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One Year of In-Flight Results from the Prisma Formation Flying Demonstration Mission

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ABSTRACT

The Prisma smallsat in-orbit test-bed was launched on the 15th of June, 2010 to demonstrate strategies and technologies for formation flying and rendezvous. The mission consists of two spacecraft: Mango and Tango. Mango is 3-axis stabilized and is equipped with a propulsion system providing full 3D orbit control capability. Tango has a simplified solar magnetic control system and does not have any orbit control capability. The two spacecraft were launched clamped together into a 720/780 km altitude sun synchronous dawn-dusk orbit, and later separated in August of 2010. Since then, the two spacecraft, and rather lean operations team, have been performing a steady march through a tight mission and experiment timeline.

This paper gives an overview of the Prisma mission in general and will focus on the lessons that have been learned from running a relatively intense, yet lean, small satellite technology demonstration mission. It has proven to show the value of autonomy and small platform applications, allowing for a high return on effort.

Spacecraft autonomy and small, highly competent teams have allowed for quick and cost effective adaptations to changes and problem situations. The broad range of flight results from only one year in operation support these conclusions.

INTRODUCTION

The Prisma mission is a technology demonstration mission with the primary purpose of demonstrating formation flying and rendezvous technology, both in terms of Guidance, Navigation and Control (GNC) software and algorithms, but also in terms of new instruments and operational aspects.

Prisma consists of two spacecraft: Mango and Tango. Both spacecraft are 3-axis stabilized where Mango uses a traditional star-tracker / reaction wheel based control system, while Tango implements solar magnetic stabilization strategy[1]. Mango is equipped with full 3D orbit control capability while Tango does not have any means of controlling its orbit, acting as a rendezvous target for Mango. The mission also acts as a demonstration flight for several other key technologies and developments at OHB Sweden and SSC, of which the new "High Performance Green Propellant" propulsion system is the most important.

OHB Sweden is the prime contractor for the project which is funded by the Swedish National Space Board (SNSB) with additional support from the German Aerospace Center (DLR), the French National Space Center (CNES) and the Technical University of Denmark (DTU).

MISSION DESCRIPTION

Demonstration and timeline

The figure below is a summary of the space segment hardware that constitutes the Prisma mission.

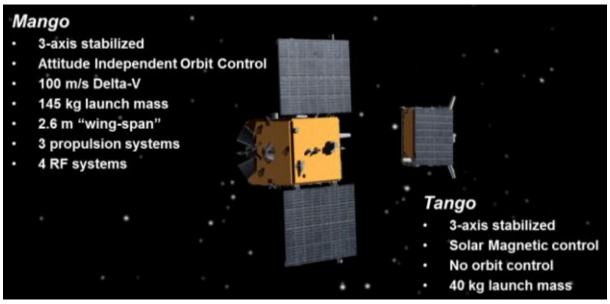

Figure 1, Prisma space segment summary

The above space segment hardware is thus intended to support the defined mission to demonstrate formation flight and rendezvous, whilst also providing "first flight" opportunities for a number of new sensor and actuator technologies. Thus demonstrations can be divided in to GNC Experiments and Hardware Tests.

The two tables below list all of the intended GNC and hardware demonstrations.

GNC Experiment Demonstrations	
Passive formation flying	
Autonomous formation flying (AFF)	OHB Sweden
Autonomous formation control (AFC)	DLR
RF-based formation flying	CNES
Forced motion	
Proximity Operations (PROX) Final Approach and Recede (FARM)	OHB Sweden
Forced RF-based motion Collision avoidance	CNES
Autonomous Rendezvous (ARV)	OHB Sweden

Table 1, GNC experiments and responsible organization[2]

Hardware Flight Demonstrations	
HPGP Motor Tests	ECAPS
Microthruster Motor Tests	Nanospace
Relative GPS receivers	DLR
Vision Based Sensor (VBS)	DTU
RF Sensor Tests	CNES
LEON-3 on-board processor	OHB Sweden
PRIMA MEMs mass analyzer	IRF
Digital Video System	Techno Systems

Table 2, H/W experiments and responsible organization[2]

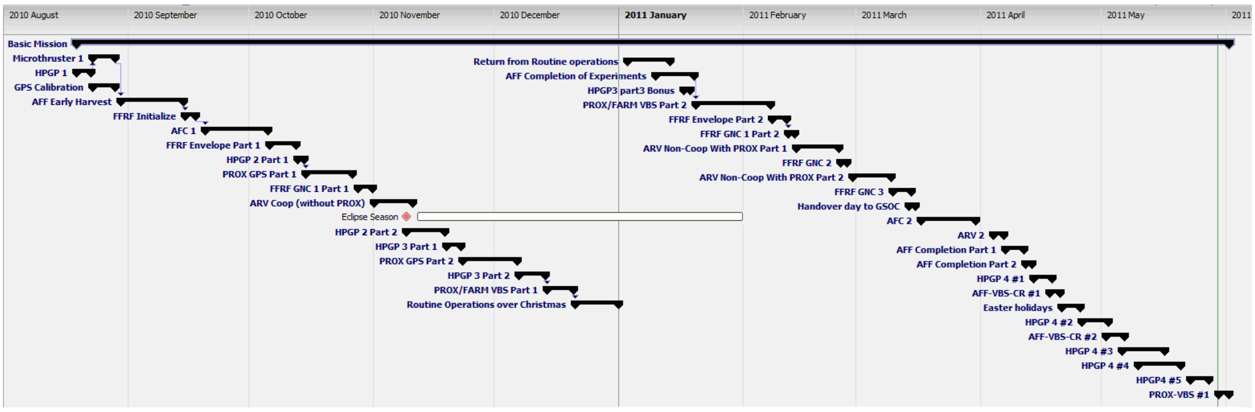

Figure 2, Basic mission timeline, from Mango/Tango separation

Every row in the above timeline represents an allocated experiment slot and within these slots there may also exist secondary ("passenger") experiments that are not shown. The result is that between each experiment, there is a handover involving a required experiment validation, post-condition, and pre-condition. Due to the short ten-month mission time, a high degree of responsiveness has been required from both mission control as well as the experimenters themselves.

With the exception of a few +/-days, the project has followed the timeline as originally planned.

Operational Concept

The original plan for operations planning was to utilize two control centers: one Operational Control Center in Kiruna, Sweden, where command operators would be stationed, and one Mission Control Center (MCC) in Stockholm, where mission experts would plan and lead the mission. Early operational rehearsals showed that many of the mission phases would be difficult using this approach as communication between the operator and mission control proved too slow and too easily misunderstood over voice only contact. This led to a restructuring of the concept, where the operator was also moved to the MCC.

The operations team was built using almost exclusively engineers with significant experience from the development and test phases of the satellites. This approach meant that little focus on platform training had to be done during preparations and more time could be used for pure operational training.

The team is split into three separate functions: Operator, GNC expert and Flight director. Their responsibilities are as shown in the table below.

Role	Responsibilities
Operator	− Commanding − Data archiving
GNC Expert	− Attitude and Orbit control − Experiment validation & support
Flight Director	− Passage planning − Platform monitoring − Anomaly handling

Table 3, Operational team responsibilities

During the LEOP and commissioning phases of the mission 3-shift operations was used to perform the platform checkouts in a rapid fashion. When going into the basic mission after Tango separation, operations were reduced to only two shifts as from that point most experiments were closed-loop and less active commanding had to occur.

Prior to launch an agreement was made with DLR GSOC to transfer operations to Munich for part of the extended mission when a large part of the DLR experiments were to take place. In preparation for this MCC was cloned at GSOC and training of the DLR operations team was performed in the Stockholm control room where DLR engineers took the role of operators for hands-on training to learn about both the platform and the operational concept employed during the mission.

