Satellite Design Aspects Relevant to Mission Operations

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Any spacecraft design decision taken by a manufacturer drives subsequent ground segment design as well as operational concepts. As a result operating a certain satellite may be more complex or simple compared to others, relating directly to risk and cost of mission operations. The German Space Operations Center (GSOC) operates missions of different types since several decades. For each new mission spacecraft design is to be agreed with the satellite manufacturer. Based on a subset of our LEO and GEO missions operational key design aspects are identified for selected tasks, compared and related from an operational point of view. We start with the commanding concept of the different satellites. Afterwards onboard TM and payload data storage is discussed. Comparison of TC and TM concepts of different missions is supplemented by outlining example types and behavior of satellite/subsystem modes together with the specific operational impact. Finally the different concepts of satellite activation during LEOP and commissioning are compared.

Based on the analyzed missions a list of key design aspects is compiled, their impact on ground segment and operations is discussed. This information should serve as a basis for spacecraft design discussion and decisions, to be used by mission operations and management teams as well as spacecraft manufacturers.

I. Introduction

THE German Space Operations Center (GSOC) is responsible for operations of many different space missions. Operations experience dates back to the sixties, when the first satellites were operated from the control center. Meanwhile a fleet of missions (LEO and GEO) with various sensors onboard is operated; beside completely scientific missions also technology demonstrations and security relevant missions. Furthermore the European part of the ISS - the Columbus module - is operated.

Several times a year potential future missions request technical and cost estimations for ground segment preparation and operations execution from GSOC. Mission types vary from mainly LEO missions with different payloads, LEO technology demonstration satellites and GEO satellites. In each case it's necessary to provide a rough order of magnitude cost estimate and to define operations concepts during early stages of satellite development. It's therefore necessary to identify the approximate workforce needed for preparation and operation execution with only a rough idea of how the space segment might look like. Basically for each new mission cost is estimated based on preparation of the existing (multi) mission system and an estimated addition for work specifically for that mission. Deviations from the in-house standard are usually expensive. This paper discusses the relevance and influence of certain selected space segment design issues with respect to impact on mission operations. Selected design aspects and their realization in different missions are discussed. If possible a conclusion with a recommended design and hints on potential operational pitfalls are provided. The project experience of the authors and the GSOC mission operations department is used as an information basis.

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II. Space and Ground Segment at Early Project Phases

New satellite missions are usually designed by the space segment provider based on overall mission requirements set by the customer. These requirements drive already the rough design of the spacecraft and the selected orbit. A certain orbit is usually selected in response to the required coverage on ground or envisaged target; illumination conditions (in-orbit and/or on-ground) and space debris avoidance. Size and required subsystems of the spacecraft are driven by the type of payload used. Also constellation or formation flight requirements including the number of spacecrafts is pre-defined by the overall mission. Rough mission design is therefore assumed to be given. Nevertheless this doesn't constitute the complete spacecraft design as many details which are relevant for later operations can be defined during spacecraft development.

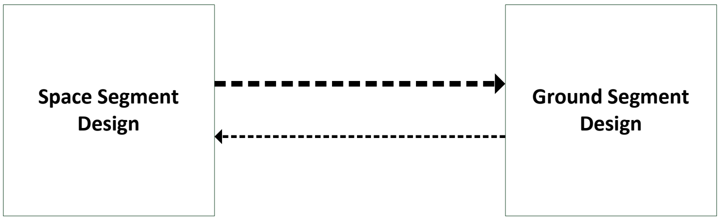

Figure 1: Mutual design influence between space and ground segment. *As main mission goal and orbit are usually defined the spacecraft design is driving mainly the ground segment, the influence in the other direction is often of lower significance.*

Definition of spacecraft design details is usually done as a collaborative action between space segment and ground segment. Basic approach should be reduction of overall mission cost, therefore not shifting cost to either space or ground but to find the optimal (cheapest) solution while still ensuring quality and safety for the project. This is opposed by the fact that often space and ground segment are provided by different contractors. As a result it's not in the interest of the contractors to take care for overall operations efficiency. This conflict can only be reduced if the main customer issues only one contract for space segment, launch and ground segment including operations. Although this approach is obvious it's routinely not used for several reasons which are often based on political or structural issues. For GSOC missions it's often a separate contract for ground segment preparation and operations. Even in case of separate contracts a common project development is followed by technical consultation and joint review of mile-stone documentation. During meetings and review discussion a solid basis for discussion is needed. Standards like ISO 14950 or ECSS-E-ST-70-11C as well as compiled project experience can be used for this. This paper aims at collecting and providing experience gathered during preparation and operations of our GSOC missions.

