

IAC-11-D1.5.6

TET-1 SATELLITE OPERATIONS LESSONS LEARNED: PREPARATION OF MISSION, LEOP AND ROUTINE OPERATIONS OF 11 DIFFERENT EXPERIMENTS

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TET-1 is a small experimental satellite with 11 different space experiments on-board. Built by German space industry it's a satellite dedicated to verification of newly developed space hardware and software. The German Space Operations Center (GSOC) as part of the German Aerospace Center (DLR) is responsible for satellite operations.

Development of space and ground segment started back in 2006, with a scheduled launch in the second half of 2011, expected in December. Keeping this in mind we perform a survey of mission preparation activities focusing on first the reuse of existing GSOC mission infrastructure and second the specific adaption's necessary for TET-1. Lessons learned are compiled with respect to applicability for other missions, especially with respect to flight procedure development and satellite commanding. Operations team training started in 2010 with different training and simulation sessions. Engineering models and the flight model itself have been used; no dedicated software simulator has been available. Advantages and disadvantages of this approach are discussed.

After a concise conclusion of preparation of LEOP and commissioning sequences that are commanded from ground control center a short introduction to the activation sequence of the satellite is given. This sequence is a set of predefined commands executed after spacecraft activation at separation. Discussion is extended to our planned routine operations concept for 11 different payloads. We conclude with a collection of space segment design decisions with the biggest (positive as well as negative) impact on ground segment design and subsequent operations.

I. SATELLITE MISSION OVERVIEW

TET-1 (see Fig.1) is a small satellite built by Kayser – Threde (KT) [2], Munich for the German Space Administration. Intention of the mission is technology demonstration and on-orbit verification. Therefore the satellite is the first of a series of satellites built in the frame of the On-Orbit Verification (OOV) program in Germany. Ground segment preparation and operations are conducted by German Space Operations Center (GSOC), an institute of DLR located in Oberpfaffenhofen close to Munich.

Satellite payloads consist of experimental solar cells, GPS receiver, infrared camera, memory cells, battery cells and different sensor and computing experiments.

Satellite

The whole spacecraft weights approx. 110 kg at dimensions of 58 x 88 x 67 cm in launch configuration. Solar cells are assembled in three panels; one body mounted and two to be deployed during LEOP. A three axis stabilisation allows pointing the solar panel towards the sun as needed. The satellite is divided into the two segments bus and payload (Nutzlastversorgungssystem - NVS). The bus segment is built by Astro- und Feinwerktechnik, Adlershof; NVS and overall satellite integration is executed by KT.

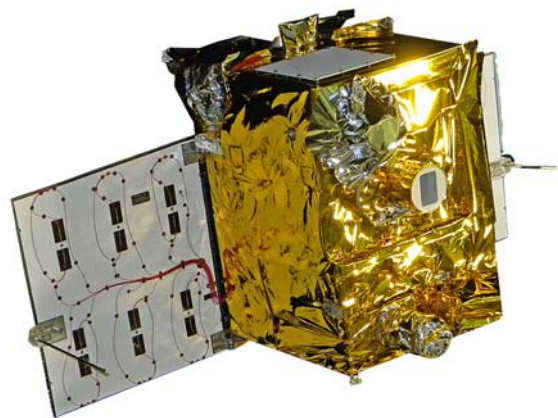


Fig. 1: TET-1 satellite image, view from below to backside of solar cells and the infrared camera. Star camera head units are shown in the upper area as well as the radiator (grey).

Bus

The bus provides energy via solar cells and immediate storage in NiH₂ batteries for eclipse times. Telemetry (TM) data is stored in a ring buffer, keeping the data depending on the commanded sampling rate.

All communication with ground is done via S-band, either low rate (137.5 kbps) or high rate (2.2Mbps).

NVS

All payloads are assembled in the NVS, separating bus and payloads. Power supply, temperature control as well as fault isolation are done by this system. The system controls execution of the experiments, together with storage of payload data in mass memory.

