Mission Design of the Dutch-Chinese FAST Micro-Satellite Mission

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Abstract

The paper treats the mission design for the Dutch-Chinese FAST (Formation for Atmospheric Science and Technology demonstration) mission. The space segment of the 2.5 year mission consists out of two formation flying micro-satellites. During the mission, new technologies will be demonstrated and, using spectropolarimeter and altimeter payloads on both spacecraft, observations will be performed characterizing atmospheric aerosols and seasonal variations of height profiles in the cryosphere. The mission is divided into four phases, each with a different orbital geometry. The rationale for and the orbital geometry during these phases as well as the transitions between the phases are treated in detail. A major complication to the mission design is the amount of data that can be sent to the ground. Since only two moderately capable ground stations, one in Delft and one in Beijing, are baselined, as much data processing as possible has to be performed onboard to allow high duty factors for the science payloads. When this is not possible, alternative payload operation modes have to be sought with which maximum scientific data return can be obtained through as little payload operation as possible. Both options are dealt with in the paper.

1 Introduction

The Dutch-Chinese FAST (Formation for Atmospheric Science and Technology demonstration) mission is a collaboration between Delft University of Technology in the Netherlands and Tsinghua University in Beijing, China. During the 2.5 year mission, two micro-satellites flying in a loose formation will demonstrate new technologies and, using spectropolarimeter and altimeter payloads on both spacecraft, will perform observations characterizing atmospheric aerosols and seasonal variations of height profiles in the cryosphere [1-3].

The FAST mission is described in detail in the coming sections. First, the mission objectives and mission architecture are provided. These are followed by a detailed description of the various mission phases. The fifth section explores several ways to maximise science data return whilst minimizing the amount of data sent to the ground stations. Finally, several conclusions are drawn.

2 Mission objectives

The top level mission objectives for the FAST mission are threefold, namely: technology demonstration, science, and education. Each objective is discussed in the following subsections.

2.1 Technology demonstration

The technology demonstration objective is split into one primary and two secondary objectives. The primary objective is to demonstrate autonomous formation flying using various communication architectures with distributed propulsion systems and MEMS technology optimizing propellant consumption. The secondary objectives are to demonstrate distributed, fault tolerant, out-of-core computing using two spacecraft and to demonstrate real-time GNSS ephemerides updates for onboard navigation solution improvement.

2.2 Science

For the FAST mission, the opportunity exists to fly several advanced science payloads: SPEX (Spectropolarimeter for Planetary Exploration), SILAT (Stereo Imaging Laser Altimeter), and a modified Chinese altimeter earlier flown on Shenzou-4. This allows the formulation of the following scientific objective: Characterize atmospheric aerosols and monitor the seasonal variation of height profiles in the cryosphere and correlate data to visual and stereoscopic imagery for improved science return.

2.3 Education

In the field of education, the FAST mission has as objective to teach cutting-edge technology, broaden the international view of students and boost skills through exchange of students and staff members between Delft and Beijing.

3 Mission architecture

The baseline orbit for both satellites, which are foreseen to be piggyback launched on a single Chinese launcher at the end of 2011, is a 650 km high sun synchronous orbit with an ascending node time of ~10:00 hr. This orbit is a compromise between spatial resolution, coverage, ground station contact time, and expected launch opportunities. The ascending node time follows from the need to have a substantial angle between the orbital plane and the sun vector for optimal spectropolarimeter science output. The ground segment of the mission consists of a science data centre, a mission control centre, and two S-band university ground stations: one in Delft and one in Beijing, cf. Fig. 1.

The 2.5 year mission is divided into four phases, each with a distinctly different orbital geometry. The rationale for and the orbital geometry during these phases as well as the transitions between the phases are treated in detail in the next section. As will be explained, the total velocity change (ΔV) per satellite is estimated to be around 5.5 m/s for the entire mission duration. However, taking into account the possible failure of the propulsion system of one of the satellites and allowing for operational anomalies and disturbances not taken into account in the calculations, a ΔV budget of 12 m/s is currently assigned to each satellite. This results in approximately 1 kg of propellant mass in case of cold gas propulsion.

