2 System Simulation in System Engineering

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2.1 Development Process Phases for Spacecraft

The system development of spacecraft is divided into four developmental phases, plus an operational phase and - if necessary - a disposal phase, as depicted in the figure below. The system manufacturer, e.g. of an entire satellite or a subunit, usually participates in the first four phases as well as in the start up at the beginning of phase E. Established during this development process are some important milestone reviews with the customer (which for a spacecraft usually is a space agency or a commercial contractor, for a subsystem it is the spacecraft prime contractor).

The typical milestones, their position within the spacecraft development process together with their abbreviations are outlined in the figure below, too.

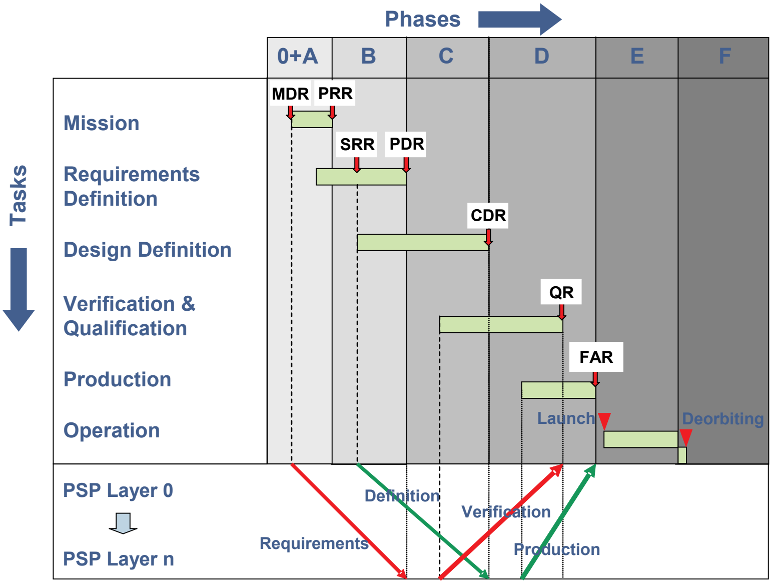

Figure 2.1: Phases and milestones in space projects. Source: ECSS-M30A

Phase A, sometimes including a previous conceptual phase 0, is carried out as a study. During this phase the spacecraft manufacturer analyzes the requirements for a satellite in order to accomplish a specific mission with particular quantitative results. One example is the analysis of requirements for orbit parameters and characteristics in order to achieve the designated resolution and revisit cycles with a certain payload. At this point with the "Mission Requirements Review", (MRR), definition of requirements starts for the the overall system level, which is Level 0 of the "Product Structure Plan", (PSP). This implies design requirements for the satellite itself concerning power supply for the payload, data transfer to ground, attitude and orbit control and requirements for the power and thermal control systems. This analysis is initially limited to pure budget analyses, (e.g. necessary battery capacity on board, memory capacity etc.). The only exceptions are detailed orbit and ground station contact simulations. Phase A is finished by the "Preliminary Requirements Review", (PRR).

The work contracts of phase A are usually assigned to two or more competitors simultaneously, so that the customer, e.g. the space agency, receives at least two different, independent analyses and concepts worked out for the planned mission. The customer chooses the best of the received phase A concepts and submits an "Invitation to Tender", (ITT), for the development phases B, C and D. The phase B/C/D development is awarded in most cases as one contract to the winner of the B/C/D tender. This contract usually includes the support of the satellite operations from the manufacturer at the start of phase E.

During phase B the requirements for the components of a satellite are worked out, for example

- algorithmic requirements for attitude and orbit control,
- qualitative and quantitative requirements on equipment components and their design,
- qualitative and quantitative requirements on the entire system design regarding structure, thermal and power control functionality,
- functional and performance requirements on payload and its control,
- and, last but not least, technical requirements concerning the on-board software.

After the adequate specification of requirements for orbits, system, operational and payload functionalities etc., the "System Requirements Review", (SRR), with the customer takes place. The design definition on system level now begins:

- Initial attitude / orbit control algorithms are developed.
- The exact system topology is specified as product structure.
- First CAD drawings and electrical block diagrams are created.
- Furthermore, thermal and mechanical calculations are performed for the first time.