Experiment Types	Specific Operations Requirement
Experimental battery	High energy consumption during battery loading
Different types of solar cells	Sun pointing
Memory cells	Nothing specific
Pico satellite propulsion system	Specific attitude in order to avoid satellite bus contamination
Radio transmission experiment	No regular TM/TC transmission possible during experiment
Experimental GPS receivers	Operations with good GPS satellite view which requires an attitude different from sun pointing
Infrared camera	Nadir pointing, high power consumption and high data generation during operations, satellite rotation about nadir axis by 180° for star camera operations
Sensor and software experiments	Operations as long as possible. No specific other requirements

Table 1: Experiments on-board TET-1.

Launcher

The Soyus – Fregat launcher has been selected, launching TET-1 as a piggy-back payload from Baikonur, Kazakhstan. Four more satellites are launched together with TET-1, with our satellite as the 3rd separation.

Orbit

TET-1 will be placed in a circular sun-synchronous orbit semi-major axis of 6890 km, LTAN 11:27 min and inclination 97.43°. The resulting orbit period is approx. 94.8 min.

II. GROUND SEGMENT OVERVIEW

Operations during all mission phases are controlled by GSOC [3]. For routine operations two ground stations in Germany are used, Weilheim (close to GSOC

in southern Germany) and Neustrelitz (northeast of the country). This network is extended during LEOP by ground stations in Norway and in Canada as can depicted in Fig. 2. During routine operation 4 out of 5 or 6 possible contacts over German ground stations are selected and scheduled for contact. As a result we have two contacts in the morning and two contacts around midnight local time. One of the morning contacts will be used to uplink time-tagged telecommands (TC); whereas all other contacts are planned as pure downlink-only passes.

Spacecraft is operated on a 24/7 basis with a DLR core project team responsible for preparation of daily command schedules, analyses of TM and solution of potential problems. During routine operations, core team is usually onsite only during office hours, therefore 8/5. During night times and weekends or holidays the Multi – Mission Flight Support takes care of operations in a 24/7 mode. In case of TET this means reception of telemetry and payload data, basic analysis of core TM data and uplink of new telecommands. Only in case of an anomaly the on-call support is used to call core TET team personnel for further analysis and problem solution.

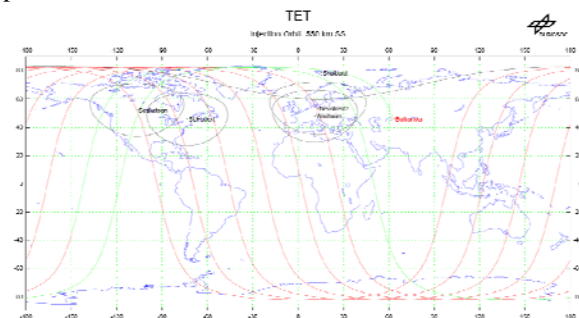


Fig. 2: Ground station network used by TET-1 including the additional LEOP stations.

III. GROUND SEGMENT – REUSE OF EXISTING SYSTEMS

As TET is a small satellite with only limited financial resources as well as for efficiency reasons a maximum reuse of existing operations tools and systems is the goal of ground segment development. After LEOP an commissioning the mission is ‘moved’ into the multi mission operations environment, a specific control room where most of GSOC satellite missions are operated together by one multi mission operations team. Beside of that general operations decision to integrate operations with other mission a variety of tools or systems has been reused with slight or with-out modification for TET:

TC & TM

Main tool for satellite commanding is the Spacecraft Control and Operation System (SCOS). This system is standard for most missions operated by GSOC; therefore it is also used for TET. Some specific adaptations have been made with respect to command handling by the satellite – in SCOS the so called MAP-ID must be switched according to operations need. Setting of MAP-ID determines the goal of the commands onboard the spacecraft.

For display of real time TM during a ground station pass a tool named SatMon is used. All TM stored by the satellite in between passes is analyzed with a different tool named ROOTS, which takes processed offline TM as input data.

Procedure Development

The procedure development was done with the COTS tool MOIS. MOIS is a system on basis of Microsoft Office Products and extends them with Visual Basic for Applications (VBA) to enable the user to develop flight procedures. This tool was also used by other missions.

The MOIS system stores a flight procedure in a MS Access database. Viewing and editing is done using an Excel and Visio. The system provides a huge toolset but its main focus is the preparation of single procedures. It is not optimized to develop many procedures at once; each procedure must be adapted manually. An example: it is not possible to change common parameters for all procedures at once.