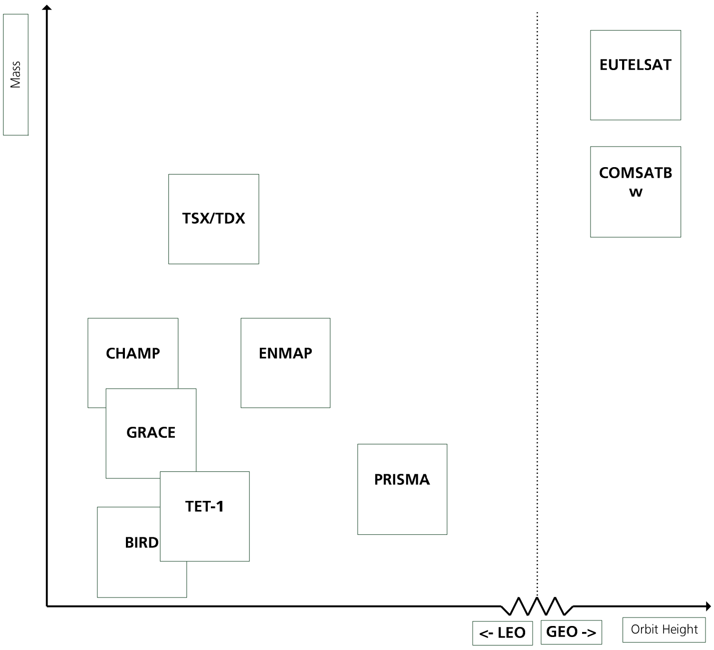

Figure 2: GSOC missions analyzed for this report

For the compilation and selection we choose the following approach:

1) Brain storming of potential issues of mission operation
2) Identification and selection of a subset of interesting issues

Brain storming of relevant issues brought a lot of key words concerning design of space segment (e.g. standards for TM and TC, size of timeline, organization of queues) and ground segment (e.g. observability of the space segment status) and ideas how those relate to each other. Furthermore a discussion with flight operations managers and project leads in our department turned out to be abundant sources of information. For selected tasks we,

1) did a survey of solutions for this subject for our missions (existing and upcoming)
2) derived (if possible) a potential “standard” solution which suits operational needs of most missions
3) tried to qualify and quantify the operational impact of a the selected space segment design

Finally we identified the areas of telecommanding (TC), telemetry reception (TM) and activities during LEOP and commissioning phase as interesting and comparable between the missions. In general it must be mentioned that it was difficult to discuss the differences in mission design due to the fact that each mission uses its own wording to describe the same technical fact (e.g. name for the onboard timeline storage: active list or telecommand stores, schedule).

III. Telecommand

The telecommand function is used to control the spacecraft from ground, request telemetry, change on-board configuration and to update software. Basically a distinction between real-time and time-tagged commands (RT-TC & TT-TC) can be made. Usage of TT-TC requires the ability of the spacecraft to store commands and execute them upon a certain point in time or occurrence of an on-board event. Operational relevant design parameters of the spacecraft are:

1) Spacecraft RT-TC handling
2) Spacecraft TT-TC handling
3) Handling of software updates

A. Spacecraft RT-TC Handling

Real-time commands are sent and executed immediately upon reception and successful verification. A comparison of current GSOC missions showed no big conceptual differences for operations. However, there are some lessons learned that are applicable (and have already been applied) for arbitrary missions. For example a general consensus is that it is not advisable to have “big” commands that accumulate multiple functions or configuration settings, unless every single step or configurable item can also be set individually with a single command. If no such atomic commands are available for a given accumulated set, configuration control on ground can get very complex and consequentially, commanding becomes error-prone. An interesting aspect is also acknowledgement of these commands by the satellite which is discussed in the next chapter in further detail as this is applicable for RT and TT TC.

B. Spacecraft TT-TC Handling

Time-tagged telecommands are stored on-board the spacecraft, this is done by LEO and GEO missions as well. For LEO missions storage is required due to only very short contacts to ground station, nearly all required operational activities are therefore stored and executed without ground contact. Also GEO missions require the possibility to store TT-TC. Main reason for this are maneuvers which essentially require a precise execution time for e.g. eclipse phase mode transitions for AOCS or execution of orbit maneuvers.