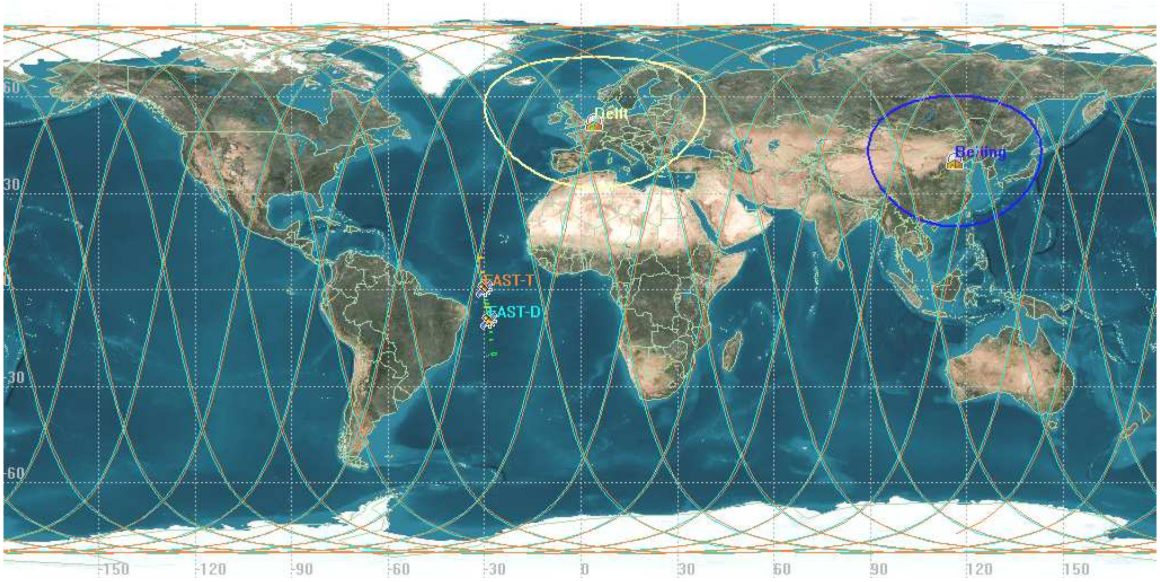

Fig.1: FAST mission architecture

4 Mission phases

Since FAST has both technological as well as scientific mission objectives, the mission design is a compromise between these two. As a result, the first weeks of the mission focus on technology demonstration while the remainder of the mission focuses on science. After the launch and early operations (LEOP) phase, the mission consists of two distinct one year phases, science mode A and science mode B. The aspect that sets these two phases apart is the line of sight between the satellites: in science mode A, there is a direct line of sight between the two satellites while in science mode B the distance between the satellites is such that no direct line of sight is existing. The coming subsections detail the various mission phases.

4.1 Launch and early operations

The LEOP phase consists out of the launch, orbit insertion, detumbling, and checkout of the two FAST spacecraft, called FAST-T (Tsinghua) and FAST-D (Delft). The two spacecraft, which are not mated during launch, will be inserted into the same orbit with a small along-track separation. At any time during LEOP, the two spacecraft will not fly in formation. However, since collision of the two spacecraft has to be prevented, passive collision avoidance measures need to be implemented during this phase. The current approach to achieve this is to insert the spacecraft with the smallest ballistic coefficient, currently FAST-T, into orbit before the other spacecraft with sufficient Δt and ΔV with respect to the other spacecraft to rule out any chance for collision during LEOP. After LEOP, which will take approximately one month, a small manoeuvre will be performed to attain the correct orbital geometry for the science mode A1 phase.

4.2 Science mode A1

During science mode A1, the two spacecraft will demonstrate the ability to autonomously maintain an along track separation of 1±0.1 km by means of autonomous formation flying (AFF) using propellant optimized distributed propulsion, cf. Fig. 2. This capability requires a propulsion system on each spacecraft as well as an inter-satellite communication link.

Since the FAST mission is foreseen to be launched in 2011, the mission timeline coincides with a period of maximum solar activity. When assuming for FAST-D a mass of 50 kg, a drag coefficient of 2.2, and a ballistic coefficient that differs 30% from the ballistic coefficient of FAST-T, the two spacecraft will rapidly drift apart in along track direction. In fact, the relative drift is such that a 1 km drift is achieved within 5 days for solar maximum conditions. Since LEOP takes approximately 1 month, a small manoeuvre will therefore be required to bring the inter-satellite distance back from approximately 60 km to 1 km. An attractive option to accomplish this is to lower the perigee of FAST-D and to increase the apogee of FAST-T to let FAST-D 'catch-up' with FAST-T. Once the distance between the satellites is as desired, the orbits are re-circularized and science mode A1 commences. When one day is chosen as the time frame for this manoeuvre, a ΔV of 0.1 m/s needs to be provided by each satellite.