Flight procedures will be exported from the MOIS database in an xml and ssf file format. The later file format is the SCOS2000 file format and can be read directly by the SCOS system. The xml file provides some additional information's which are used by the XMLGUI and Merger. We learned that we only needed a small subset of the MOIS functionality whereas most of the settings to be made when developing procedures confused the development team.

Validation Tracking

Flight procedures are a critical component of the operation concept in spaceflight. Therefore it is very important that flight procedures pass a review and validation process after creation to ensure the overall correct execution of the task described by the procedure. By working with the procedures during the validation phase new Insight in the handling of the procedure and spacecraft is gained and therefore improvements of the procedure will be done. For the TET mission roughly 300 flight procedures were prepared. To keep track which of these procedures are validated, not validated or changed after the last validation it was decided to implement a database where these information's could be stored.

The list of procedures and their general information's (ProcedureID, Name, Objectives) and more critical information's like their actual version number, last date of modification and name of last editor could be imported directly from the MOIS system. This enables the TET project to update the procedure information's each time a new set of test procedures were exported from the MOIS system.

The flight operations manager was than able to export a report to get an overview of the validation status and could advise his subsystem engineers which procedures need validation or revalidation (e.g. when a validated procedure gets an update, it may be necessary to revalidate this procedure).

The subsystem engineers could enter their validation results both by using a dialog form and by using an excel sheet which can be used as a validation log. This log is also imported into the database.

Merger & XML GUI

These two tools are some of the core tools used in GSOC satellite mission operations. The XML GUI is used for selection and modification of single or assemblies of several flight operations procedures. It provides an easy overview for all flight operation engineers in the team and allows selection of an execution time. Procedures prepared by this tool are send directly to the Merger.

The Merger receives XML files and translates the files into SSF files, which are SCOS readable.

Offline System

The Offline System is mainly used to process all offline TM received during a satellite pass. The system is setup as a multi mission system – only the Mission Information Base (MIB) is satellite specific. Some difficulties in TET-1 resulted from the fact that TM with identical timestamps may be received several times from one Spacecraft Board Computer (SBC) or even (after switching board computers) from a different one. As a result ground processing has to analyse if TM samples have already been received or not – this caused significant extensions to the ground processing. Lesson learned for upcoming project: If the satellite bus is the same stick to existing concept or – if different – identify the most critical issues as soon as possible in the project (is TM send several times, how many sources on-board the spacecraft possibly send the same value, are identical TM values packed into different packets..)

OPSWEB

The Operations Web (OPSWEB, depicted in Figure 3) interface is a multi-mission web server system allowing access to project information like:

- TM / TC definitions
- flight operations procedure information
- anomaly reports and recommendations
- access to project documentation
- TM and TC products (e.g. history)
- information on passes (times, logs...)
- limited access for external partners

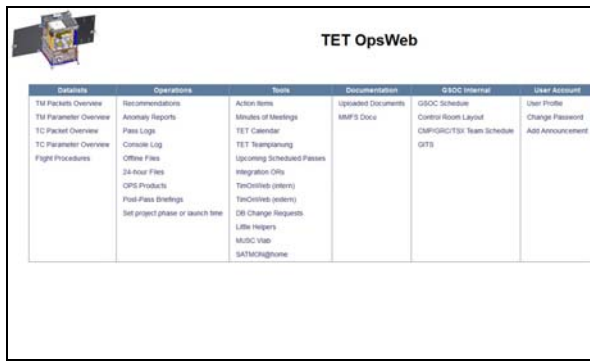


Fig. 3: Access to all project relevant operations information – the TET-1 OPSWEB

Access is shared between all projects and used as the central information base for operations. Beside the use as a source of information, also recommendations and anomalies are handled through this interface. A recommendation is issued if some of the team members require a certain procedure to be commanded immediately or time-tagged later on. An issued recommendation is subsequently reviewed by relevant team leads and confirmed for execution. In case a recommendation contains recurring activities it is marked as a “standing recommendation” and executed each time necessary.

An anomaly report is issued once anything happens that is not anticipated by the operations team, usually this is an error in either the spacecraft or the ground segment. The anomaly handling process is monitored by GSOC quality assurance for errors handling according to standards.

