ESA's Kiruna Station Monitoring & Control System evolution – An innovative approach for the replacement of the ground station's "brain"

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Abstract

Kiruna G/S [1] is the prime TT&C station utilised by the Copernicus Sentinels missions [3]. The monitoring and control system deployed at the station, the so-called Central Station M&C System (CSMC), was based on a non-virtualised solution relying on a legacy operating system (QNX 6.3.0). The usage of this operating system imposed some limitations in terms of maintenance and evolution of the CSMC due to the obsolescence of the supported hardware. In addition, the current system was not optimised for handling the needs of the Copernicus Sentinel satellites. Therefore, the system upgrade was declared as a critical activity that involved not only a pure system upgrade in terms of up-to-date technology, considered as an end-to-end industrial service, but also to handle a stringent environment for deployment and operational validation. Station downtime had to be avoided, so a very thorough and adaptable planning was generated closely among all the stakeholders. Even more, the system had to be extended to cope with the new requirements required by different Copernicus missions [2] which made the activity highly challenging and to face a non-expected situation derived from the COVID pandemic. The result was a successful operational deployment and validation of a critical complex system under a very constrained environment. This goal was reached thanks to the highly flexible infrastructure, which was exploited at its highest limits, allowing a fully remote deployment without impacting the operations.

This paper describes the CSMC replacement focusing on the innovative operational deployment and validation activities with no operation impact.

Keywords: "operations" "ground station" "availability" "remote validation" "virtualization" "stringent environment"

Acronyms/Abbreviations

Central Station Monitoring and Control (CSMC)
European Space Agency (ESA)
ESA Operations Centre (ESOC)
European Space Tracking (ESTRACK)
ESTRACK Control Centre (ECC)
Ground Station (G/S or GS)
Ground Station Reference Facility (GSRF)
Graphical User Interface (GUI)
Human-Machine Interface (HMI)
In-Factory Acceptance Test (FAT)
Inter-process communication (IPC)
Low Earth Orbit (LEO)
Monitoring & Control (M&C)
Network Operations Centre (NOC)

Operations Control Centre (OCC)
Operating System (OS)
Portable Operating System Interface X (POSIX)
Real-Time Operating System (RTOS)
Remote Work Station (RWS)
Telemetry, Tracking and Command (TT&C)
Virtual Private Network (VPN)

1. Introduction

Upgrading an operational Ground Station (G/S) without impacting the operations (i.e., minimizing or even avoiding the need of any downtime) is a very challenging task. Depending on the upgrade activities to be performed, avoiding service interruptions is often unfeasible for ground stations having a single antenna and, even for multi-antenna ground stations (i.e., G/S with multiple front-ends, downlink and uplink chains), the augmented complexity and coordination effort are rather aspects to be carefully assessed and considered, especially for G/S supporting heavy operational workloads.

This is the case of ESA's Kiruna Ground Station (see Fig. 1), located in Salmijärvi region, in northern Sweden. A key element of the ESTRACK core tracking network, Kiruna is a multi-antenna site serving as prime ground station for Telemetry, Tracking and Command (TT&C) operations for all Earth Observation missions operated by ESA, including Earth Explorers and the Copernicus Sentinels satellites. Additionally, it serves as prime communications hub for ESA´s critical scientific missions such as Integral. The station is loaded to its maximum tracking capacity, currently supporting an average of 30 passes per day for 18 different missions, circa. 750 tracking hours per month comprising long duration passes (typically > 48 hours) for scientific missions and Earth Observation missions with multiple passes of shorter duration (typically <15min). To meet these requirements, adopting automated ground station operations is a must.

Fig. 1. Kiruna Ground Station Aerial view (Main Operational Building, Power Plant, Kiruna-1 and Kiruna-2 antennas)

The full automation is implemented by Kiruna's ground station "Central Station Monitor & Control system (CSMC)". Sometimes referred as "the ground station brain", the CSMC allows the ground station to support fully automated operations and provides full monitoring and control to the station by means of a remote operational network. It has been designed to cope with highly demanding requirements on dynamic configurability and resource management of Low Earth Orbit (LEO) satellite tracking stations. To this purpose, it provides several utilities for mission-specific configuration and multi-mission support, such as multi-antenna handling, parallel operations and resource management, to guarantee optimal exploitation of both simple and complex multi-antenna configurations as well as multi-chain ground stations.