For solar maximum conditions, it will take the satellites slightly over one day to traverse the 200 m control window of this mission phase. To maintain the desired formation geometry, taking into account differential drag only, a ΔV of 2 mm/s is then required to bring the inter-satellite distance back to the other extreme of the control window.

Although the orbital geometry is not optimized for it, some first science observations will be performed during this phase of the mission. Due to the relatively small inter-satellite distance, this phase lends itself well to perform distributed computing experiments between the two spacecraft and to perform cross-calibration between the instruments on the different spacecraft since they are essentially measuring the same properties at almost the same moment in time. The AFF demonstration will be performed for several weeks and will be followed by a transition to the required relative geometry for science mode A2.

4.3 Science mode A2

In this mission mode, the along-track separation between the satellites will be 1225±5.7 km. This orbital geometry lends itself extremely well to perform synoptic and synergetic observations with the altimeters and especially the SPEX instruments on both spacecraft. The orbital geometry combined with the nine Earth looking fields of view (FOV) of the SPEX instrument [4] results in many simultaneous intersections of SPEX FOVs and in several overlapping SPEX FOVs at the Earth's surface, cf. Fig. 3. This allows retrieval of aerosol characteristics at specific altitudes at a single moment in time and it allows making more observations of geolocations from various angles during a single pass (especially near the equator), which is highly desired for aerosol characterization. The ±5.7 km accuracy in the inter-satellite range is driven by the pixel size of SPEX at 650 km altitude, which is approximately 11.4 km [4].

Changing the orbital geometry from mission mode A1 to mission mode A2 can be achieved simply by letting the two satellites drift apart due to differential drag and by correcting afterwards for relative orbital node drift. However, this will take roughly 100 days even for solar maximum conditions, which is too long. Therefore, the same approach as earlier is adopted only now the inter-satellite distance needs to increase. Thus, an increase in apogee for FAST-D and a decrease in perigee for FAST-T are required. When the change in semi-major axis for both satellites is set to 2 km, the manoeuvre requires a ΔV of 1 m/s for each satellite and will take a bit over two days. For one year of formation maintenance, again taking only differential drag into account, approximately 0.6 m/s of ΔV is required per satellite and a manoeuvre needs to be executed every nine days.

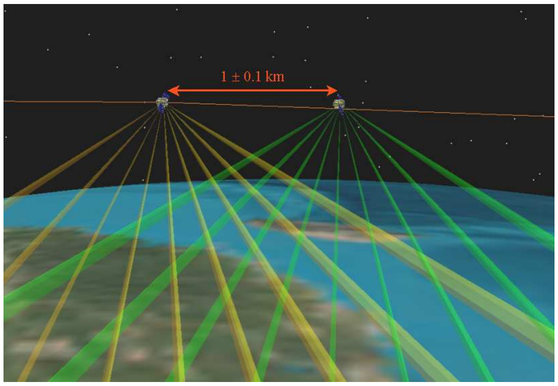

Fig. 2: Science mode A1

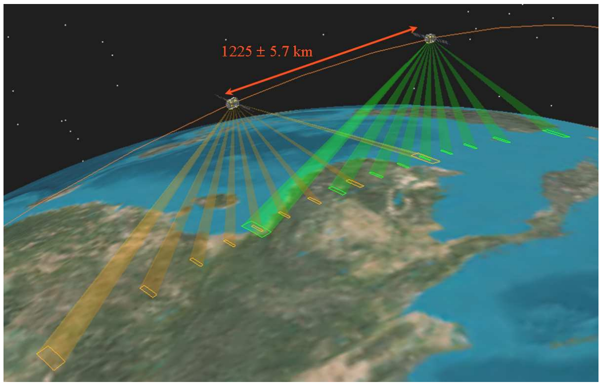

Fig. 3: Science mode A2

4.4 Science mode B

For science mode B a large temporal separation between the satellites is created, allowing valuable spectropolarimeter observations to be made of locations that exhibit a high temporal dependence on local aerosol characteristics such as cities and industrial sites. Ideally, the temporal separation is in the order of hours, allowing differences to be measured between e.g. morning and afternoon. Unfortunately, this requires a relative plane change to be performed by the satellites, which is very expensive in terms of propellant. For that reason, the current mission plan foresees in an orbital geometry where the satellites are separated 180° in the same orbit, creating a 49 minute temporal separation.