Some of the information can be provided to the operations team by limited external access. This allows review of current operations status by team members during on-call times; therefore weekends or public holidays. The advantages of this approach is that problems can often be solved without showing up in control center but calling the MMFS and providing instructions on what to do in order to solve the problem.

TimOnWeb & SOE Editor

The sequence of events (SOE) is the consolidated plan of activities developed by manufacturer and operations team necessary for LEOP and

Commissioning Phase. The SOE Editor is a web based software tool which was developed in GSOC. This tool imports the predicted orbit events like AOS and LOS times and provide an mechanism to insert events relative to these orbit events as well as reoccurring events like, post- and pre-pass briefings.

This mechanism helps preparing the SOE before launch. This tool also supports the activities during LEOP and commissioning. Changes occur regularly when unforeseen activities have to be inserted in the SOE, like recommendations.

An improvement to this tool would be the ability to react to antenna stations outages. In such a case the whole SOE must be shifted or some activities must be dropped. The later is possible but the shift of activities is not that easy because not every contact has the same length. In the worst case it may be necessary to distribute the activities from a double-contact to several smaller contacts. Currently it is possible to do this with the SOE Editor as is, but the user has to be very careful.

The other tool used in context with the SOE is the TimOnWeb tool, which stands for 'Timeline On Web'. This is a display for the SOE. As you can see in Figure 4 in the upper half there is a graphical representation of the SOE. Ground contacts are represented by the green bars on blue ground. The Procedures which shall be executed during the contacts are represented as a Gant plot. In the lower half the SOE is also shown as a table. The display always shows the next upcoming activities and some of the passed activities.

This display can be monitored on big screen in the control room as well on the individual consoles of each subsystem engineer. Even external partners can monitor this from everywhere world-wide.

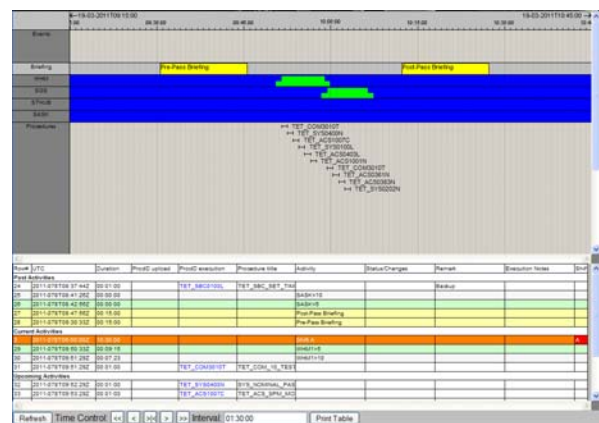


Fig. 4: TimOnWeb view of a ground station contact and procedures to be commanded.

IV. MISSION SPECIFIC SYSTEMS

Routine Operations Preparation with PINTA

Operation of this mission necessitates development of a dedicated operations concept. Previous missions in GSOC have been either fully automated with one main payload only or operations have been prepared manually as the load of payload settings didn't require more support. TET-1 requires planning of 11 different payloads with different requirements on switching cycles, operation times and satellite attitude. Requirements have been collected by KTH from the payload owners. To generate a valid operations concept also the satellite bus capabilities must be collected and analysed. All information together is stored in an Excel sheet, containing all payload activities for the first year of operation. The Excel sheet keeps one row per each minute of the missions first year. A typical row is:

DOM00358,ON01,RZ00000,N02M00V 32,ATTSPM,LCH,DUR00660,COM

The row indicates that on Day Of Mission (DOM) 358, orbit 1 experiment N02 will be switched on. Required attitude is sun pointing fix mode (SPM). KTH used this to first analyse impact of experiment operations on satellite budgets (e.g. power, memory, attitude) and second to prove fulfilment of operations requirements toward the experiment principal investigator. This of course means only the principal possibility of fulfilment as operations are conducted by GSOC. Based on this sheet, operations will be planned and executed by GSOC – several experiments running in parallel. This generates of command load of roughly 400 commands daily during routine operations. For this reason software support by PINTA (Program for Interactive Timeline Analysis) is required.

