optical sensors and laser interferometers can provide the required formation flying metrology performances. Examples of these types of missions are given in Europe by the infrared space interferometers DARWIN and PEGASE and in USA by the NASA's Terrestrial Planet Finder (TPF).

1.3 DLR/GSOC Mission Statement and Goals

Research and Development (R&D) activities within DLR/GSOC are concentrated in the GNSS Technology and Navigation Division as part of the Space Flight Technology Department. The goal of these activities is to respond to the increasing demands in scientific, technological and commercial applications of space assets and ultimately provide enabling technologies for novel mission concepts.

The focus of the activities lies in the following three areas:

1. Development, test and in-flight validation of space-borne GNSS receivers.
2. Guidance, navigation and control techniques for multi-satellite missions.
3. High precision low latency navigation services for space systems.

Evidently the research and development in the framework of autonomous formation flying, and in particular formation flying metrology, require a high level of synergy between the aforementioned disciplines. Advances in satellite technology allow for increased autonomy and give the possibility to transfer tasks to the spacecraft which are traditionally performed on-ground (e.g. orbit navigation and control).

Formation flying metrology at DLR/GSOC has been based so far on the Global Positioning System (GPS). As detailed in the next sections, this has given the possibility to acquire know-how and expertise on the topology of formation flying missions linked to SAR interferometry and Earth's gravimetry. In addition to their inborn scientific and commercial value, these LEO missions are considered as a fundamental milestone for the in-orbit validation of proximity operations and formation flying technologies. In view of the increasing need for inter-satellite navigation, the research at DLR/GSOC has focused on the development of real-time navigation systems using representative space hardware and supporting multi-spacecraft operations in a fully scalable manner. On the other hand, highly accurate post-facto relative spacecraft positioning using GPS has demonstrated millimeter level accuracies at large inter-satellite separations using data from the GRACE mission.

Meanwhile, DLR/GSOC is following the advent of the European global navigation satellite system Galileo and the upcoming upgrades of the GPS constellation (e.g. L2C frequency) with great technical and political interest. These advances are opening new possibilities in the area of absolute and relative navigation, with the envisaged improvement of integrity, robustness and availability of global navigation signals. The integration of Galileo into the R&D activities is undergoing and represents a fundamental step in order to provide affordable durative access to advanced GNSS technology for space missions.

As identified in the previous section, formation flying metrology has to overcome the altitude limits imposed by the GNSS constellations. To that end, activities are currently expanding into the area of relative navigation based on radio frequency sensors. These sensors reproduce locally a GNSS-like signal system and are consequently self-contained. The possibility to make maximum re-use of available GPS hardware technology and navigation algorithms renders Formation Flying Radio Frequency (FFRF) the best candidate for future research at DLR/GSOC.

2. FORMATION FLYING TECHNOLOGY OVERVIEW

2.1 GNSS Based Relative Navigation

2.1.1 Simple Relative Navigation in the GPS Orion Receiver

Ref. [1] presents the concept and prototype implementation of a space-borne relative navigation sensor based on a pair of GPS receivers. It employs two individual receivers exchanging raw measurements via a dedicated serial data link (Figure 1). Besides computing their own navigation solution, the receivers process single difference measurements to obtain their mutual relative state. The differential processing provides a high level of common error cancellation while the resulting noise is minimized by appropriate use of carrier phase measurements. A prototype relative navigation sensor making use of the above concepts has been built up based on the GPS Orion 12 channel L1 receiver and qualified in hardware-in-the-loop tests using a GPS signal simulator. It provides a relative navigation solution with representative r.m.s. accuracies of 0.5 m and 1 cm/s, respectively, for position and