Mainly driven by the obsolescence issues of the precursor system, a full evolution encompassing all aspects of the CSMC was required to comply with the high reliability and availability standards required by the current and future missions. The adoption of novel approaches was instrumental for the replacement of such a critical system in order to avoid operations interruptions. Moreover, the COVID-19 pandemic obliged us to redefine the development/deployment approach in the course of the project, aiming at minimizing the impact on budget and schedule of the crisis. The solution adopted was based in a fully remote implementation and deployment.

This contribution aims at sharing some high-level concepts and experiences with the space operation community, mainly related to the deployment, testing, and operational validation of the new version of Kiruna G/S's CSMC. This was a major upgrade of the ground station aiming at porting the CSMC from obsolete hardware and software platforms (based on Industrial PCs and a legacy real-time operating system, QNX 6.3.0) to a fully virtualized environment based on Linux SLES-15. Additionally, the ported system included further adaptations and enhancements to optimize the systems and cope with the increased support demand required by the Copernicus and Earth Observation multi-mission systems.

The upgrade was successfully accomplished, ensuring operational continuity during the whole upgrade period, by using some innovative practices and technologies, such as:

- Early validations by incremental implementation and deployment: An incremental development cycle was adopted to enable early validation campaigns of the most critical CSMC components (e.g., kernel, communication protocols, real-time performance, dynamic mimics, flexible tailoring…).
- Virtualization: The continuous obsolescence of the HW IPC used for this kid of systems implies a regular SW upgrade that can be avoided by integrating it in a virtualized environment. This scheme provides more advantages such as flexibility and scalability, backup support, reduced reaction time under stringent circumstances…
- Remote test and validation in operational environment: Remote access via a Virtual Private Network (VPN) to all CSMC nodes in Kiruna/ECC to conduct tests in the real operational environment was one of the keys for a successful upgrade. This was one of the cornerstones to deal with the COVID-19 situation and adapt to the stringent G/S availability with no operations impact.
- Ground station splitting: Drawing on the modular and flexible distributed architecture of the CSMC, it was possible to split the station into two independent systems running in parallel for the test campaigns: an operational system, comprising the subset of GS devices required to keep providing the GS services, and a test system, with a subset of GS devices to be used in the tests. Each system being managed by its own independent instance of the CSMC, allowing the coexistence of both, the old and the new system during the validation campaign.

In this paper we describe all these features and how they were exploited to achieve the successful deployment and operational validation of the new system in Kiruna.

The paper structure is broken down in the following sections:

- Motivation for the Kiruna G/S brain upgrade.
- The upgrade.
- The deployment strategy.
- Results and current status.
- Discussion and lessons learnt.
- Conclusions

2. Motivation for the Kiruna G/S *brain* upgrade

The Central Station Monitor & Control System (CSMC) is an application intended for ground station management, not just M&C. It allows the ground station to support fully automated operations and provides full access to the station from a remote operations network. The CSMC has been designed to cope with highly demanding requirements on dynamic configurability of LEO satellite tracking stations. Therefore, it provides utilities for mission-oriented G/S configuration and multi-mission support: multiantenna sites, parallel operations, and resource management.

The CSMC ran on a standard PC platform, on top of a real-time UNIX, POSIX compliant operating system specially design for the PC platform (QNX). QNX has true microkernel design, and its modular architecture enables to create highly optimized and reliable systems.

The CSMC architecture is modular and is distributed over several machines (normally referred to as nodes), attending to system complexity and size (scalability). It is automatically configured on a role basis: At start-up, each node reads the CSMC processes to run (i.e., the "role" it will play) and the inter-node relationships. Usual CSMC roles are:

- ACQUISITION: Accomplishes the interface to any GS subsystem or equipment.

- MASTER: The MASTER node is the responsible for the centralized prime services, like main logging, scheduling and serving the remote interface.

These roles are not exclusive, so one node can play several roles, and they can be re-assigned dynamically. This flexibility brings the possibility to implement different types of redundant or high availability configurations, including hot redundancy. In this way the system allows, for example, easy replacement of faulty nodes keeping the system operational. The deployment of the CSMC for Kiruna comprises nine nodes in total, five locally at the ground station and four at the remote ESTRACK Control Centre at ESOC (ECC). These nodes are all synchronised, running the same CSMC software version. The adaptation of the CSMC to a particular ground station is accomplished by means of a tailoring process, in which software development is reduced to a minimum.