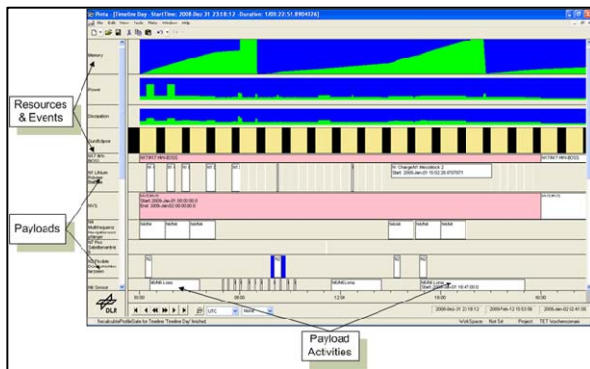


Fig. 5: PINTA view of planned TET-1 activities. Red bars indicate operational conflicts, black and yellow sun eclipse phases, green lines indicate resource usage

All information from the Excel sheet is taken by a macro and processed into a PINTA compatible format.

After this step import of planning information is done on a daily basis together with information on the orbit, eclipse phases and ground station contacts. In case of any conflicts between experiments or the commanded satellite attitude and planned operations an indication is given to the operator allowing for manual correction by drag and drop (see Fig. 5). Once all activities for one day are complete and without conflicts an export into a XML file is done, containing all experiment procedures with their respective parameter settings. This file is send to the XML2SSF merger tool for conversion into SSF files readable by SCOS command system. During the uplink pass all new commands are uploaded. More details concerning timing and complexity of the operations concept can be found in [1].

Config Mirror

The TET satellite subsystems could be more or less configured via TC. Unfortunately the configuration set on-board is not completely displayed in the real-time TM and in some cases also not even in the extended telemetry. In addition TET has four different SBC. Two hot redundant and two cold redundant. Because the two cold redundant SBC cannot receive configuration commands, we also must consider that the configuration can differ. In worst case it is even possible that all four SBC differ in their configuration setting.

To keep track of such configurations the ConfigMirror has been developed. The ConfigMirror is a database in which configuration of each SBC is stored. Via an Excel interface each subsystem engineer can view and edit the current spacecraft configuration. It is possible to track the configuration for all SBC's on different excel tables. All these tables are version controlled so that you can also track the history of configurations.

The workflow in using the ConfigMirror is split into two steps. In the first step the subsystem engineer enters a new parameter or changes an existing one. This is followed by commit to the database. Now the parameter is temporarily stored, meaning marked for change. Usually this step is done parallel in preparation of the configuration command itself. In the next step usually after the uplink of the commands the Flight Operations Manager (FOM) will review the database and ask the subsystem engineer if the configuration change did succeed. If so the FOM will confirm the new configuration table and sign it. The ConfigMirror stores a new version number and sets the old configuration to a read-only status.

The system is designed for a multi-user environment. A mechanism is implemented to prevent the accidental over-writing of parameters by other subsystems.

ROOT

By now GSOC didn't use a common tool for offline data analysis. It was up to the projects to select tools to be used. Often this was done with an Excel sheet extended by VBA macro functionality. Starting with the TET mission GSOC will establish a common tool for all in-house projects. This tool is based on the plotting software ROOT.

ROOT is developed by CERN and provides an API to adapt to the need of the users. GSOC develops tools to use ROOT together with the satellite TM generated by GSOC offline system. These tools convert the offline products to ROOT files and also let the user configure which TM is plotted. It is possible to plot several telemetry parameters over time or one can plot two parameters against each other. The ROOT system allows users to zoom in, move and analyse the data. The plot views can be stored in several formats for use in reports or for archiving purposes.

V. TEAM TRAINING AND SIMULATION

Team training has been done using a staged approach, starting with the implementation of the ground segment. Some, but not all, team members have been involved in project already during phase A studies. This provides of course certain background knowledge on how to operate the satellite – but for most of the team members reading of the space segment user manual (SSUM) and subsystem design documentation was the starting point of training. With this theoretical background in mind subsystem engineers started development of flight operations procedures (a set of instructions on how to reach a certain goal under satellite operations conditions) for TET; a process together with the satellite manufacturer. Originally it was planned that the manufacturer delivers a complete set of operations procedures (a set of instructions on how to reach a certain goal) to GSOC but this turned out not to be reasonable: On the manufacturer side the awareness on operations conditions wasn't sufficient and the operations team didn't know all operational relevant details of the spacecraft. Every now and then even the manufacturer team was surprised by results of commanding a newly developed flight operations procedure as they usually only command the satellite or its subsystems under integration and testing aspect but not in the framework of overall operations. As a result we conclude that a joint development of flight procedures with the subsystem engineers of the manufacturer and the operations team is the best and most efficient solution.