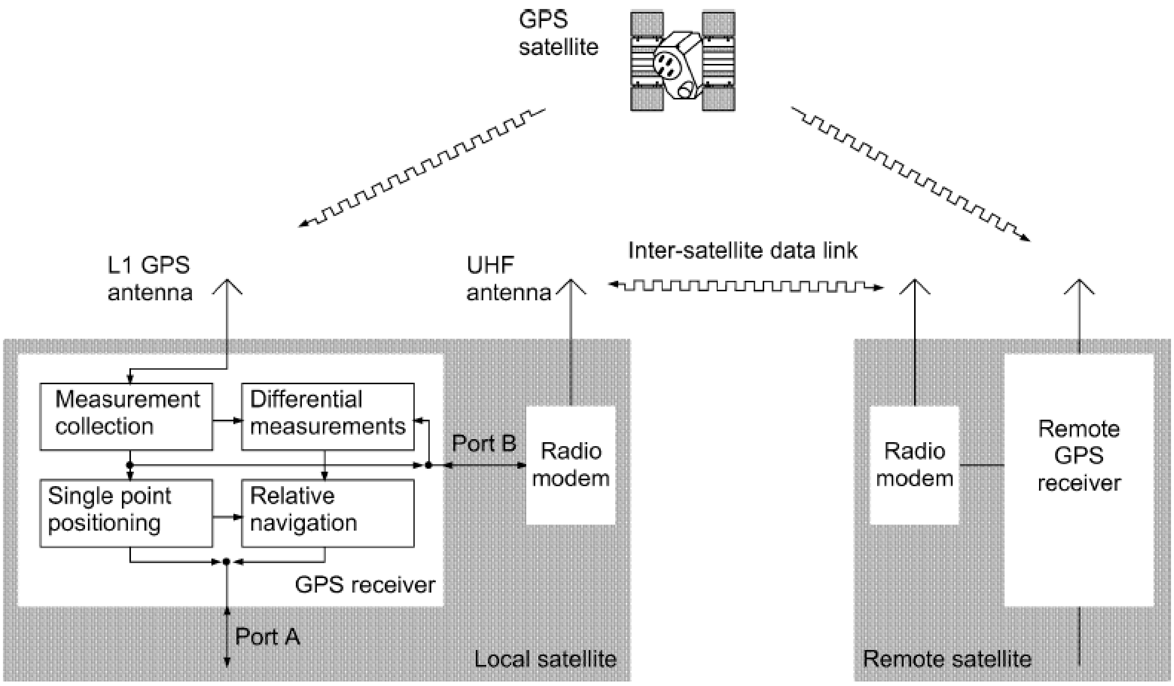

Figure 1. Conceptual design of a twin GPS receiver system for real-time kinematic relative navigation of two spacecraft. From [1].

velocity. For ease of use the relative state is provided in a co-moving frame aligned with the radial, cross-track and along-track direction. The purely kinematic nature of state estimation and the small latency make the system well suited for maneuvering spacecraft, while the minimalist hardware requirements facilitate its use on micro-satellite formations.

2.1.2 Hardware-in-the-loop Formation Flying Test Bed

Ref. [2] describes the design and prototype implementation of a navigation system that enables high-precision relative navigation of multiple formation-flying satellites in real time using representative space hardware. A fully decentralized system design has been adopted, in which each spacecraft is equipped with its own single-frequency GPS receiver and navigation computer (Figure 2). A continuous exchange of raw measurements between any two satellites in the formation is achieved through a communication architecture using multi-channel radio modems operated in a time-multiplexed manner. Multiple Kalman Filters running concurrently on each navigation computer provide estimates of both the local spacecraft's absolute state vector and the relative state vectors of all remote satellites in the formation. Using GPS signals generated by a signal simulator, the proper operation of the navigation process and the communication architecture has been validated in a realistic environment at ESA/ESTEC's navigation laboratory. Here, real-time relative navigation could for the first time be demonstrated for a formation of up to four spacecraft with an accuracy of 1.5 mm (position) and 5 μm/s (velocity) over a 4-km baseline.

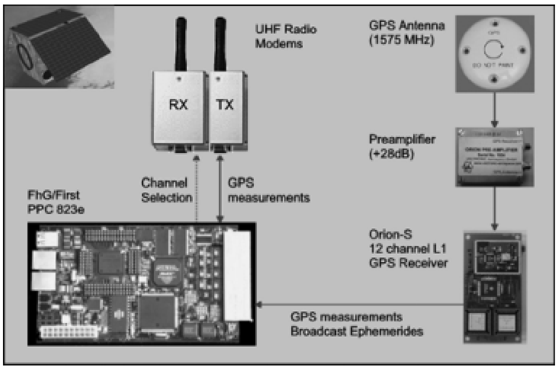

Figure 2. Hardware components employed in the prototype implementation of the real-time navigation system. Each of the 4 satellites in the formation is assumed to carry the same (or compatible) equipment. From [2].