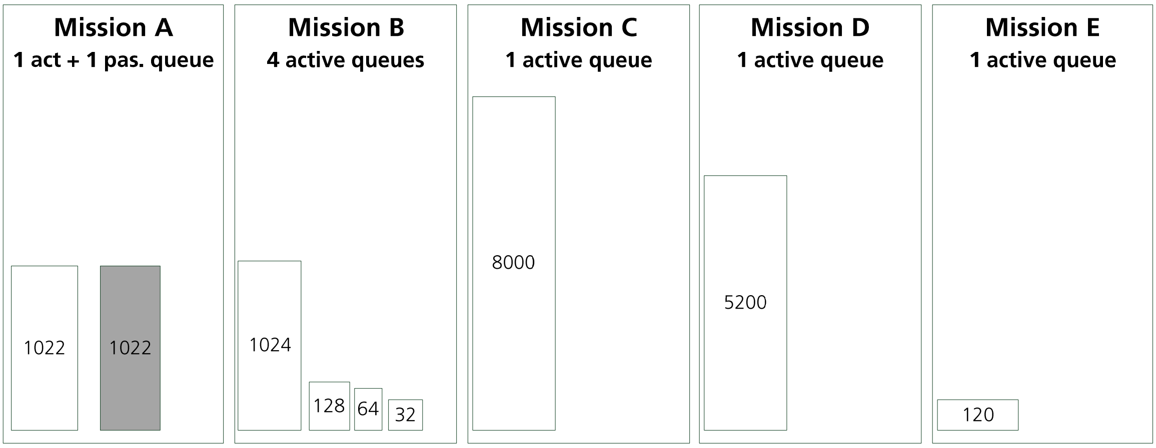

Figure 3: Different onboard TTTC queues for LEO spacecraft

Figure 3 shows the different queue types and sizes used in some of our LEO missions. For the first mission (A) one active queue is accompanied by one passive queue. Commands are uploaded into the passive one and once onboard copied as a whole set and appended to the active one. All other mission have active queues only, mission B has different queues for different TC sizes, biggest commands can only be stored in the smallest queue with 32 spaces. Number and size of the commands must be taken into account during commanding.
In general queue size is driven by the required number of commands between the two longest successive uplinks during (routine) operations, the so called autonomy period. The count can be estimated by the number of required commands for payload/experiment operations, routine ground station contacts and other routine commanding. If we furthermore assume that every now and then one uplink may fail (e.g. control center not ready, ground station problems) we can constitute that a good design approach would be to have the command storage capability of at least twice the size needed for the time between two nominal uplinks and no distinction between size of the commands.

Once uploaded a general requirement is to verify that the uploaded commands are correctly stored in and executed from the on-board schedule. Several verification strategies are conceivable:

- An acknowledgment of the command confirming on-board reception
- Acknowledgements confirming the status of execution
- A counter reporting the number of commands loaded in the schedule (or multiple counters in case of different schedules or sub-schedules)
- A memory dump of the area containing the schedule in its on-board representation
- Reports of the schedule (as defined by ECSS PUS or in a mission-specific format)
- Event reports upon completion of complex tasks

A comparison of the in-house missions (see Figure-4) showed that only the mission that implemented the full set of verification strategies listed above were able to reliably trace the current status of their on-board schedule, even in case of failures. The other missions however only provide means to ensure correct reception and execution during nominal operations. In case of failure however all other missions are forced to delete their schedule in case of doubt and repeat all previous commanding. Furthermore its recommended to use sub-schedule ID's and a commit concept for uplink of essential and payload operations schedule to ensure consistent on-board commanding of big operations timelines by mission planning.