Once development of all procedures has been finished (actually some changes on certain procedures where still necessary) testing could be started. As this project is a small one no dedicated spacecraft simulator could be provided. Instead different models have been

used, Engineering Models (EM) and the Flight Model (FM). Based on the project structure we mainly used a bus engineering model (Bus-EM) and a payload engineering model (NVS-EM). Physical separation of both models limited testing of flight procedures to either this or that model; testing of overall satellite was only possible on the FM. Nevertheless a lot has been learned by the team during this testing. First and foremost that data connection from the control center to the different models needs to be set up and tested as earlier as possible. More than once we scheduled a test with the remote EMs and the connection didn't work. Usually some of the settings on the path through the different networks were modified without our knowledge. As the VPN connection is partly routed via normal Internet configuration control wasn't possible. Some changes were also made on manufacturer side, without being aware of the configuration controlled environment. As mentioned earlier in the text our recommendation is: Setup and test connections as earlier as possible and schedule line tests with sufficient advance before using the connection. Finally, an End2End test has been conducted with the FM. Testing incorporated a long duration test of 24 hours of autonomous satellite operations (as done during routine operations) as well as testing of the complete LEOP activation sequence. Commissioning phase activities have been tested as far as possible (e.g. some calibrations couldn't be tested on ground).

Simulations have been executed in two different ways: An internal simulation (GSOC operations team only) followed by an external simulation (operations team and manufacturer team. Internal simulations concentrated on the workflow within the DLR team and operations whereas the focus for the external simulations shifted to interaction with the manufacturer team. Content of the external simulations were usually LEOP and Commissioning phase activities as these two are the only one with on-side (control center) support from the manufacturer. Content of the internal and the follow-on external simulation were the same in order to ensure a good prior training of the GSOC team. Besides training of engineers the external simulations also provided a good opportunity for building an integrated team. For all training activities either EM or FM has been used as a source of TM and for reception of TC.

Finally we conclude that use of EM and FM only instead of a solution with a spacecraft simulator yield some advantages and some drawbacks. Advantages are the far more real reactions of the data source on any commanding by the operations team as well as consistency of the received TM. Also hardware and software problems with EM or even the FM system have been found by the operations team during GS implementation and testing – an additional source of

information for the overall team. But drawbacks should be neglected: The configuration and configuration control of the VPN connection to the different models have been a headache for the team, regular testing is highly recommended. Furthermore the organisation between manufacturer integration activities and usage by ground operations has been a permanent issue. Remote on-side support at the model has been necessary.

VI. LEOP & COMMISSIONING

Once the spacecraft is separated from the Fregat upper stage it is powered and the board computers start booting. This is accompanied by loading and activation of a LEOP command sequence from flash memory. This set of commands is time-tagged relative to activation of the satellite; last command is executed after 5 minutes. During separation we don't have visibility of the spacecraft via our ground station network. Commands loaded from flash memory are therefore set the initial configuration of the satellite after activation. Mainly all relays are commanded into a defined position and software modes for SBC) and attitude control system (ACS) are commanded. TM sampling rate is initially high and reduced after a while. This allows for a more detailed analysis of the initial system activation. Furthermore the TC list contains the commands for autonomous activation of TM sender during passes over our ground station network. Therefore we should receive the satellite TM already during our first acquisition without dedicated commanding. Especially in case of (slight) injection errors it is easier to search for the spacecraft if the transmitter is switched on. Also if we; e.g. due to network or ground station problems; miss one pass we can still wait for the next one with an activated transmitter. Once a secure uplink is established the SBC on-board time is set (GPS is not yet activated) and new TCs for follow ground station contacts are uplinked. During subsequent passes the solar panels are deployed and GPS is switched on for better orbit determination. All main LEOP activities are finished after 1 day if everything works as expected. In that case we start seamlessly with commissioning of the subsystems, based on a daily basis starting with the ACS system.