2.1.3 High Precision Relative Navigation using Dual-Frequency GNSS

Ref. [3] demonstrates the feasibility of purely kinematic, high-precision relative navigation of formation flying spacecraft using dual-frequency GPS measurements. The best possible navigation results are obtained by applying the Least Squares Ambiguity Decorrelation Adjustment (LAMBDA) method to the estimation of the double difference carrier

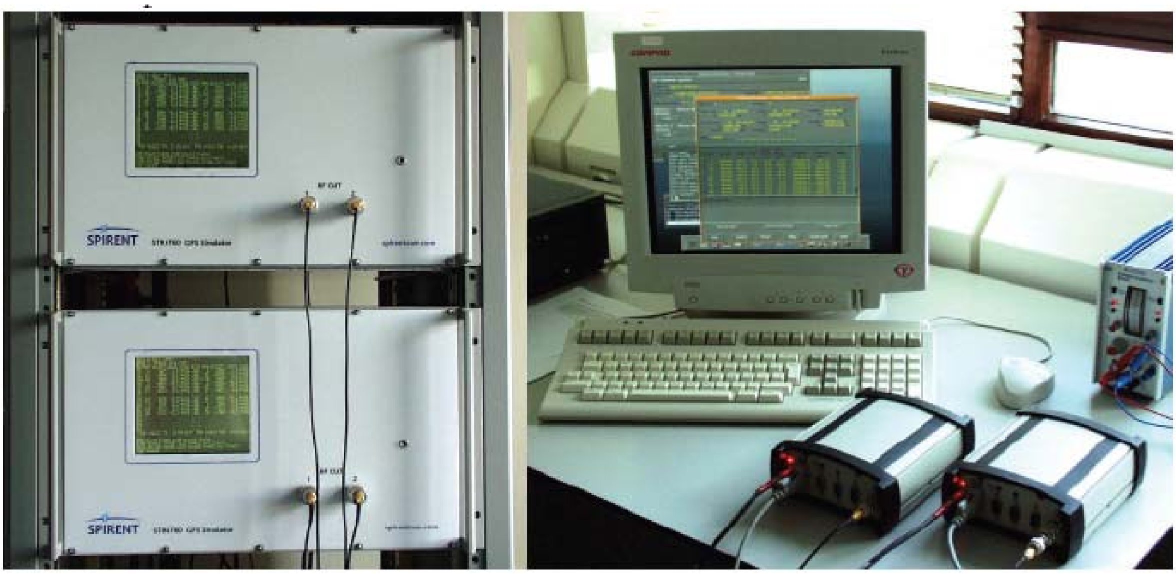

Figure 3. Formation flying test bed at ESA/ESTEC comprising (left) a 2x24-channel GPS signal simulator with control workstation and (right) two GPS receivers modified for use at high altitudes and orbital velocities. From [3].

phase ambiguities. Integer ambiguities of the L1/L2 carrier phase can be resolved within several minutes for baseline lengths of 10-100 kilometers. The subsequent relative position fixes exhibit a typical 3D accuracy of 3-5 millimeters that is essentially limited by the carrier-phase noise (around 1 millimeter) and the Position Dilution of Precision (PDOP) value (1 to 3). The method is tested with true measurements for various orbital scenarios. GPS data for these tests are obtained from hardware simulations with two dual-frequency GPS receivers and a 48 channel GPS signal simulator at the European Space Agency's (ESA), European Space Research and Technology Centre (ESTEC) in Noordwijk in The Netherlands (Figure 3).