For the basic mission only one ground station was used (Kiruna), leading to operations during night-time due to the dawn-dusk orbit of Prisma. After operations handover to GSOC a further two ground stations were qualified for use, Weilheim in Germany and Inuvik in Canada. With 3 stations available operations could be moved to daytime, significantly reducing the load on the operations team.

External experiments have been provided with on-site facilities to access real-time data to be able to gauge the progress of their experiments as they are being executed. Data is also delivered to an external data-store, accessible over the internet, with data typically being available within 1 hour from being downloaded from the spacecraft if the experimenter wants to monitor remotely.

The ground segment in MCC has been based on the in-house developed RAMSES[3] mutli-satellite control system, augmented by additional tools developed in Matlab.

The same ground segment has been used throughout the development and testing phases of the Prisma satellites, with development of RAMSES occurring in parallel. This has meant that the maturity of the ground segment has grown alongside the space segment, with new features being added as they have been needed.

RAMSES has been developed to allow ease of configuration in the operations environment. All applications run on standard Windows PCs, connected to a local area network. This has meant that applications can easily be moved from one computer to another and inserting additional computers into the operational environment has been very simple as need has arisen.

Experiment process

With so many different kinds of experiments, most of which affect the orbit of Mango, it has been necessary to establish a validation process for the experiments. An overview of this process can be seen in figure 3. This process relies heavily on the use of simulations of the experiments to be able to predict the result and to ascertain that the planned maneuvers do not risk the safety of the constellation.

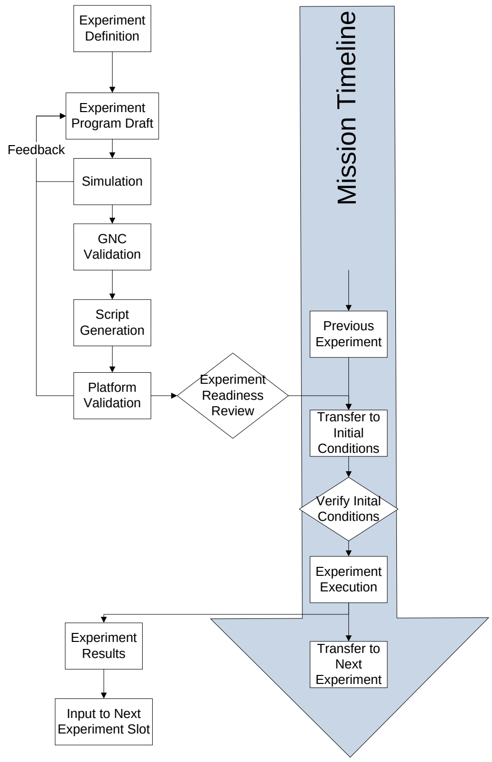

Figure 3, Experiment process

Close cooperation between experimenters and the Prisma GNC experts has been employed since well before launch. This is especially true for those partners (CNES & DLR) who provide separate GNC modes for use in closed-loop formation flying.

The simulator, SATSIM[4], is an advanced, multi-satellite simulator capable of running either all-soft, faster than real-time, or with hardware in the loop at real-time execution. This simulator has been used extensively throughout the entire development and test phase of Prisma, as well as for operational training and flight procedure validation.

All experiments affecting either orbit or attitude of either spacecraft are run through the all-soft version of SATSIM, with the result being analyzed by both the experimenter and GNC experts. This is then iterated several times until the experimenter is satisfied and the time of the experiment execution is drawing close.

The experiments are specified in XML-format, containing lists of commands and static procedures. Once the GNC validation is complete the XML is translated to PLUTO-scripts, which can be sent to the spacecraft. Before execution the scripts are validated for syntax and command verification by uploading them to the real-time simulator, which contains engineering models of the processors of both Mango and Tango.

If the experiment requires any specific monitoring during its execution this is also stated in the XML and the monitoring plan is automatically implemented into the operational environment.

The timeline has to a large extent been planned such that the initial conditions of one experiment is in the region of where the prior one ended, though in most cases some type of transfer between the two has been necessary. This transfer has been calculated by the operational team and executed using the AFF mode.

After the initial conditions have been verified the experiment is executed, monitored by both the Prisma operational team and the experimenter themselves. The data from the validation of the experiment is used as a reference, allowing near instant verification on the progress of the experiment.

EXPERIMENT RESULTS SUMMARY

Over the course of the mission a large variety of relative orbits have been flown, with distances ranging from 2m to 30km in along-track separation, up to 1000m cross-track and to 2km radial distance. Figure 4 shows how the norm of the distance has varied over the basic mission.

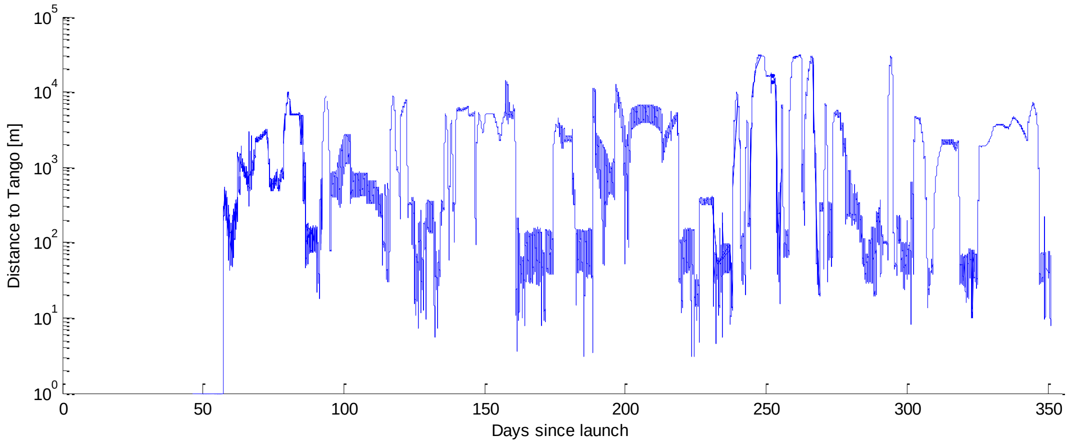

Figure 4, Relative distance over time up to 2011-06-01

***AFF* –** To date, 5 months of closed loop cooperative satellite formation flying, with 20 days in dedicated AFF experiments. The remaining time has been spent in routine operational formation flight between 30km to 10m relative distances.[5]

***PROX/GPS* –** First flight demonstration of close proximity GPS based forced motion relative orbit control over the range of 50m to as low as 2m relative distances.[6]

***ARV* –** First flight demonstration of autonomous line-of-sight only based target search, orbit determination, orbit align and approach from 30km to 50m relative distances.[7]

***CNES* –** First flight demonstration of autonomous formation flight using a radio electric relative sensor. Position accuracy was achieved in the range of 1-100cm and pointing accuracies of <0.1° over the range of 30km to 3m relative distances.[8]

***DLR* –** First comprehensive demonstration of GPS based autonomous formation flight and extraction of relative Precision Orbit Determination (POD).[9]

***ECAPS* –** First flight and space qualification of the High Performance Green Propellant (HPGP) 1N thruster system, including 34,000 pulses during 200 test sequences and 2.3 hours of firing.[10]

***Nanospace* –** First flight of the MEMS cold gas micropropulsion system. Electrical validation of control hardware was possible, although unfortunately full system demonstration could not be performed due to a propellant leak two days in to the mission.

***PRIMA* –** First flight demonstration of MEMS shutter based low energy (<100eV) ion mass analyzer.[11]

***PROX/VBS* –** At the time of writing the first closed loop proximity operations based on visual sensor were taking place. Results are yet to be analyzed.