VII. SPACE SEGMENT DESIGN DECISIONS RELEVANT TO GROUND OPERATIONS

Intention of this chapter is to highlight some (not all) of the spacecraft design decisions with positive or negative impact on ground operations or implementations.

On-board memory organisation: Satellite bus keeps TM in a memory organised as a ring buffer. Based on the TM sampling rate and daily contact times we

receive TM several times during one pass. This ensures a complete picture of TM data and must be handled by our offline data processing system. Payload data in contradiction is send only once without the possibility to re-dump. Furthermore NVS status data and all payloads have dedicated partitions for storage which are dumped sequentially. Some of our payloads generate more data during minutes of operation (e.g. infrared camera) than can be dumped during one pass. Any log message from the NVS status partition is therefore dumped during later passes; this makes NVS operations error detection on ground difficult and deferred.

Commanding by active and passive list: TC are kept in two command stores called active and passive list. The active list contains all time ordered commands for execution once time tag is reached. The passive list is used during ground contacts for uplink. Once all necessary commands are in the passive list a TC is send to move all commands from passive to active. This avoids that incomplete command sequences (e.g. some commands of necessary mode transitions within the timeline are lost) are for execution in the actives list. As this concept is found to be very useful by operations it will be kept for future satellite missions. Both lists accept commands only in the right timing order, this artificial limitation will be removed in future mission.

Satellite safemode: In case of severe problems the satellite switches to safemode. This may be caused by e.g. low power conditions or thermal problems. In that case all command lists content is deleted, the NVS is completely switched off and a safemode command list is loaded from flash memory – this is the current manufacturer's recommendation and can be modified. So there is no real failure detection isolation and recovery (FDIR) but only interruption of all operations. A staggered approach would have been much better, as impact on operations is significant: Satellite will send no signal and a blind acquisition is to be made, all commands for operations have to be uploaded again once error analysis has been finished. All payload data in the NVS will be lost, as this system is completely switched off. An operational advantage is the possibility to switch between different versions of the safemode command list. This is used to configure the satellite in case of the first safemode to use primary ACS equipment and if a second safemode occurs (e.g. because of problems with the primary ACS equipment) to switch to the backup equipment.

NVS: For commissioning purposes the NVS implements a command enabling the ground to fill the different memory partitions with artificial data. This command will be used to fill some partitions during commissioning phase with data. This data is used for a

ground station pass by dumping data continuously from begin of track (BOT) to the end of track (EOT). This will be used for testing of reception quality and setting of operational BOT and EOT limits. Implementation of such commands is considered very useful by the operations team for intense data transmission testing without operations (and possible degradation) of payload experiments.

VIII. CONCLUSION

TET-1 is a small satellite with a very limited budget. Implementation of the ground segment relied therefore on reuse of existing components from other GSOC missions. We found that some tools are too complex for a simple reuse in our mission, e.g. the MOIS tool for procedure development. Other tools like PINTA used for operations preparation needed mission specific extensions and setup. Recommendation is therefore to make reuse of existing components as far as possible but; first analyse if the complexity of the tools fits your needs and second if changes of the satellite design influence the reuse (e.g. TM dumping concept).

Furthermore we can conclude that a joint development of flight operations procedures between manufacturer and operations team is a good approach for training purposes. Also the fact that a simulator wasn't available should be a drawback, as long as a sufficient access time to those models is granted to the operations team. This must be agreed earlier in the project together with an earlier definition and setup of the TM/TC connection between operations control center and spacecraft models.

The satellite itself and the design drive some of the ground implementations and operations concepts: TM from the satellite may be received several times. This ensures complete reception but necessitates additional effort in the offline processing system. Log-messages of payload operations may send far late after generation - a

concept that should be avoided at all. With specific commanding artificial payload data can be generated which is very useful for use of pass quality assessment during commissioning. Finally the satellite allows switching between different safemode configuration, therefore in case of spacecraft failures different configurations can be subsequently executed by autonomous satellite operations.

This project is supported by the German Federal Ministry of Economics and Technology (BMWi).

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