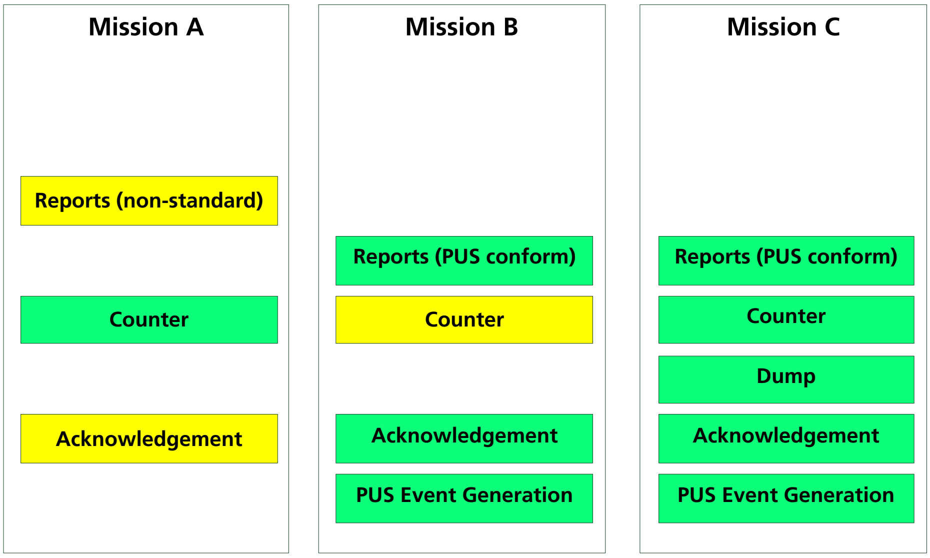

Figure 4: Functions to observe state of the on-board schedule (green – available and useable, yellow available but only limited function)

C. Handling of Software Updates

Even though formally most missions implement ECSS PUS S/W upload service, this is the operational task with most differences across the considered GSOC missions. As for uploading TT commands, also the strategies how to verify what has already been uploaded are differing a lot. A common observation for all missions is that it is critical to receive a feedback on a possible upload failure as fast as possible to enable a fast reaction of the ground segment. E.g. only generating a checksum after the complete upload has been finished may not reveal an error at the start of the upload before several uplinks have already been wasted. Ideally, the satellite should be able to cope with segmented uploads, that can be completed independently and in an arbitrary sequence. So in case of an uplink failure, the ground segment only needs to retransmit a small subset of the upload. This approach significantly helps to reduce the overall time needed to complete a software upload.

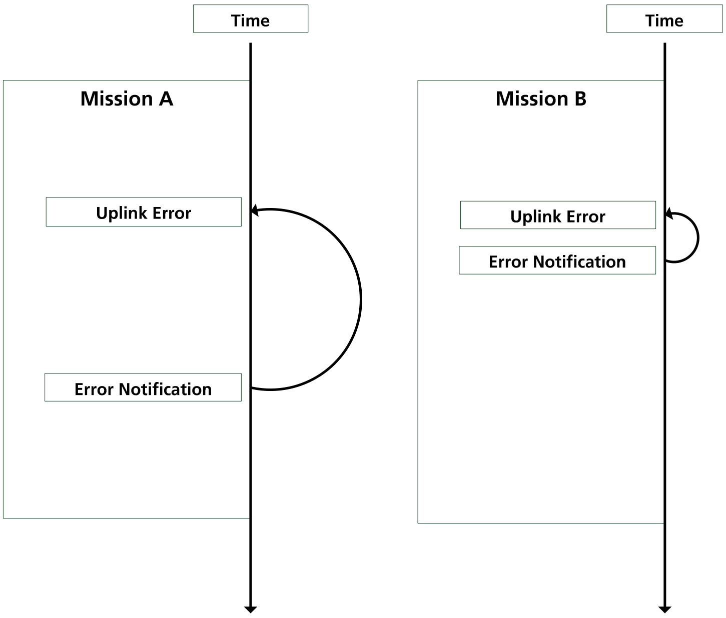

Figure 5: Retransmit interval when uploading commands or software to a satellite

The recommended approach is shown in the figure above as mission B: The timespan of error notification is for mission B significantly lower compared to A. If we consider the time axis to be one pass of a LEO satellite over a ground station the amount of commands to be transmitted in case of an error is lower for B. This allows for efficient use of the available uplink time.

IV. Telemetry

Telemetry is used to receive data from the spacecraft with the main purpose to monitor and determine the status of the spacecraft including the payload. We can distinguish between: (1) Spacecraft real-time-TM and (2) spacecraft historical TM (housekeeping & payload).

D. Spacecraft Realtime-TM

RT-TM is used to control the satellite during ground station contact phases. For CCSDS-based missions, all TM generated and send by the satellite is wrapped into virtual channels, VC0-VC7 according to standard. Typically, only the fraction of VC0 must be processed in real time but it must also be secured that the amount of data in this channel is compatible with the band width of the LEOP ground station network (all real-time data received must be forwarded in real-time to the control center). Furthermore it’s important that all real-time available VC0 packets must be also available as history TM. This is not obeyed by all missions according to our mission knowledge.