PRISMA AUTONOMY

Designing GNC for Autonomous Formation Flight

The design of the GNC subsystem of Prisma is primarily focused on maintaining the safety of the formation. As Tango does not have any maneuver capability all functionality for formation keeping has been implemented onboard Mango. Tango aids this by continuously providing GPS measurements.

Onboard Mango formation safety is paramount; all modes except for Safe Sun contain functionality for maintaining the formation. Among these the Autonomous Formation Flying (AFF)[12] has been designated as baseline to be used throughout the mission, as can be seen in figure 5.

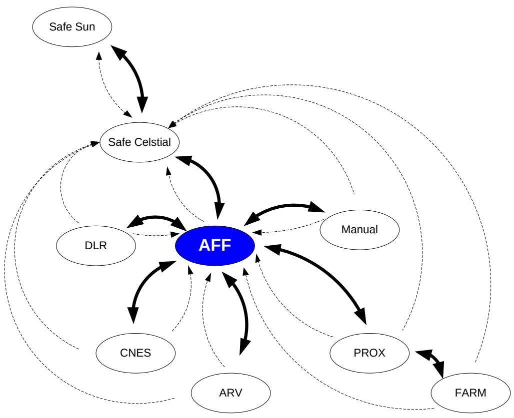

Figure 5, GNC Mode overview, solid lines indicate transitions by command only, dashed autonomous or commanded transitions

AFF has been chosen for this role as it is the most flexible of the modes, providing capability for both autonomously establishing stable T-periodic orbits and for reconfiguring the relative orbit for transfers between experiments.

In Safe Celestial formation safety is handled by Safe Orbit Guidance[13], which has the express purpose of establishing a safe relative orbit. This is done by ensuring that the along-track distance is safe and that both cross-track and radial distances are >0.

AFF consists of two main parts:

1. A ground support toolbox. The AFF Toolbox is used to specify requirements on the relative orbit and with the help of an optimizer a relative trajectory is calculated that fulfills the requirements using a fixed number of delta-Vs. The toolbox is used by the flight dynamics team to plan and optimize transfers between different orbits.
2. Onboard guidance and control software. The AFF software onboard is a smaller version of the ground support toolbox. It is using a Model Predictive Control framework to compute required maneuvers to achieve and maintain the trajectory specified by ground. The AFF can be used to execute, in closed loop, a trajectory uniquely specified by ground, achieve a goal trajectory autonomously in a certain time or achieve the closest T-periodic orbit from the current state.

The relative positions are maintained within a defined "control box" which allows the operations team to define the range of acceptable control error on the requested relative distances. The iteration time for this control loop can also be defined for a faster control loop. For instance, during the 2m approach on the 25th of January, 2011, the control period was set to 150s and box to a demanding [0.3 0.3 0.2] meters.[6]

While AFF has been the default go-to mode during gaps between experiments both modes have been used as Safe Orbit Guidance is faster at establishing a safe relative orbit while performing proximity operations as no transfer needs to be calculated. It has also been used in cases where there has been a large cross-track separation to conserve fuel when that distance is expected to be brought back down within a short time-frame by another experiment.

Running in the background in all modes are the collision and evaporation detectors. These functions continuously monitor the formation, ensuring that no experiment runs the risk of either colliding with Tango or going too far away and thus risk losing contact.

The collision detector is configurable by mode, allowing different experiments to approach to separate distances. Collision detection for Prisma is a combination of contact computation when they are very close, as is possible during the approach and recede experiment, and predictive collision monitoring for modes when the spacecraft are far enough apart that they may be modeled as spheres.

Upon detection of a possible collision or evaporation a transition to Safe Celestial will be requested, where the Safe Orbit Guidance will attempt to deal with the situation.

Over the course of the mission AFF has indeed been the work-horse for formation-flying, nearly 50% of the mission timeline has been spent in the mode, as can be seen in figure 6.

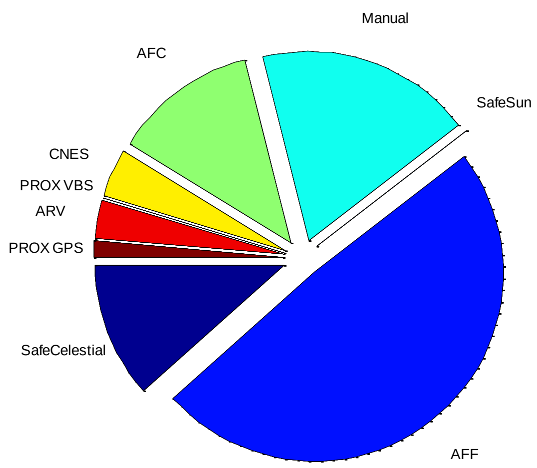

Figure 6, relative use of GNC modes after Tango Separation, as of 2011-06-01

AFF has not only been used for transfers and dedicated AFF experiments, it has also been employed during other experiments. It has, for example, been extensively used for standby orbits during proximity experiments and has also been the default mode used during FFRF sensor validation before the CNES GNC Closed-loop experiments.

The large amount of time spent in Manual mode is explained by the fact that all HPGP experiments use this mode as the objective for these tests is not formation flying but qualification of new thruster technology.

The relatively small amount of time spent in proximity operations is due to the short duration of such forced motion experiments. Between experiment sets AFF has been used to maintain a close relative position while conserving fuel and minimizing risk of collision.

The tightly packed timeline has resulted in large amounts of mode switches, mostly between AFF and higher modes. Figure 7 shows how the mode has changed since the start of the Basic Mission.

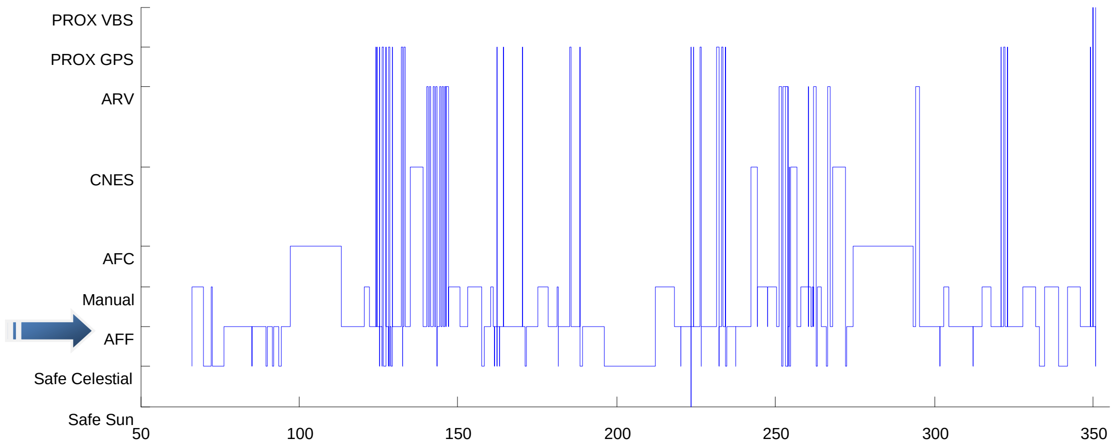

Figure 7, GNC Mode in flight up to 2011-06-01

Metric	Value
Number of days in closed loop AFF	136
Number of AFF formation reconfigurations	122
Number of times used AFF auto T-periodic	47
Closest distance in AFF	10 m
Farthest distance in AFF	30 000 m

Table 4, AFF usage until 2011-06-01

Failure Detection, Isolation and Recovery

An important factor in allowing the use of a small operational team has been the implementation of a robust, well tested and configurable Failure Detection, Isolation and Recovery (FDIR) system.