Phase B is finished with the "Preliminary Design Review", (PDR).
After this review milestone the invitations to tender for equipment subcontractors are submitted subsequently for development and manufacturing of elements on the lower PSP levels.

Phase C is in fact the real definition phase. The design on system level is consolidated once again. Components and subsystems are defined at the level of subcontractors (PSP levels 1 to n). Phase C is completed with the "Critical Design Review", (CDR). For standard components on subsystem level also first equipment verifications take place on hardware breadboard or engineering models.

The subsequent phase D is the production phase, which is finished by the completion of an operational system, e.g. the satellite. The final acceptance milestone is the "Flight Acceptance Review", (FAR). The complete production must be finished by then. For the spacecraft prime contractor however, mostly more critical is the previous milestone, namely the "Qualification Review", (QR). This review marks the successful completion of all equipment verification tests, integration tests and system verification tests. The latter also comprise complex verification in a thermal vacuum chamber and mechanical vibration tests on a shaker. For QR also all parts must be space qualified, (e.g. electronic components such as application specific integrated circuits), as well as all applied manufacturing processes for electronics, soldering, bonding etc.

After phase D, the system is taken into operation (e.g. through launch of a satellite). And within the operational phase E, the system manufacturer still is bound to support the spacecraft operating agency during the commissioning phase and the on-orbit characterization and calibration of payloads etc. For completeness, the disposal phase F shall be mentioned, which takes place after the operational phase E and comprises shutdown and eventual de-orbiting of the spacecraft.

2.2 A System, its Control Functions and their Modeling

A system, except for a few of its passive elements, typically can be abstracted to control functions and controlled physics. This applies for both entire spacecraft as well as subcomponents, for example, a radar payload, a rocket stage etc. Examples for entirely passive elements are, for example, the central structure of satellites - without deployable antennae - or sunshields for optical instruments and so forth. The design analysis for such parts shall not be topic of this book.

Instead the focus of this volume is on system functionalities and control functions which will be formally analyzed and modeled. The design and verification of such functional systems these days is mostly performed through applying system simulation technologies. In this scope both the physics of the system functions, (w.r.t. electrics, mechanics, thermodynamics, fluid dynamics etc.), are to be modeled as well as the specifications of the system controllers. These might range from pure mechanical controls to software based applications. For this sort of integrated engineering approach for system physics, plus control technology, typically system simulations are applied on various levels of detail. The technical criteria for such simulations are focusing on

- analysis and simulation of the interaction of all system components,
- resulting in the simulation of the complete system as a whole, achieved by modeling of:
  - ◊ System components and their functionality,
  - ◊ Component interfaces and interactions through such connections,
  - ◊ The system's external environment throughout operation.

The level of detail and the complexity of system modeling are driven by questions raised from the domain of system engineering. Simulation models only reflect the real equipment functionally, which means, for example, concerning the equipment's communication protocols, its operational modes or power consumption. In functional simulations the goal is not to exactly reflect the internal design of an equipment component. Rather, the level of detail in modeling, the modeled effects and on the other side the resulting simplifications in the simulation are adapted to the requirements and the requested precision. These requirements are driven by the type of system analyses to be performed with the simulator.

System simulation is characterized by application in different development phases of the project. It is an integrated task inside the domain of system engineering. The resulting questions from system engineering - such as system performance verification or system internal failure management verification - impose the boundary conditions onto the applied simulation techniques in a project. Simulation technologies nowadays are very advanced, so that entire complex applications like aircraft, satellites etc. can be developed purely based on simulation techniques. The former development philosophy to implement, for example a separate mechanical prototype for a satellite, (see figure 2.7), and a separate thermal model before assembling the real flight model, is outdated. The old approach also no longer can be financed according to the shrinking mission budgets of private and institutional customers. The reduced number of models however may not endanger mission success. Risk mitigation therefore is achieved via

- a system design based on standardized components as far as possible,
- the simulation of elaborated configurations before start of hardware manufacture,
- and an extensive use of simulation techniques to support all important steps of system design verification, and of "Assembly, Integration and Testing", (AIT).

This technology approach is called, "model-based development and verification". CryoSat 1 was the first European Space Agency satellite project in which the satellite engineering model prototype was replaced entirely by simulation.