E. Spacecraft Historical TM

Historical TM in this context refers to all data generated on-board while the satellite is not visible by a ground station (nearly irrelevant for GEO missions). As data cannot be dumped, it has to be stored for later retrieval. We distinguish two types of historical TM: Housekeeping TM relating directly to surveillance of the satellite bus and payload TM relating to all data generated during payload operations.

1. Housekeeping TM

During our mission survey we found different concepts of on-board TM storage (see Figure 6).

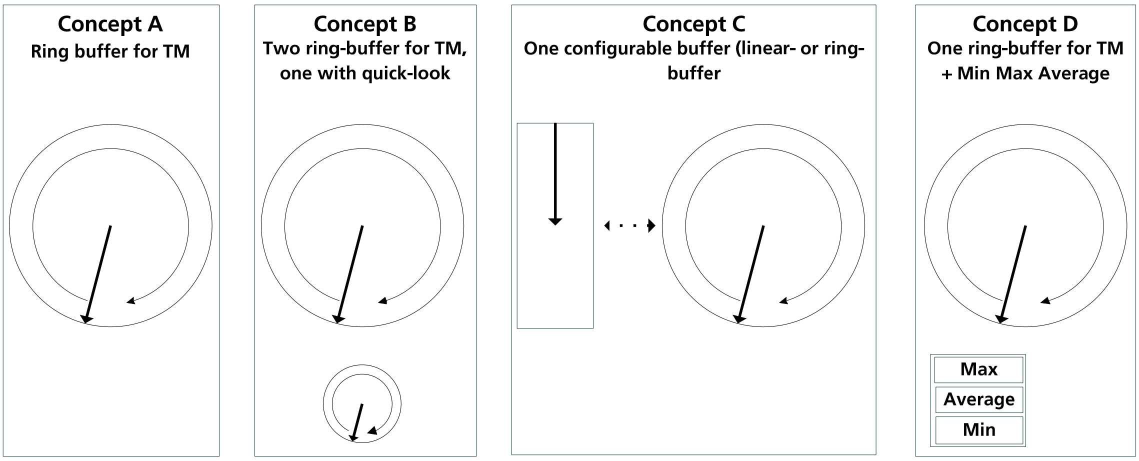

Figure 6: Different storage concepts for on-board historical TM

All missions analyzed by us used a ring buffer concept for TM storage, securing that the most up to date spacecraft TM is stored onboard. In case of an overrun, oldest data is overwritten first. Some missions additionally use extended concepts (see Figure 6):

- Concept A: ring buffer, standard for most missions

- Concept B: Like Concept A, with an additional quick-look buffer, storing TM at a very low sampling rate between contacts, dumped first during pass and shown in time lapse in the control room providing a short summary of the TM since the last contact for the engineers

- Concept C: reconfigurable buffer model, used as linear buffer during LEOP to secure complete data of the spacecraft activation, during first LEOP pass reconfigured to ring buffer when successfully dumped

- Concept D: Like Concept A, with additional information on min, max and average value for selectable values in history TM since last contact (as defined in ESA PUS standard), a very memory efficient concept (only the values per defined TM value to be send additionally)

Recommendation would be usage of a concept based on C and D which combines operational requirements for the subsystems as well as data processing requirements.

2. *Payload TM*

Most of the LEO satellite missions store payload data onboard to be downlinked once ground station coverage is available. Concepts of data storage vary, therefore no good or bad standard could be identified. But within some mission problems or concepts requiring a later on operational work around can be named. First it’s the fact that all data required for later ground processing should be integrated into the payload TM. It may often be that precise attitude or orbit data is needed or other types of satellite housekeeping TM. If directly packed into the payload data stream subsequent routing and correlating of payload and housekeeping TM is avoided. This is also helpful if complete raw data is to be archived; the data set is always complete. Secondly, one should analyze where health data produced by the payload (e.g. instrument) is stored. Operationally essential data produced should be in the housekeeping TM, not in the payload TM. Finally complex management of the payload memory itself should be minimized, a basic FIFO concept of acquisition, storage and dump without loss-less data compression is preferable. All more sophisticated concepts result in substantial grow of operations and mission planning effort.

V. LEOP and Commissioning

Analysis of the two early phases of satellite activation where done in order to identify communalities between the different mission concerning the specific activities and drivers for this phase.