2.2 Qualification testing of Dual-Frequency Receivers

As shown in Ref. [4], detailed performance analyses of semi-codeless dual-frequency GPS receivers for use in Low Earth Orbit (LEO) has been performed at DLR/GSOC over the past years. Qualification testing capabilities are available for different types of receivers including flight-proven hardware (e.g. IGOR receiver) as well as geodetic receivers entirely based on commercial-off-the-shelf technology (e.g. COTS receivers like NovAtel OEM4-G2 and Septentrio PolaRx2, Figure 4). Using extensive signal simulator tests, the cold start signal acquisition, tracking sensitivity, differential code biases, raw measurement accuracy and navigation accuracy of receivers are assessed. Tests are based on scenarios which are representative of actual space missions and provide the realistic simulation of the signal dynamics and quality on scientific LEO satellites. Given the limited resource requirements of nowadays GNSS receiver development, the capability of extensive and systematic testing is the key for precise orbit determination applications and ionospheric sounding onboard micro-satellites with tight mission budgets. Furthermore the developed test strategies provide a guideline for future analysis and serve as a basis for an extended comparison of space-borne GPS receivers. The results contribute to an optimal utilization of GNSS receivers for high-precision relative navigation in LEO formation flying missions as well as to the implementation of low-cost relative navigation sensors for university-class missions.

3. DEMONSTRATION MISSIONS

3.1 GRACE

The GRACE mission, operated at GSOC since 2002, consists of two identical formation-flying spacecraft (S/C) in a near-polar near-circular orbit with an initial altitude of approximately 500 km. The spacecraft have a nominal separation of 220 km. The primary mission objective is to measure the time varying changes in the Earth's gravity field, which is accomplished by the mission's key instrument, the K-Band Ranging System (KBR). This instrument measures the change in distance (biased range) between both S/C, which is a measure for the change in gravity, within a precision of 10 μm. Both S/C are equipped with a BlackJack

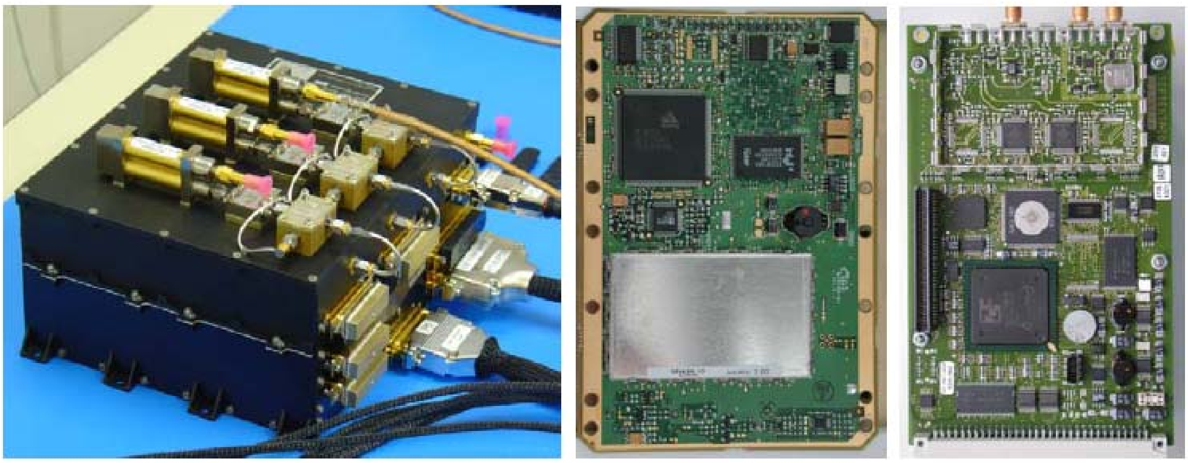

Figure 4. Test receivers: IGOR, NovAtel OEM4-G2, and Septentrio PolaRx2 (left to right; note different scales). From [4].

GPS receiver and instrument processing unit (IPU), which processes the Star Camera and KBR signals in addition to making the usual GPS observations (Figure 5). Frequency generation for both the KBR (24 and 32 GHz) and GPS (1.2 and 1.6 GHz) reference signals is done by an Ultra Stable Oscillator (USO). KBR observations can be used to independently validate the along-track component of the relative S/C position computed by solely using GPS observations.