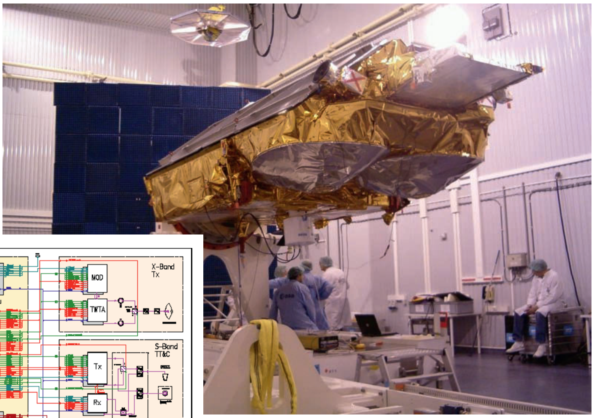

Figure 2.2: CryoSat 1 © ESA

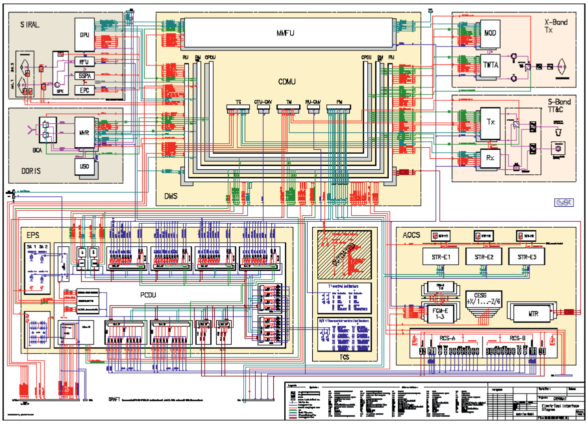

Figure 2.3: Cryosat electrical block diagram. © Astrium

At this point, discussing simulation based system verification, it is relevant to precisely define terms "Verification" and "Validation":

- Verification means checking that all defined system requirements, which are laid down in a formal requirements document, are fulfilled. Proof can be achieved by analysis computation, simulations, tests and inspections - the appropriate method to be chosen according to the requirement type.
- Validation is to check that the system, all in all, performs as originally expected - e.g. for a satellite payload, that it provides the images with desired spacial respectively spectral resolution.

The next paragraphs will start explaining the concepts of system physics simulation and functions simulation. Thereafter the discussion will lead over to verification and validation topics and will explain the verification and validation tasks in overall system engineering that can be based on simulation technology, and tasks which need support by further means.

2.3 Algorithms, Software and Hardware Development and Verification

The application and embedding of system simulation within system engineering is discussed on the basis of the figure below. Modern complex systems, such as spacecraft, automobiles, airplanes, power plants or other machinery installation these days are realized as a combination of hardware equipment and software for control. Figure 2.4 explains the elementary interrelations which are applicable both for the development of overall systems as well as for subsystems, such as satellite payloads.

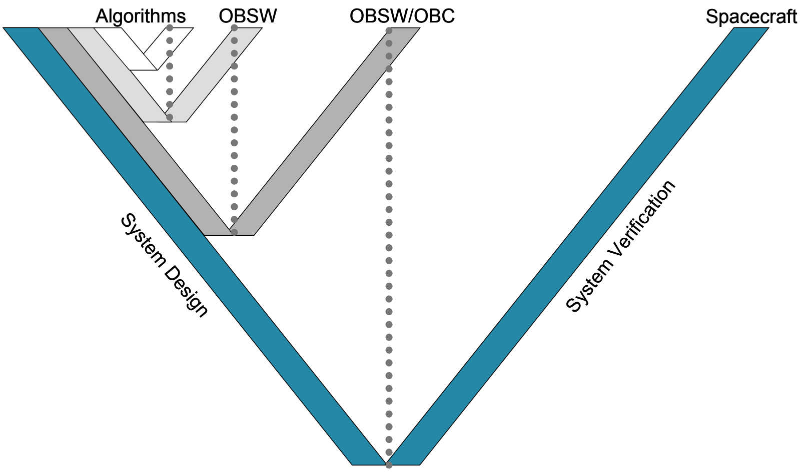

Figure 2.4: Functional design and verification.