FDIR on Prisma has been designed to encapsulate the software application cores, allowing all cores to provide input but having spacecraft configuration take place outside their basic functionality. The encapsulation is implemented through two components; the System FDIR (FSYS), performing data validation, and the

Application FDIR (FAPP), controlling the spacecraft configuration. See the figure below.

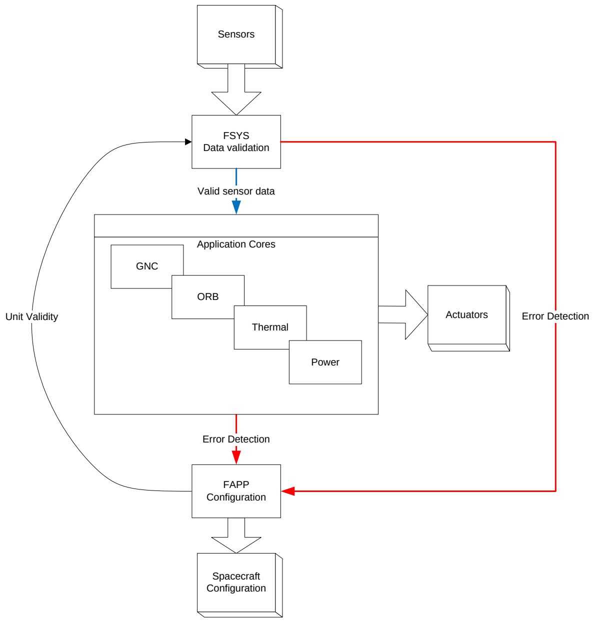

Figure 8, FDIR encapsulation

All sensor data is processed in FSYS on a rudimentary level, assuring that e.g. data has been delivered as expected and that all Remote Terminal Units (RTUs) are performing within specification. The early validation of data done by FSYS ensures that no invalid data is passed on to the other software cores, preventing autonomous decisions being taken on invalid data. This data is then processed by each separate application core and application specific error detection is made. Any detected error is immediately classified based on severity and is then forwarded to FAPP, which then carries out recovery actions based on the severity level. If a unit is declared as invalid by FAPP the FSYS may not override this decision.

Error detection severity is classified according to the following table:

Severity class	Interpretation
0	No error
1	Invalid
2	Anomaly
3	Failure

Table 5, Error severity classification

FAPP has one configuration setting for each of the severity levels, defining which state the unit is to be set to and which configuration is to be done. Depending on the unit the available recovery actions may differ slightly, some may have a mode switch available as a recovery while others do not. The most commonly used configuration, however, is that of a cold redundant hardware unit, where the possible actions are as listed in table 6.

Action
Mark as invalid
Set active branch
Flag branch A as unhealthy
Flag branch B as unhealthy
Force switch to redundant processor
Command branch A on
Command branch B on
Reset error state

Table 6, Unit recovery actions

The actions are defined as a vector of true/false flags for each severity level. Default behavior is typically to flag the current branch as unhealthy, switch to the other branch and resetting the error to allow the redundant unit to be used in the control-loop. A subsequent failure on the redundant branch leads to a switch to the redundant processor.

Each step of the FDIR approach is configurable in flight without requiring software patching. Detection levels for faults can be tuned, as well as severity levels. In addition to this the requested recovery action can also be configured easily. This has proven to be a very useful approach, for example during the commissioning of the spacecraft redundant units could be checked out by reconfiguring the FDIR such that any detected errors would have simply caused a switch to the nominal branch instead of progressing further to more severe recovery actions.

Another example of the strength of the configurability of the FDIR has been the handling of the onboard GPS receivers. Due to the risk of radiation caused single-events the FDIR was initially reconfigured to switch the receiver off in the case of an upset, instead of switching to the redundant branch. This was done to be able to monitor a restart of the GPS during ground visibility to be able to verify that the receiver was still working nominally. Following a series of on-ground tests it was established that the single-events did not pose a danger to the hardware and the recovery actions were again reconfigured. The current recovery is to perform a power-cycling of the receiver as soon as a probable radiation-event has been detected. This has proven to be a safe implementation which minimizes the time without GPS navigation on-board and thus reduces the impact of the phenomenon on the ongoing experiments. As of the time of writing close to 60 restarts due to suspected radiation events have occurred with no discernable decrease in performance of the receivers.

Through the separation of spacecraft configuration from error detection in the encapsulated way done on Prisma, the testability of the error detection at application level has greatly increased. This has had the added bonus of increasing confidence in the spacecraft autonomy, allowing the operational team to focus on the mission itself, instead of continuously doing routine health checks best left to automated processes.

Total Thruster Impulse Monitoring

With many different controllers requesting the use of delta V for orbit reconfiguration an maintenance it is important to be able to detect excessive thrusting during all phases of the mission. For Prisma this is done by the Total Thruster Impulse Monitors (TTIMs), which monitors the accumulated on-time of the thrusters. Impulse monitoring is done in two separate locations of the OBSW, in GNC and on system level. These two each have separate detection limits and recovery actions associated to them and essentially serve two different purposes.

The GNC TTIM has two detection limits, the lower limit leading to a switch to AFF while the higher leads to a transition to Safe/Celestial. This allows the GNC Core to monitor any ongoing experiment and recover to a safe state if the experiment exceeds its expected deltaV. Both levels can be tuned to correspond to the ongoing experiment, using input from the validation, and the limit can be reset prior to each new experiment.

The system TTIM checks the accumulated on-time since the last reboot of the spacecraft. Instead of, like the GNC TTIM, working with the calculated on-time it monitors the on-time actually sent to the thrusters. This gives an added safety as it is completely independent of the GNC control loop. The TTIM level is periodically raised to account for the ongoing experiments. Recovery from a system TTIM triggering is the complete shut-down of the thruster system, including power-down of the thruster electronics.

Managing the TTIMs is in most cases done in parallel, i.e. a reset of the GNC TTIM is paired with a simultaneous rising of the system TTIM. This approach allows for consecutively harsher recovery actions as each level is exceeded: An experiment consuming too much fuel will be aborted and AFF will attempt to establish a T-periodic orbit. If this fails Safe Orbit Guidance will attempt to stop any drift and realize a safe relative orbit. Should this also fail the thruster system will be shut down and mission control needs to take additional recovery actions.

As the system TTIM does not reset unless a reboot is performed it has become a very useful tool to track fuel consumption. The development of the TTIM over the mission can be seen in figure 9.

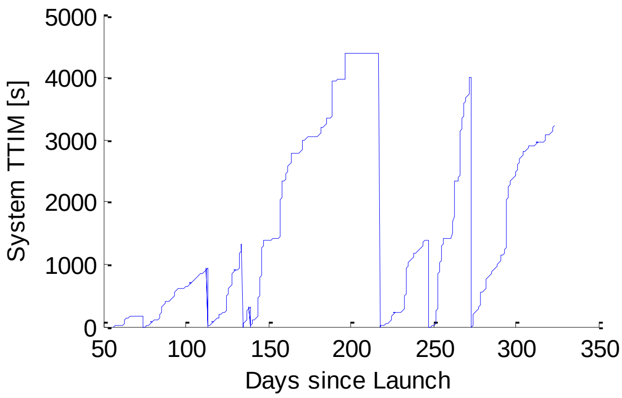

Figure 9, System level total thrust on-time

MISSION EVENT EXAMPLES

Considering the above described Prisma mission and operational architecture, the following three mission events serve well for case studies from in-flight experience.

Case Study 1: Autonomous collision avoidance

Near the end of the AFF completion experiment slot, time was allocated for preparations for VBS close range activities. The purpose was to further characterize the camera and how it could be employed as part of the control-loop for PROX/FARM experiments further along in the mission.