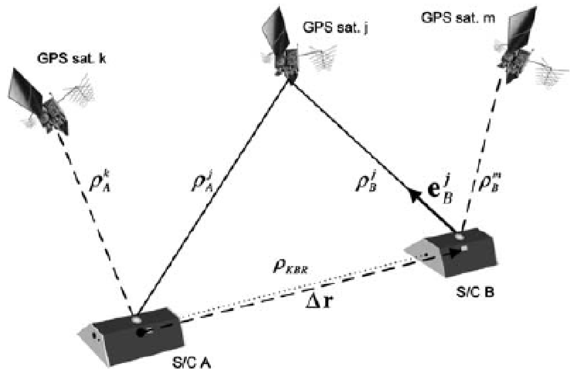

Figure 5. Viewing geometry for the formation-flying GRACE spacecraft (S/C A and B). From [5].

Although kinematic relative positioning techniques demonstrate promising results for hardware-in-the-loop simulations [2], they were found to lack an adequate robustness in real-world applications. To overcome this limitation, an extended Kalman Filter modeling the relative spacecraft dynamics has been developed [5]. The filter processes single difference GPS pseudo-range and carrier phase observations to estimate the relative position and velocity along with empirical accelerations and carrier phase ambiguities. In parallel, double difference carrier phase ambiguities are resolved on both frequencies using the Least Squares Ambiguity Decorrelation Adjustment (LAMBDA) method in order to fully exploit the inherent measurement accuracy. The combination of reduced dynamic filtering with the LAMBDA method results in smooth relative position estimates as well as fast and reliable ambiguity resolution. The method has been validated with real data from the GRACE mission. For an 11-day data arc, the resulting solution matches the GRACE K-Band Ranging System measurements with an accuracy of 1 mm, whereby 83% of the double difference ambiguities are resolved. The highly accurate results obtained for the relative position between both GRACE spacecraft proves that the implemented processing scheme works for real-world formation flying S/C applications. The implementation of the relative dynamics significantly helps to filter out the measurement noise and other small errors, still present in the kinematic solution. It is furthermore a key element for successful integer double difference ambiguity resolution.

3.2 PRISMA

PRISMA comprises a fully maneuverable micro-satellite (MAIN) as well as a smaller sub-satellite (TARGET) that will be released from MAIN after initial commissioning. The mission schedule foresees a launch in 2009 of the two spacecraft into a Low Earth Orbit with a targeted lifetime of at least eight months. The PRISMA mission objective is to demonstrate in-flight technology experiments related to autonomous formation flying, homing and rendezvous scenarios, precision close range 3D proximity operations, soft and smooth final approach and recede maneuvers, as well as to test instruments and unit developments related to formation flying. In four major areas DLR/GSOC provides contributions to the PRISMA mission. These comprise the GPS system hardware for both spacecraft (Figure 6), a GPS based navigation system software to support formation flying during all phases, dedicated experiments for relative and absolute orbit control as well as an on-ground automated Precise Orbit Determination (POD) for off-line verification purposes.

One of the main challenges of the PRISMA formation flying is the realization of an on-board navigation system for all mission phases which is robust and accurate even for various spacecraft orientations and frequent thruster firing for orbit control. The requirements for the GPS-based PRISMA real-time navigation software represent the key drivers for the design of the system. The goal of the absolute and relative orbit determination is to achieve an accuracy of 2 m and 0.1 m, respectively (3D, r.m.s.) and to provide continuous position and velocity data of the participating spacecraft at a 1 Hz rate for guidance and control purposes as well as for the PRISMA payload. As detailed in [6], [7] and [8], this is achieved by two software cores residing in the MAIN on-board computer. The two cores are executed at 30 s and 1 s sample times to separate the computational intensive orbit determination task from orbit prediction functions with low computational burden. An extended Kalman Filter has been developed which processes pseudo-range and carrier-phase measurement data issued by the local Phoenix GPS receiver on MAIN and sent via an Inter Satellite Link (ISL) from the remote Phoenix GPS receiver on TARGET. The filter concept applies an ionosphere-free linear combination of pseudo-range and carrier-phase data known as GRAPHIC (Group and Phase Ionospheric Correction) to estimate the absolute orbits and use single-difference carrier-phase measurements to implicitly determine the relative orbit with utmost precision. The originality of the design stems from the fact that only the absolute spacecraft states are explicitly estimated by the reduced-dynamic 49-dimension Kalman Filter. The accurate raw carrier-phase measurements are differenced among common visible GPS satellites and used, when available, to enhance the information about the relative states of MAIN and TARGET.