The figure depicts the development process as a classic V-model, consisting of the main branches, design and verification. This V-Model however, in the engineering of an entire system, breaks down to a set of interlinked V-steps as shown in figure 2.4. It can be read as follows - from right to left:

- To be able to verify the detailed requirements on the system (here a spacecraft) by system testing, a suitable target computer based control software has to be available.
- This means, hardware (HW) / software (SW) integration has to be completed for this step.
- To verify the proper HW / SW integration, already a pre-verified control software must be available. In spacecraft engineering this is on-board software.
- And finally to be able to pre-verify the on-board software, for the integrated control algorithms - e.g. for attitude control - reference data must be available. The latter come from an algorithm verification campaign, which itself has to be already completed at that point.

The majority of project management literature only tackles, in a simplified way, design and verification of system and subsystem, (PSP levels in figure 2.1), as a semi-two layer problem. The interdependencies from algorithm design down to system verification as shown in figure 2.4 are not addressed. These interrelations however, are essential for understanding which participant in a project at which time is dependent on which input results. Or, formulated vice versa, who in the project will be pushed onto the critical path in development by delayed input.

Figure 2.4 furthermore points to an important fact concerning system modeling and verification infrastructures. For verification of any functionality test, infrastructure is needed, independent from the level being of simplest algorithm verification up to extremely complex top level system tests. So in a system development, a design and test environment must be foreseen

- for the control algorithms,
- for transformation of the algorithms into on-board software code (before being integrated with target hardware),
- for hardware / software integration and finally,
- for the entire system - here spacecraft - including its integrated on-board computer.

In the ideal case, all these infrastructures should be based on a common toolkit suite and the results should be portable from one development step to the next. The requirements, functionalities and implementation examples for such an overall infrastructure are presented in chapter 3. The verification concept for a spacecraft including its on-board software, as shown in figure 2.4, already depicts a stepwise development principle, which also is applied in many other industries:

- In an initial step, the physics of the system is modeled - in software or as a test stand - and the developed control algorithms are integrated to control the system. The algorithms mostly are not yet implemented in the target programming language, neither on targeted hardware. This type of test is called "Algorithm in the Loop“.

- Secondly, the algorithms are coded in software in the target language. The now available control software is loaded onto the - eventually modified - test stand, again, to control the system. This type of tests is called "Software in the Loop“.
- The third step is to load the control software onto a representative target computer, which now controls the hybrid test stand. The final software on the target computer now has simulated system physics. This principle is called "Controller in the Loop“. The first step of tests is the software integration on the target computer.
- The fourth and final step of system testing now aims to make the control software on the target hardware now control the real system, and no longer the test stand's system simulation. This deployment phase is called "Hardware in the Loop“, (HITL). In spacecraft development simulators here are required for computations of stimuli parameters to reflect gravity-free space conditions.

For all these steps, each time the requirements documentation for the "Item under Test“ - the algorithm, the on-board software, etc. - must be written. The principal verification approaches are to be documented, the design of the item under test is to be documented and finally test plans for the verification are to be generated and results are to be collected and analyzed in test reports.

This kind of simulation based system development approach requires fundamentally new workflow processes to be applied, both concerning applied technology as well as with respect to project organization and distribution of responsibilities. In brief, what is to be managed can be summed up as

- the integration of engineering disciplines such as mechanics / kinematics, electrics, thermal and system operations / data handling,
- the allocation of a simulator infrastructure responsible to the project. This role also is called "simulator architect", and the task is to manage the in-time and requirement compliant development and qualification and installation of the simulation infrastructure.
- The tasks to be managed furthermore comprise the consistent application of simulators, system models, configuration databases and test procedures over all project phases, (B, C / D, E).
- The system design, simulation and verification environment has to be standardized as much as possible to reuse qualified elements in the next space project.
- And finally a consolidated work process is needed for the integrated development and test of
  - ◊ satellite hardware and software,
  - ◊ system simulator,
  - ◊ check-out software and equipment.

It has to be kept in mind that the functionality of the simulation based test stands has to be defined, implemented and verified following an analogous process as explained for the spacecraft itself above.

2.4 Functional System Validation

At end of a system development, the goal is to have a validated system design. This means - see definition of the term, "validation", beforehand - that at system delivery, launch, series production or plant commissioning it is assured, that the system functions as expected. And this is regarding functionality, reliability and especially performance.