Specific experiments were set up, using AFF to go closer to Tango to acquire images and check performance for the VBS. The experiment was configured to keep Mango at a distance of 15-20m from Tango, while Tango was set to rotate to be able to view all panels of the smaller satellite.

The experiment ran smoothly for some time, before the collision detector requested a recovery as the distance was too small.

In the figure below the along-track position (green) follows the AFF reference (blue) quite well for several orbits, but the error gets larger and larger as time goes on.

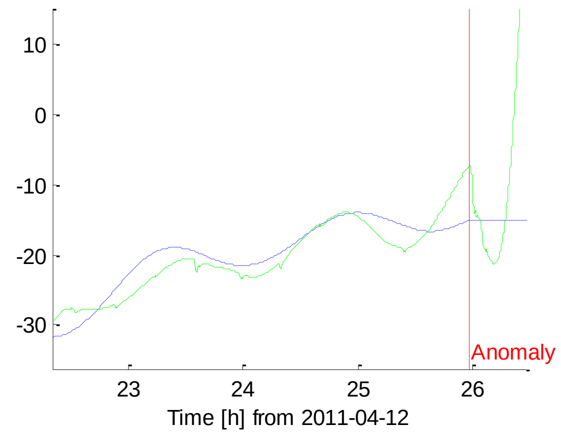

Figure 10, AFF reference (blue) vs relative position (green) [m]

As long as the actual relative position is within the AFF control box it will continue to try to correct for the measured error, which it does for a while. However, at just before 2AM (at the red line in figures 10 and 11) the measured relative position violated the collision detector setting and a transition to safe mode was performed.

After the mode transition, Safe Orbit Guidance immediately performed recovery actions by performing a 8.5s long thrust to increase the along-track distance. Shortly thereafter an additional thrust was performed to establish a safe ellipse around Tango. The resulting orbit can be seen in figure 11.

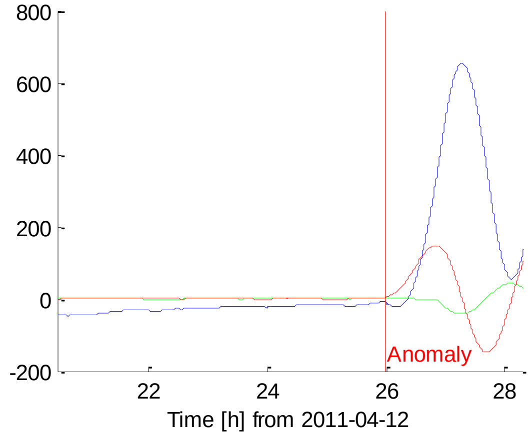

Figure 11, Establishing a safe orbit after collision avoidance (along-track, cross-track & radial [m]).

Investigation into the cause of the diverging along-track separation showed the cause to be poor navigation due to the rotation of Tango. The incorrect Mango navigation settings to account for the rotation were used during the execution. Using a more robust setting at a later date allowed the necessary data to be gathered successfully.

As the navigation indicated a much too small separation than desired the collision avoidance maneuver was necessary, albeit unfortunate.

Case Study 2: Safe Mode recovery with assisted autonomy

Part of the CNES closed-loop experiment 'FFRF GNC2' included an approach to 50m separation, followed by proximity operations from that point and closer. The experiment is then ended with a drift away from Tango. The simulated validation result of the experiment can be seen in figure 12.

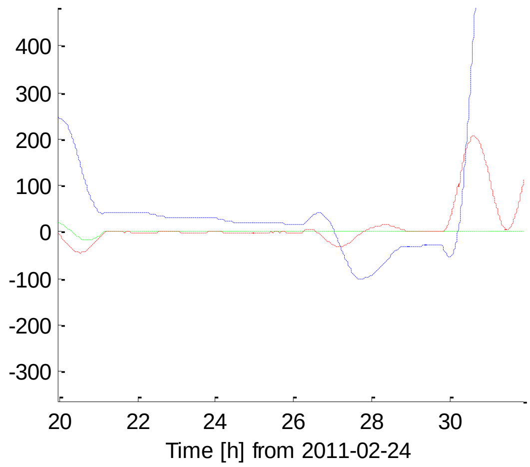

Figure 12, Expected relative distance (along-track, cross-track and radial [m]), simulation result

Due to the need of a transfer maneuver to the initial conditions for the experiment, the start was delayed by one orbit compared to the simulation, but the sequence started nominally.

After the initial approach to 50m an anomaly occurred with one of the secondary experiments, which unfortunately affected the primary experiment by causing a mode switch to Safe Celestial. This switch led to the ongoing experiment being aborted in favor of recovery actions. As the orbit at that time completely lacked both cross-track and radial components, the Safe Orbit Guidance deemed it unsafe and performed a maneuver to safe-guard the constellation. The new orbit had a relative distance of up to 500m, with substantial cross-track and radial components, quite far from where the experiment was planned to be.

The anomaly was detected in passage 3664, where some immediate actions were taken to investigate why the mode switch occurred and to ascertain that neither primary nor secondary experiments had suffered any form of permanent effects. As it caused the primary experiment to be aborted it was categorized as a major anomaly, possibly affecting the mission timeline.

Analysis quickly showed that the primary experiment was ok, but the secondary experiment would require some additional investigation. The decision was taken to attempt to restart the primary experiment, but without the secondary.

Using the AFF-toolbox, a transfer from the current relative orbit to the initial conditions of the experiment was calculated and uploaded to Mango only one passage later. At the cost of a reasonable amount of delta-V the maneuver could be executed within one orbit and the primary experiment could be restarted only 2 orbits after the anomaly was first detected. The actual flight data of these hours can be seen in figure 13.

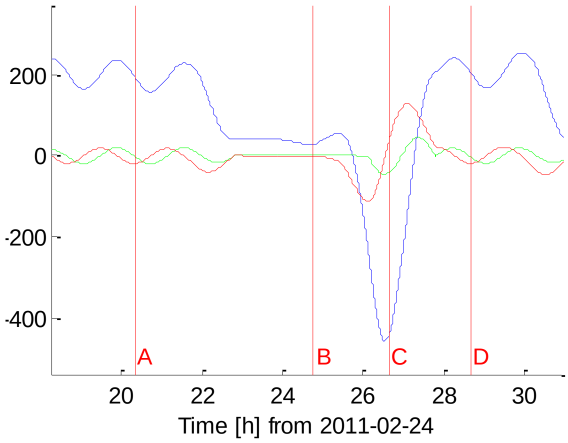

Figure 13, Relative distance (along-track, cross-track & radial [m]), flight results;

A denotes experiment start, B time of anomaly, C start of transfer and D is restart of experiment

The rest of the primary experiment could be carried out without any issues. Subsequent analysis identified the issue with the secondary experiment, which could be corrected and then be re-run at a later time.

As the experiment was the last to occur before a weekend without any experiments planned it was allowed to proceed for the extra 4 hours needed to finish, meaning that the overall mission timeline was not affected at all due to the rapid recovery.

Case Study 3: Safe Mode entry due to improper experiment validation

Due to the small team-size, the GNC-experts have often been forced to take on the role of both experimenter and GNC-responsible. For most of the mission this has been a workable, albeit taxing, solution, but there have been a few instances where the two roles have come in conflict and experiments have suffered from it.

The most serious of these instances occurred when what was supposed to be a minor experiment had expensive repercussions in fuel consumption due to insufficient validation prior to the execution of the experiment.

The experiment was set up to investigate the behavior of the navigation during GPS antenna switches as either satellite rotates. In-flight experience has shown that there are jumps in the navigation as the antennae are switched; a potentially serious issue for proximity operations where even small jumps in navigation could have serious consequences.