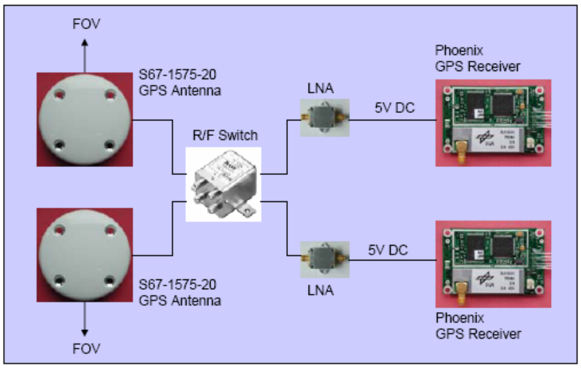

Figure 6. PRISMA Phoenix GPS system on MAIN and TARGET. From [7].

The inherent robustness of the symmetric filter design originates from the fact that common GPS satellites visibility is not a prerequisite to reconstruct the relative state. Even in the case of spacecraft with completely different attitude, the relative state can be determined by simply differencing absolute estimates exclusively based on GRAPHIC data types. As shown in [7], the unified filter design simplifies the initialization and the maneuver handling procedures, and, consequently, improves the flexibility of the navigation system and its reliability during the formation flying experiments. The testing of the navigation flight software is performed on a real-time embedded processor representative of the PRISMA onboard computer.

3.3 TanDEM-X

TerraSAR-X (TSX) is an advanced SAR-satellite system for scientific and commercial applications, which is realized in a Public-Private Partnership (PPP) between DLR and Astrium GmbH. The satellite has a size of 5 m x 2.4 m, a mass of 1341 kg and carries a high-resolution Synthetic Aperture Radar (SAR) operating in the X-band (9.65 GHz). A Russian DNEPR-1 rocket launched from Baikonur, Kazakhstan, has injected TerraSAR-X into a 514 km sun synchronous dusk-dawn orbit with 97° inclination and an 11 day repeat period. TerraSAR-X is planned to be operated for a period of 5 years and will therefore provide SAR-data on a long-term, operational basis. DLR/GSOC will provide the Mission Operations Segment (MOS) using ground stations at Weilheim and Neustrelitz. As a complement to TSX, the TanDEM-X (TDX) mission is under development in the frame of new Earth observation missions within the German national space program (Figure 7). It involves a second spacecraft, which is almost identical to TerraSAR-X and shall likewise be operated for 5 years. The two spacecraft will fly in a precisely controlled formation to form a radar interferometer with typical baselines of 1 km.

TanDEM-X will be equipped with an Autonomous Formation Flying (TAFF) system developed at DLR/GSOC. This offers a unique chance to both enhance and intensify the knowledge and experience in the area of formation flying. Furthermore, the implementation of autonomous formation flying functionalities on the TDX spacecraft is considered to be a key driver for a more efficient use of the available on-board resources. The objective of TAFF is to enable a simple and robust formation control in order to ease on-ground operations. To achieve this goal dedicated functions for formation guidance, navigation and control will be implemented onboard TanDEM-X. Navigation will employ GPS data from the Mosaic GNSS receivers on-board TanDEM-X and TerraSAR-X. TSX GPS data will be provided through a dedicated S-Band inter-satellite link (ISL). Instead of raw code and phase measurements, TAFF will make use of the dynamically filtered GPS navigation solutions. These are differenced and then processed in a Kalman Filter employing a Hill-Clohessy-Wiltshire dynamical model of the relative motion. The