For this validation, either multiple test stands are required - not to be mixed up with the verification infrastructures discussed in the previous section, since for verification of system requirements a test stand eventually only needs to comprise parts of the overall system. Alternatively, also a test operation of the real system can be performed. In the automobile industry, an example for performance validation would be testing a new car prototype on a roller rig following a specified load cycle to validate the fuel consumption. A real system test could, for example, be a road test on a test track, a drive under polar or desert climate conditions.

However, here exactly are where the specific problems arise for spacecraft. An automobile prototype which on the test track does not accelerate, brake as desired, shows insufficient steering control response or otherwise performs inadequately can be reoptimized before series manufacture starts. E.g. drive train geometry can be perfected.

Spacecraft - and especially Earth observation satellites and deep space probes - themselves are prototypes. A validation of single major components, e.g. of a radar payload in an EMC chamber, usually is achievable. Tests comprising the entire system under real space conditions impose a huge effort. System tests which typically are still carried out before launch, based on "test stands" are thermal tests in a thermal vacuum chamber,

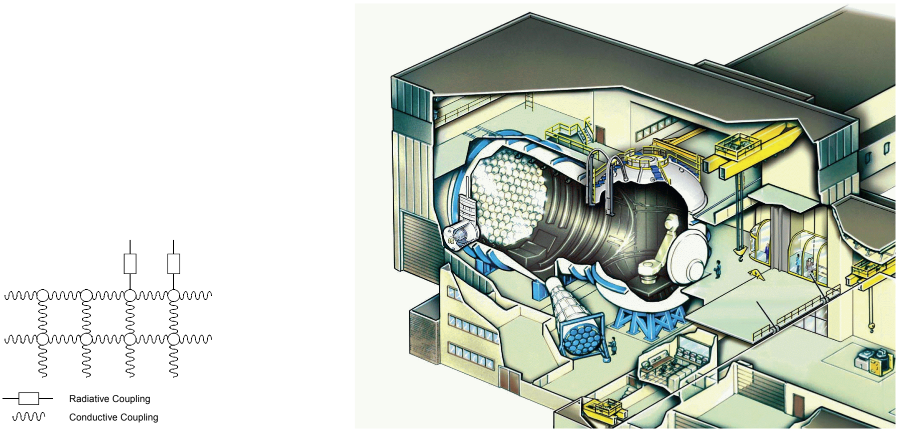

Figure 2.5: Analyses and tests of thermal design. Cutaway © ESA

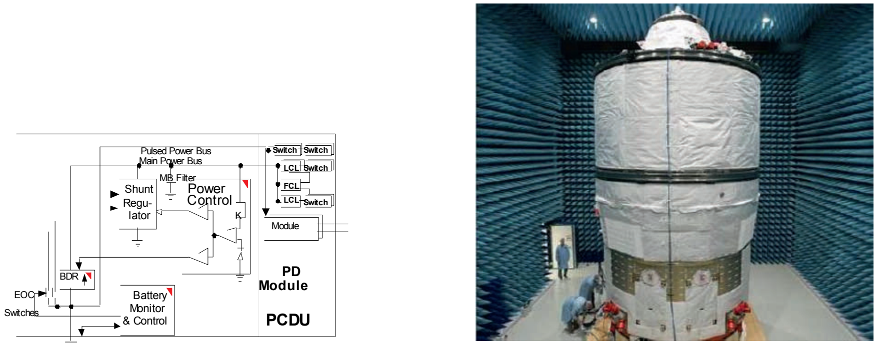

Figure 2.6: Analyses and tests concerning electromagnetic compatibility. © Astrium

tests concerning electromagnetic compatibility, (EMC), of the overall system in an EMC chamber as well as tests concerning structural mechanics compatibility to the load spectrum of the foreseen launcher. These tests are performed with the spacecraft on a shaker.