The objective of the experiment was to perform rotations of Mango, disabling the GPS input filter for short periods where the antenna switch would occur. As the experiment was not in the original timeline it was scheduled to be performed at the end of the week, in-between two other experiments.

Due to a minor anomaly at the end of the execution of the previous experiment operations for the night were extended for an additional passage in order to configure the system back to default configuration. This passage would occur about 10 minutes after the first of the antenna-switch experiments.

At the start of the passage, Mango had fallen to Safe Celestial and was thrusting significantly. The cause was found to be the relative navigation indicating a distance of exactly 0. As this was clearly not a reasonable result the navigation filter was reinitiated and at the end of the passage relative navigation was re-established, showing a relative drift of 5km/orbit.

On the following passage Safe Orbit Guidance had attempted to stop the drift and almost succeeded before the system TTIM had shut down the thruster system due to the extremely large amount of thrusting performed. During the passage the hydrazine system was brought back online and the rest of the platform was checked to be in good order.

One additional passage later, the drift had been completely stopped, but the orbit was very different from what would be desired with a maximum distance of almost 15km and large radial and cross-track components as can be seen in figure 14.

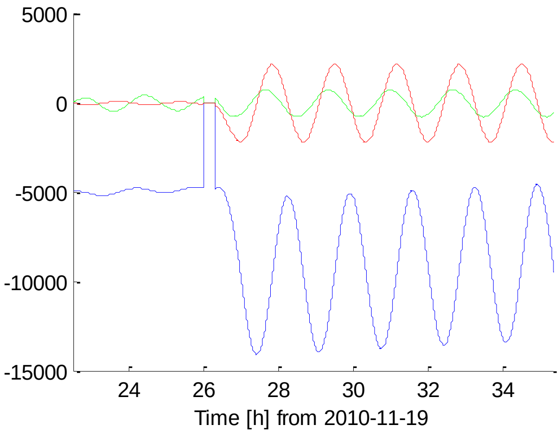

Figure 14, Relative position (along-track, cross-track & radial [m]) during critical anomaly

The following day a transfer back to a more normal relative orbit was performed. As no experiments were scheduled during the weekend the overall mission timeline was not affected, though a very large amount of delta-V was consumed, both during the anomaly itself and for the transfer back.

Due to the severity of the anomaly (it was classified as critical; risk of mission loss) a larger investigation into the cause was made. Several issues were identified, but the primary factor was the lack of proper validation of the experiment. A simulation of the experiment would have shown that disabling of the GPS input filter would cause serious issues problems for the navigation and the experiment as a whole should not have been performed.

Safeguards have been implemented in the software to prevent similar situations from occurring again. An additional sanity check for the relative distance has been introduced where the navigation is marked as invalid if the distance is identical to 0m. Other measures were also implemented, both in the software and in the operational routines.

The issue of the GPS antenna switched has since been improved by software updates, though the performance is not yet sufficient for close proximity operations. A workaround was implemented where antenna switching is prevented and instead using the fact that the back-plate of the active antenna actually does allow GPS reception. This approach has allowed repeated close proximity operations down to distances of 2m.

OPERATIONAL EXPERIENCE

Open- and Closed-loop experiments

Throughout the Prisma Basic Mission both open and closed-loop experiments have taken place. Operationally the experience with the two types has differed greatly with regards to experiment preparation, validation and execution.

In general the closed loop experiments have had a greater deal of operational maturity, very much due to the simulation campaigns. By their very nature these experiments require less interaction during their execution as the entire point of them is to demonstrate autonomy.

The operational difficulty with the closed-loop experiments has been in the configuration. This has included things such as updating default values used onboard and configuring FDIR limits which may otherwise be violated during the course of the experiment such as the collision detector. This has been especially true for proximity operations, where additional activities such as DVS imaging are commonly requested by the experimenter.

Open-loop experiments tend to require even more configuration during the preparation for the execution. In this case it has more to do with circumventing onboard functions which may autonomously interfere with the experiment if this is not prevented. It also includes configuration of the orbit and attitude of the spacecraft to serve the experiment. There are most commonly performed using already tested closed-loop functions such as AFF.

Where the two types of experiments differ most operationally is the required amount of commanding. Closed loop experiments strive to minimize the amount of ground commands, allowing on-board software to perform most configurations and commanding. The open-loop experiments are quite the opposite, with large amounts of commands needing upload. The table below indicates the typical amount of commanding used for the different experiment types.

Experiment	Typical Command load	Typical experiment length	Type of experiment
AFF	10-20 cmds	1-3 days	Closed-loop
PROX GPS	5-10 cmds	1-3 orbits	Closed-loop
FFRF sensor validation	700-1000 cmds	1-2 days	Open-loop
HPGP	200-300 cmds	1 orbit	Open-loop
Prima	50-75 cmds	12-24 hrs	Open-loop
CNES GNC	50-100 cmds	1-3 days	Closed-loop
DLR AFC	5-10 cmds	2-3 days	Closed-loop
ARV	20-30 cmds	1-2 days	Closed-loop
DVS	10-20 cmds	1 orbit	Open-loop
Microthrusters	800-1000 cmds	1 orbit	Open-loop

Table 7, Experiment commanding

It is worth mentioning that several of the experiments perform multiple activities in the same upload: An AFF experiment of 20 commands will perform several orbit reconfigurations and a FFRF sensor validation sequence will do large amounts of advanced manual attitude rotations, requiring a significant amount of commanding.

In-orbit software updates

As a large part of the mission is focused on trying different algorithms for formation flying patching of the fight software while in orbit has always been in the planning. As new parts of the flight code are tried during different experiments new software bugs will be identified. At times these will cause experiments to fail, at which point an anomaly report will be generated to track the issue. At other times post-analysis of experiment results will show ways of tuning to improve performance and reliability. Both will eventually result in a new software version being built and tested on-ground before being uploaded to the spacecraft.

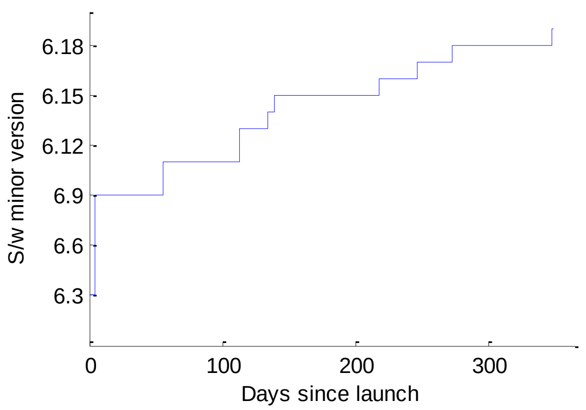

Figure 15, Software version history for Mango

Up to the point of writing a total of 8 software patches have been performed on Mango, but only 3 for Tango. One additional patch is currently in the process of upload. Figure 15 shows that the timing for software updates for Mango is very spread out in time, some versions only being used for a few days while others lasting months.

Of the nine software patches performed to date 4 have been initiated by experimenter software updates and 5 are due to platform bugs discovered during flight.

Anomaly database analysis

As a result of the experimental nature of the mission, anomalies and inconsistencies are encountered. Although, in comparison to other demonstration or science missions, the total number of anomalies of all nature is relatively low.

Despite these events, the spacecraft robustness and autonomy has resulted in the fact that all 38 experiment slots have been successfully completed (with exception of the full demonstration of micropropulsion experiment), and the mission schedule has been on-time. Prisma has now even planned for mission and experiment extensions well in to 2012.