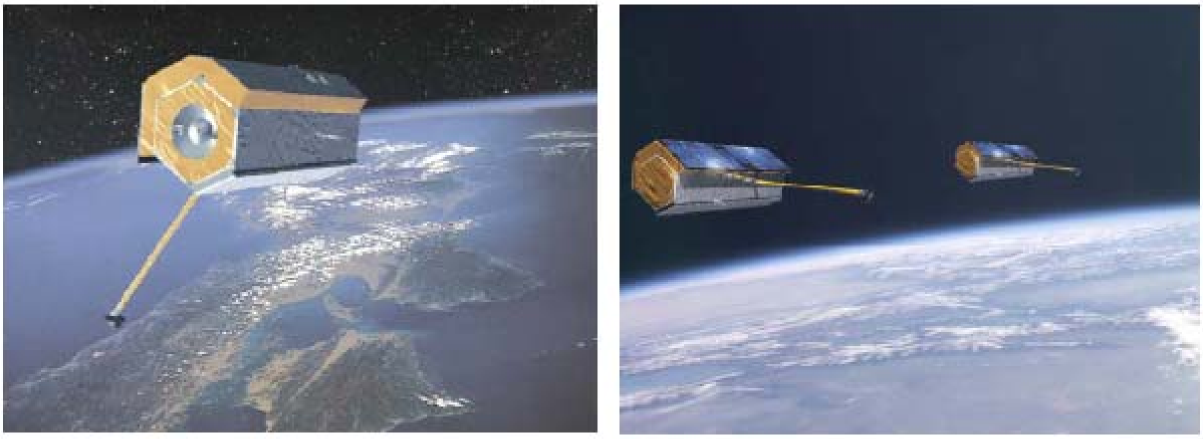

Figure 7. The TerraSAR-X spacecraft (left) and the TerraSAR-X/TanDEM-X formation (right). Courtesy of EADS Astrium.

robustness of the formation control will be achieved by guidance and control functions which are based on the separation of relative eccentricity and inclination vectors. This allows a robust formation configuration with minimum collision risk [9], [10].

TerraSAR-X/TanDEM-X will furthermore be the first operational mission requiring a post-facto baseline reconstruction with an accuracy of 1 mm. The feasibility of achieving this goal using GPS dual-frequency measurements of the IGOR GPS receiver has earlier been demonstrated in the GRACE mission. The respective algorithms will further be refined and adapted to benefit from the short separation of the two spacecraft, which would even allow a single-frequency integer ambiguity resolution. Furthermore, the impact of phase pattern variations will be addressed through dedicated calibration campaigns of the antenna system.

4. FUTURE ACTIVITIES

Future activities at DLR/GSOC in the frame of autonomous formation flying will focus on three main topics:

1. Formation Flying Radio Frequency (FFRF) sensor analysis.
2. Combined orbit and attitude control of formation flying spacecraft.
3. Robotic and in-orbit servicing missions.

FFRF offers integrated functionalities like three-dimensional localization, inter-satellite link and multi-satellite synchronization at typical separations between 3 m and 30 km. The adopted GNSS-like metrology provides observables like range and range rate, line-of-sight (LOS) and LOS rate, pseudo code and phase measurements with overall performances at 1 cm level (relative positioning) and 1° (relative orientation) on the line of sight axis. These characteristics make FFRF a perfect candidate for future outer space distributed telescopes. The comparison of GNSS-based relative navigation with results obtained from self-contained formation flying metrology sensors like FFRF is extremely valuable for the validation of these novel technologies. To assist the validation of the FFRF sensor in the PRISMA mission, SSC, CNES and DLR have agreed on a mutual exchange of GPS and FFRF data in that mission.

In order to enable advanced formation flying missions, the tasks of orbit and attitude determination and control should be studied as a single combined problem. Research at DLR/GSOC will focus on the coupling between orbit and attitude dynamics and on combinations of various measurement types issued by navigation devices (e.g. GNSS, FFRF) and attitude sensors (e.g. Star trackers). Decentralized formation control efforts will be studied, using modern control theory to provide optimal orbit/attitude formation control with minimal information passage between the individual spacecraft.

Formation flying radio frequency, optical metrology and combined orbit/attitude control represent the key technical challenges to precise and reliable in-orbit servicing or inspection missions. To assist pre-flight simulations of such complex technologies, the build-up of a new robotic simulator for proximity operations is currently considered by DLR. If implemented, it would provide a follow-on to the presently operated European Proximity Operations Simulator (EPOS) facility and provide a valuable test-bed for future LEO and GEO servicing missions.

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