F. LEOP

The hot phase of the LEOP starts when the satellite is separated from the launcher upper stage. Initial activation and configuration of the satellite is the next step. For initial board computer configuration we found two different concepts: (1) Usage of a certain area of the flash memory where the configuration is stored and read directly at computer startup. In this case of configurations are stored as a part of the software image and initial subsystem configuration is read from this area. (2) Usage of a list of telecommands which are loaded after computer boot is finished. A list of configuration telecommands is loaded and stored for execution, like a normal time-tagged telecommand queue. All times are handled relative to computer boot-up. Time dependent configuration steps are therefore easy to handle. Furthermore this list can be used to also store transmitter on and off times for LEOP ground station contacts. This feature is used by one of our missions to control ground station contacts during the first LEOP hours without interaction (commanding of transmitter) from ground as operational or political constraints may limit transmitter operations to certain regions of the world. Nevertheless most missions activate real time TM downlink right after separation following an “always on” strategy. This “always on” should also be considered with respect to energy and thermal balance.

Next step after activation is usually setting of the on-board time by command from ground for LEO missions, needed for relation of time tagged commanding. This is usually followed by deployments of different types, mainly solar generator and antenna deployments. Deployment usually requires a stabilized satellite (earliest point in time). In case of a solar generator; deployment should be completed before significant power problems for the bus arise (latest point in time). The satellite should be designed such that the time window to safely accomplish this task should ideally cover several subsequent ground station contacts to take potential problems into account and allow for an in-depth analysis of the problem before the next try.

Finally most missions have activation of GPS foreseen in the predefined activation sequence to allow for precise orbit determination. It it's recommended to secure during the design phase that a sufficient number of GPS measurements per orbit is generated by GPS for precise orbit determination. Furthermore GPS data should be available to the ground right after activation of GPS: Concepts are known where GPS data require exact pointing of high rate antennas or further activation / mode transitions of the satellite before reception of this data. Goal should be to have this data available in any possible satellite configuration to simplify LEOP operations.

It has been found that the LEOP sequence show similarities for all missions, main drivers are communication and power limitations which should be designed with respect to maximum fail safe operations.

G. Commissioning

The commissioning phase is usually driven by the time needed to check, test and configure all satellite subsystems. Furthermore the type of payload(s) drives length of this phase; complex transmitter, optical payloads or radar instruments may have specific requirements varying from mission to mission. Subsystem check-out is usually done starting with the most relevant sub-system (e.g. AOCS) and finishing with payload activation. It is advisable to avoid timing constraints during this phase, e.g. a certain activity must be completed after a predefined time. An example may be batteries in a payload. Or in general: A high-prio component in low-prio subsystem can be considered as bad design. This requires successful LEOP and subsystem activation and finally activation of the payload in order to load the battery and avoid permanent damage. This latest loading time may significantly drive other activities.

VI. Conclusion

During our survey we analyzed different missions operated in-house. First difficulty was identification of interesting themes which are more or less relevant for all missions. Furthermore the abundance of different wording used by the projects was not anticipated by us as we started our work. It took us quite some time to map our technical subjects to the vocabulary used by the different missions. After that we found three main areas interesting for further review: TM, TC and LEOP & commissioning activities.

The TC and TM capability of the satellite should in general adhere to CCSDS standard to facilitate cross agency support in general. During our survey we found that the different missions usually do not implement the complete set of recommended functionality for on-board schedule observability, telemetry storage and dump as well as size of the schedule. Also the fact that the command upload feedback loop is often too long in case of errors (e.g. upload of software) is often not consequently considered by the missions. This leads to unnecessary additional delays and inflexibilities during operations.

Finally we would recommend as a general design guideline that all on-board activities, configurable items and variables should be observable in a short and concise way by ground during routine operations. This should not preclude the possibility to increase the observation level in terms of e.g. sampling rate, additional related telemetry and event notification as required in contingency cases.

For LEOP and commissioning we found communalities between LEO missions on the one hand and GEO missions on the other. In general the projects should try to identify potential drivers in these phases (e.g. power problems, necessary deployments, mode transitions) and relax the time constraints for these activities as far as possible.

Appendix A

Acronym List

EO	Earth Observation
GEO	Geosynchronous Satellite
GSOC	German Space Operations Center
LEO	Low Earth Orbit Satellite
LEOP	Launch and Early Operations Phase
PUS	Packet Utilization Standard
RT-TC	Realtime Telecommand
TC	Telecommand
TM	Telemetry
TT-TC	Time-Tagged Telecommand
VC	Virtual Channel

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