An online anomaly log has been kept using the Hansoft tool, allowing anyone on the project team (mission control, support engineers, project managers) to enter anomalies as they occur. They are categorized, discussed, tracked and eventually closed by action or response. From this, a high level assessment of the nature of events can be made. This is presented below, for data from launch up to 14th May, 2011.

Anomalies are given one of four severities: Critical – potential loss of mission, Major – potential loss of experiment, Average – potential loss of performance, Minor – low consequence.

A breakdown of the anomalies by function can be made (figure 16), and here it is clear that as a result of the complexity of formation operation, 25% of the anomalies are related to Experiments and 25% related to GNC and Systems. All other subsystem anomalies are as would be expected for a smallsat demonstration or science mission.

With 50% of the anomalies related in some form or another to the experimental formation flight of two spacecraft, the nominal Mission Control team of three people (Director, GNC expert, Operator) relies heavily on a stable and robust autonomy of the spacecraft.

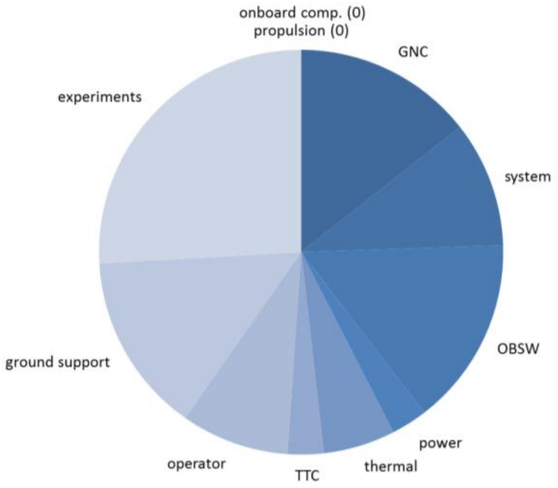

Figure 16, Anomalies per function

By sorting over segments (operator, ground, space and experiment), it becomes very clear that operations and ground support learn quickly from mistakes in the first four months of operation, while as the spacecraft and experiment related errors are still uncovered as more difficult functions are tested. It should be noted that the space segment anomalies include those from the complex GNC functions.

In most Experiment and GNC related anomalies, the spacecraft have autonomously detected and reacted to the situation, placing themselves in a safe relative "wait" state, allowing the team to assess and react accordingly. For example, many anomalies which have occurred on a weekend, unmanned, have been assessed only on the following Monday.

Operations team size

The tight timeline of continuous around-the-clock activities shown in Figure 2 above is compounded by the fact that the formation is nearly always in a state of dynamic change. This is clearly demanding on the operations team, yet as a result of migrating a core of the original design, integration and test members of the project to the operations team, a very lean and efficient daily operations could be achieved.

Below is a summary of the size of the operations team from Tango separation to May 2011. Unsurprisingly, Tango separation involved considerable support, but this was quickly ramped down to an average of 6 persons per day, covering two shifts, up until handover to GSOC in March 2011. So in short, at any one time on average, there were no more than 3 people operating this complex mission.

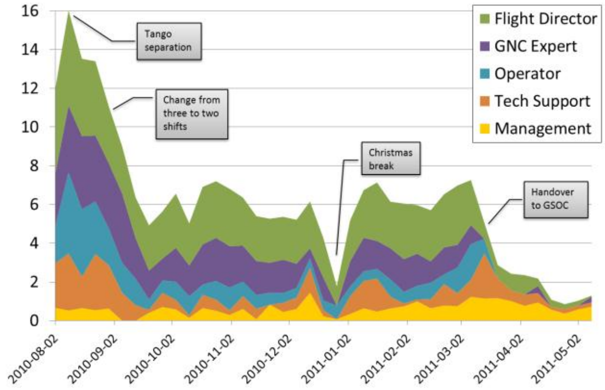

Figure 17, Persons/24hrs on the operations team

The above data in Figure 17 agrees very well with the original operations principal that was foreseen for two shifts (Table 3):

1 manager + 2 flight directors + 2 GNC experts + 1 operator + 0.5 tech support = 6.5 persons per day, covering two shifts.

The result is fast, flexible and responsive team that has allowed for maintenance of the demanding timeline, even in the event of anomalies. Interaction to experimenters and their requests is kept focused and changes or decisions can be made quickly, in some cases in just a matter of one orbit.

This has also been highly appreciated by the project experimenters who have benefited from the efficiency and responsiveness, as stated by CNES, for example:

"This proximity [of Flight Director, GNC Expert, Operator and Experimenter] allowed a better reactiveness in presence of anomalies that proved to be a key element in the respect of the timeline."[14]

"The involvement of the same engineers from system design to its operation in space (made possible by the development approach and the specific validation & monitoring tools) proved to be a key factor in the experiment success."[14]

LESSONS LEARNED

Value of simulation

A high degree of confidence in the Safe Orbit Guidance and collision detector has allowed experiments in higher modes to take increased risks, pushing the performance of these modes further and thus collecting more valuable data. This confidence would not have been possible without the extensive simulation and test campaigns performed during the development phase.

This also applies to the rest of the experiments; a high-fidelity simulator such as SATSIM has given all experimenters the possibility to test their flight-code both using the faster than real-time simulator and on the real-time, hardware-in-the-loop, simulator to verify how the software will interact with the actual flight processor and, during the AIV phase, the full spacecraft.

The simulation results have proven to be very reliable, with only small deviations from actual flight results. Figure 18 shows a comparison of the delta-V consumption for one experiment.

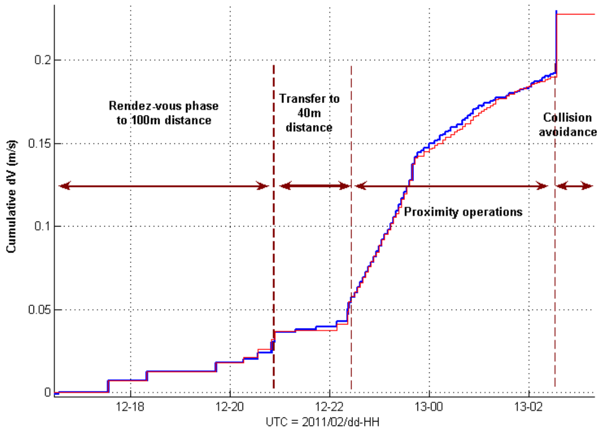

Figure 18, Simulated (red) vs Actual dV(blue) performed[15]

For this case the difference was on the order of 2%, most of which can be explained by the fact that the simulator assumes a higher drag than what the spacecraft actually experiences in orbit.

Continued use of both versions of the simulator throughout the operational phase has increased the responsiveness and flexibility of the operations team. Having near instant access to the simulator has meant quick validation of both experiments and flight procedures, greatly increasing the overall success of the mission.

Limitations of autonomy

While a high degree of on-board autonomy greatly aids the operability of the space-segment it is important to be aware of the boundaries of that autonomy. It is difficult to design for every eventuality and once the boundaries of the autonomy are being pushed operations become significantly harder. This can happen when mission requirements change during the course of operations, but also if situations arise that have not been considered in the original design.

Within Prisma, autonomy has often been employed as a layer of abstraction to the hardware, meaning that there are high-level commands for performing most actions on-board. In many cases this has greatly aided operations, though this abstraction does pose risks and can hinder certain operations.

One such case is during the commissioning phase, where the focus of activities is often more hardware related than software. The abstraction layer can at this time become a hindrance to operations, requiring a great deal more effort to perform activities which should be fairly straight forward. One example is the simple act of powering up a unit for the first time. On a hardware level this is simply a matter of a single on-command, but with a high level of autonomy and FDIR the process may become significantly more complicated where autonomy has to be fooled to allow the unit to be switched on and FDIR be disabled so that no recoveries are performed if the unit is not yet prepared for nominal operations.