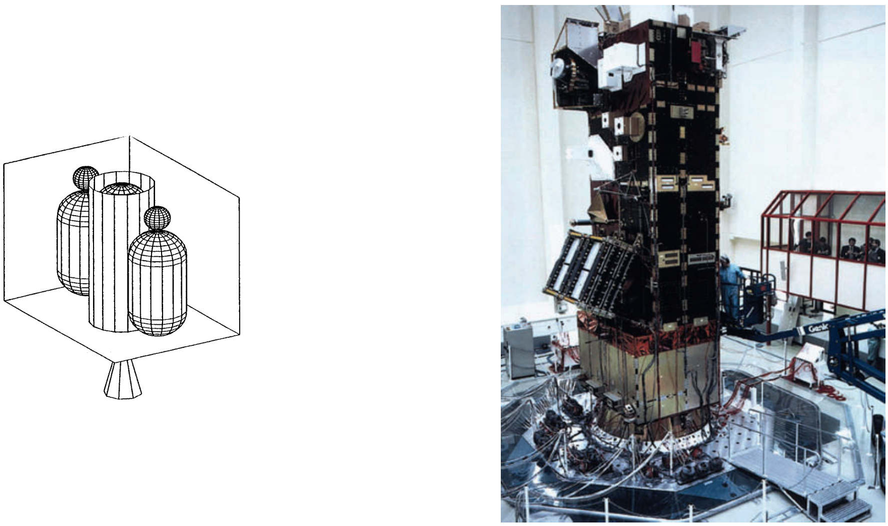

Figure 2.7: Analyses and tests concerning structure mechanics. Photo © ESA

The validation of functional behavior however, turns out to be a very difficult topic, e.g. for validation of correctness of attitude and orbit control - as an analog to the cited driving dynamics test of an automobile. For a spacecraft, the essential zero gravity conditions cannot be provided on Earth. Therefore it theoretically is necessary to work with test stands where attitude and position of the spacecraft can be modeled geometrically. On 3-dimensional turn table test stands with mounted spacecraft sensors, e.g. Sun and Earth visibilities for each sensor formerly were simulated by optical and infrared lamps. Similar setups existed for optical injection of star positions into star trackers. On these turn tables, at the same time, the angular rate sensors of the spacecraft could be stimulated.

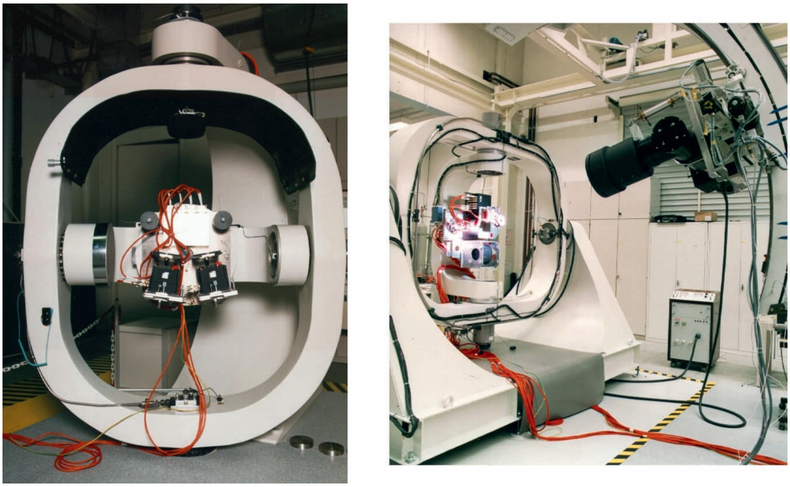

Figure 2.8: Turn table installation with Sun and Earth simulator. © Astrium

From the figure of the turn table installation shown above - which is limited to stimulation of Sun and Earth sensors of a satellite attitude control system - the test bench complexity already can be estimated. The complexity even increases if a comparable approach is to be followed for additional attitude sensors, rotational rate sensors and finally also the for satellite's actuators - eventually even the pyrotechnic ones. Including all this hardware equipment in a closed-loop verification test stand is far out of financial mission budgets today.

For this reason, at least for unmanned spacecraft, a more pragmatic approach is followed based on simulation technologies as they are treated in this book. The approach comprises

- the limitation of validation tests on component tests,
- to verify the entire system against its specifications as soon as possible,
- the verification of the on-board software, (OBSW), in a consistent approach from "Algorithm in the Loop", down to runs on target hardware against real system components and,
- to limit the system validation on the test stand types for thermal, mechanical and EMC as depicted in figures 2.5 to 2.7.

This mitigates the risk of an entirely non functional system, to an acceptable level and the final performance validation is carried out during the on orbit commissioning part of the operational phase E. In theory, not before these final tests, the system design validation is closed and the same applies for the design of all applied test infrastructures which were used for intermediate verification steps.

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