The orbital geometry for this mission phase is achieved in the same way as for mission mode A2. When a transfer time of two weeks between the mission modes is taken as acceptable, a change in semi-major axis of roughly 5.5 km needs to be achieved by both satellites, resulting in a ΔV per satellite of 3 m/s. For one year of formation maintenance, again approximately 0.6 m/s of ΔV is required per satellite.

5 Increasing scientific data return

For FAST, only two moderately capable S-band ground stations are baselined: one in Delft and one in Beijing. With an expected downlink data rate of one to two Mbps and raw payload data generation speeds of 1.2 Mbps (SPEX) and 26.2 Mbps (SILAT), low payload duty factors are inevitable for the FAST-D satellite. However, these can be improved upon using various strategies.

5.1 Strategies for SPEX

For SPEX, the allowable duty factor is much higher than for SILAT, but can easily be improved further by onboard deletion of pixels without significant information, reducing the amount of raw data produced by ~75%. The SPEX duty factor can even be drastically improved when by means of onboard processing a curve is fitted in a least squares sense through the recorded spectrum, resulting in merely six 32-bit floating-point numbers per imaged spectrum or less than 1% of the original raw data and allowing SPEX operation for the entire sunlit part of the orbit.

The curve fitting approach however requires significant onboard computing power. Even for a state of the art cell phone processor capable of speeds of 3 GFLOPS (floating-point operations per second) and a relatively low power consumption of 5 W (for the entire chipset), the energy required to do the curve fitting is roughly twice the energy needed to download the raw 10-bit SPEX data containing significant information for the same duty factor. Thus, advanced onboard data processing is in this case less efficient than downloading the raw data. However, keeping in mind that processor performance rapidly increases, performing the curve fitting onboard merely as an experiment to prepare for future capabilities is already valuable in itself. In addition, there is still the issue of a moderately capable ground segment, severely limiting the allowable duty factor of SILAT on FAST-D (currently less than 1%). Since processing the SPEX data onboard will free up a very considerable amount of bandwidth for extra SILAT data, thereby allowing a higher SILAT duty factor and increasing its science return, doubling the energy needed to download all SPEX data remains an option for the FAST mission. A final decision on this matter needs to be taken in a later stage of the design. Lastly, it is noted that to increase the tolerance of the non-space qualified processor to radiation effects, the FAST mission foresees to implement fault-detection algorithms that are guaranteed to produce a correct solution in case of e.g. bit flips for only a 10% computing overhead [5].

5.2 Strategies for SILAT

For SILAT, data reduction can be best achieved by reducing the data rate of its high resolution camera (HRC), which accounts for 95% of the raw data produced by SILAT. This can be done through technical means or through operational means. The first technical option is to bin the HRC detector pixels, resulting in lower resolution ‘macropixels’. A second option is to reduce the size of the HRC detector, resulting in a smaller swath width. The third and last technical option is to reduce the number of colour filters used on the HRC from three to one, resulting in having to make only one picture of a scene instead of three, but coming at the price of much reduced science output.

Operationally, the duty factor of the HRC can be significantly reduced by using it only at locations with large slopes, such as edges of ice sheets or mountainous regions, since those are the places where HRC information greatly enhances the SILAT data quality. However, this requires meticulous operations planning and will therefore be costly.

Currently, it has not been decided yet which SILAT performance is acceptable. Since FAST is not a science mission, non-optimal performance is a viable option, but the right balance between performance and data amount still needs to be determined.

6 Conclusions

The paper has introduced the bilateral FAST formation flying mission and presented its mission objectives. The mission architecture and a detailed mission description have been provided as well as several strategies to increase payload duty factors while maintaining an acceptable science level.

Since FAST focuses on technology demonstration as well as science, the mission design is a compromise between the two. In addition, the science return in the fields of aerosol characterization and cryosphere altimetry will not be able to compete with that of a dedicated science mission, but can be used to augment data from such missions. The formation flying capability of the FAST satellites allows the mission to be divided into several phases, each with its own orbital geometry and consequent technology demonstration and/or science benefits. Since the ground and space segments of the FAST mission only allow for moderate data rates between the ground stations and the satellites, several data processing activities are performed onboard the FAST satellites to enable higher payload duty factors and therefore increase the scientific output of the mission.

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