Autonomy and operability

The operational phase of Prisma has shown that a large degree of autonomy can significantly simplify operations. High confidence in the space segment has meant that during less active periods, such as weekends, it has been safe to leave the spacecraft in a safe relative orbit, usually in AFF, with the only ground monitoring being done remotely by an on-call engineer. In fact, one of the key design requirements for the mission was for full autonomy over at least 3 days without commanding from ground.

The passive formation flying experiments require very little of the operations team, the only input from ground for these experiments were passage planning and weekly TLE uploads. Most of these experiments were even left unsupervised for shorter periods of time, completely trusting the autonomy to control the spacecraft.

In contrast the forced motion experiments required more in the form of monitoring. This is primarily not because of less autonomy, but rather due to the inherent risk of proximity operations. Additionally these experiments usually have more in the line of passenger experiments, requiring more from the operations team.

When testing out new functionality observability is always important and even more so when it comes to autonomous systems. There is a very strong desire to view all the steps leading to any given autonomous decision to be able to track any anomalous behaviour. The Prisma spacecraft database contains some 12000 telemetry parameters which may be downloaded from the space segment, but still there are functions that have not been possible to monitor in a completely satisfactory way, leading to a certain amount of frustration.

An experimental technology demonstrator such as Prisma will by its nature require more operational support of what would normally be considered platform or routine operations. Implementing similar autonomy on future mission would hopefully require even less in the form of ground monitoring and commanding.

It is, however, important to note that autonomy will not always ease operations; operations outside the original scope of the mission will instead require more effort due to the fact that the on-board autonomy will have to be either worked around or disabled completely.

Time to recovery

It has become clear that in order to maintain the tight timeline and a responsive interaction with the partner experimenters, timely reaction to events is critical. Autonomy has provided a “safe net” that allows for the operations team to focus on the next steps rather than recovery actions, as typically the spacecraft have recovered themselves (safe orbit/orientation, eliminated relative drift, and simply waiting for the next objective).

The small and experienced operations team has allowed for decisive and quick decisions and operations. The result is often recovery periods in the order of only 1-3 orbits after an anomaly. Unplanned dV maneuvers have been identified, planned and executed in one single orbit, which in comparison to many missions can often take 24-48 hours.

This means that overall timeline is rarely affected by anomalies, since nominal operations are typically resumed after ~90 minutes.

Autonomous handover between sensor types

Part of the mission goals was to demonstrate autonomous switching of relative position sensors, as in for example the far range approach to Tango. Ideally this could be a handover from GPS at large distance to the Close Range VBS camera or from Far Range to Close Range camera.

This has proven to be significantly more difficult than expected, since the final performance of each of the sensors must be very well understood and tested. The handover requires exact match in post and pre conditions, and without stable operation of the two sensors simultaneously, this becomes difficult. The effort to match sensor performance becomes considerable and has yet to be achieved.

CONCLUSIONS

The Prisma mission has, during its first year in orbit, accomplished nearly all mission objectives, clearly demonstrating the value of on-board autonomy. By implementing a high degree of autonomy on both space and ground segments, the demanding programmatics of this experimental mission could be maintained, while also keeping an aggressive mission timeline. By employing an operational team with lengthy design and testing heritage, the daily operations have been efficient and agile allowing a relatively large amount of experiments to take place in a short period.

As a result of this affectivity and success, the nominal mission will be completed on schedule by August 2011 and with ~50 m/s of remaining dV. It is for this reason that the Prisma team invites other organizations, institutes and agencies to suggest experiments and to participate in the mission extension. A number of extension experiments have already been planned, but a list of potential considerations are:

- All on-board experiments
- Ground based or supported experiments
- Related to space situational awareness (SSA)
- Autonomous FF and relative maneuvers
- Automated checkout and planning
- Inspection, servicing, repair, 3D proximity operations
- Use of both Mango and Tango or independently
- Focus on GNC algorithms

After 2012 Mango will leave Tango permanently, after which a different set of experiments may be considered:

- SSA experiments (open definition of SSA)
- Attitude control experiments
- Drag-based FF and relative maneuvers, lower altitudes
- RDV/inspection of a non-cooperative neighbouring target object (S/C or debris)
- Focus on GNC algorithms

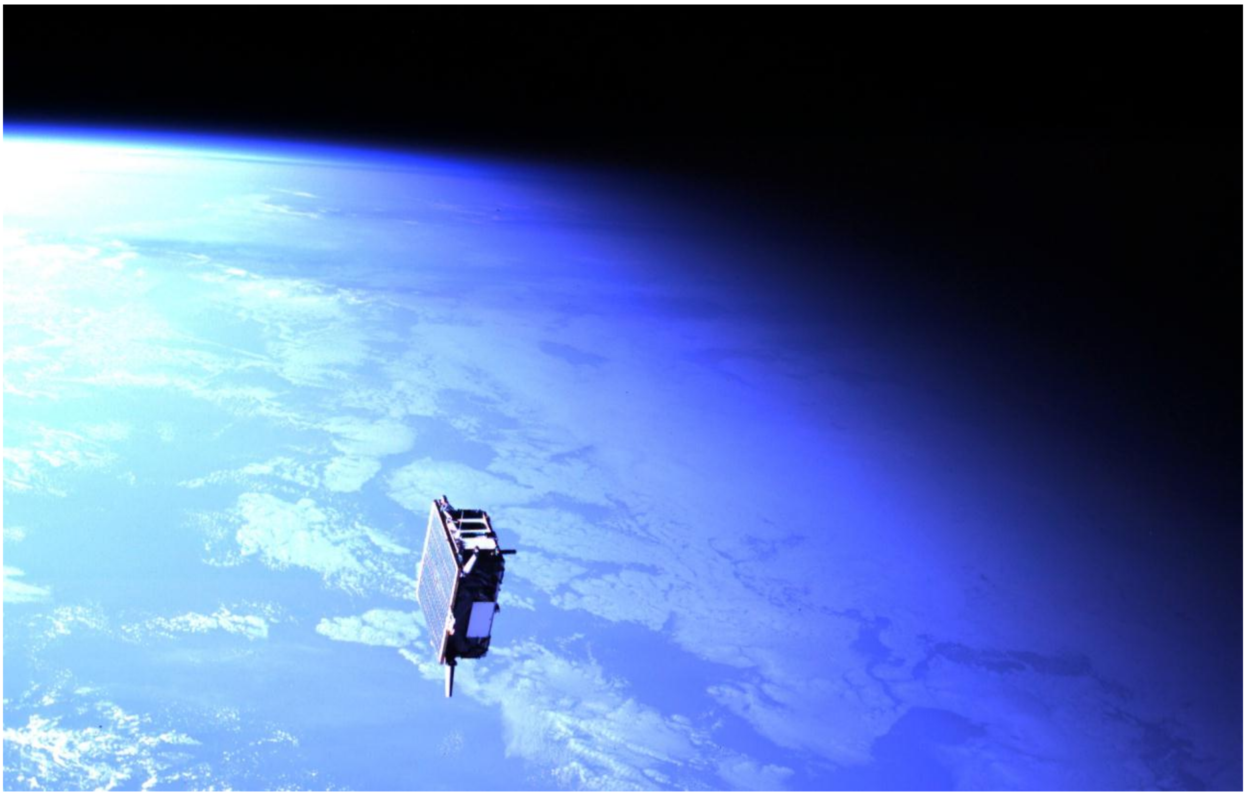

Figure 19, In-flight image of Tango, taken using the Techno Systems DVS camera from Mango at a 20m relative distance (20th October, 2010)

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