The CSMC ran on a UNIX-like (POSIX compliant) real-time operating system, QNX RTOS. This OS had been selected in the past because it was specially designed to provide real-time performance, including a powerful graphical user interface, in PCs.

QNX were still a powerful OS, widespread in critical applications. However, its evolution strategy had been gradually aiming at embedded systems and critical applications, where its micro-kernel and high-performance features make it very competitive against other solutions (e.g., Linux systems with RT-kernel and other OSs for embedded systems). The support of QNX for desktop/workstation systems as the CSMC had been gradually left aside, provided that, thanks to the evolution of the hardware in this kind of systems, the performances achieved with non-real time operating systems like Linux were acceptable for this kind of applications, so there was no need for a true real-time OS.

The evolution strategy of QNX resulted in two main problems for applications like the CSMC:

- Hardware obsolescence: As QNX was not investing effort in supporting new hardware for desktop/workstation applications, like, for example graphical boards.
- Operating System obsolescence: Conversely, it was found that new versions of the OS did not include drivers for the hardware used by the CSMC. Moreover, due to the evolution focused in embedded systems, new versions of QNX usually introduced changes in basic services without supporting backwards compatibility.

These two issues together made it very difficult to carry out OS upgrades in the CSMC platform. In consequence, the OS version used by the CSMC were an old version (QNX 6.3.0)

3. The upgrade

The solution selected to solve this problem was to migrate the system to run on top of a Linux system (SLES-15) in a virtualized environment. This OS is in line with ESA's Ground Segment Data Systems harmonization initiative, and it was already being used by other systems in ESA's ground stations M&C hierarchy. In addition, the new system had to include a set of improvements identified to cope with Copernicus missions' requirements.

Therefore, this upgrade comprised three critical activities which technically concentrated most of the risk of the project:

- Replacement of OS, from a RTOS to a non-RTOS.
- Virtualization
- New developments

Note that the first two features are major changes that, in principle, could have had a significant impact on the overall system performance. Thus, it was necessary to conduct first some preparatory studies to assess the feasibility of the upgrade. Besides, once these studies were successfully completed, an appropriate strategy for the upgrade was defined, designed to allow the early detection of any possible performance issues that could appear in the operational environment.

4. The deployment strategy

Since the aim of the project was to obtain a CSMC Linux system with at least the same capabilities, performance and functions of the QNX-based system, the use of a modern OS solved the obsolesce problems shown by the current system.

The approach selected to achieve that goal was based on the following premises:

- Incremental implementation/validation, anticipating tests to detect problems as early as possible.
- Test execution on an operational environment, as the actual conditions cannot be fully reproduced in a factory test bench or even at the Ground Station Reference Facility (GSRF). For that purpose, it was planned to start conducting tests on the real system as soon as the new hardware was available in Kiruna and the ECC. Those tests would be conducted accessing the system remotely via a VPN, as this channel was available for maintenance activities on the CSMC system.

- Minimize impact on operations: the strategy was aimed at achieving a smooth installation and operational validation of the new system in Kiruna, without interfering with the operational CSMC so no station downtime would be required. To achieve that, a gradual deployment and testing strategy was proposed, where the coexistence of both the old and the new system during the whole validation period was required.
- Provide the activity as an end-to-end industrial service, comprising all tasks from the initial analysis of requirements, implementation and verification of the technical solution identified, the tailoring of the station automatic jobs and the final operational deployment and validation at Kiruna Ground Station. The idea was to reduce dependency on the customer in station engineering issues. In order to ensure the coverage of every system's requirement a multi-disciplinary team was set, from generic software/M&C profile to ground station engineering expertise. The ground station support was required mainly for the migration, improvement and validation of jobs, the identification of possible improvements and in the whole validation process of the new system.

4.1 Virtualisation

Virtualisation was the selected solution to cope with the HW platform obsolescence. The old QNX RTOS lacked enough HW drivers as new components appeared in the market, and it made the HW evolution a very hard activity to undertake. In a very demanding physical environment (24x7), the HW must be reliable, and any failure could result in a direct operational impact. Virtualisation avoids it by encapsulating the HW details and providing a higher layer of redundancy that minimizes (or completely removes) those potential operational risks.

The deployment of the CSMC in a virtualised environment also provided the flexibility and agility required to swap from the operational system (in the old hardware platform) quickly and safely to the new system under testing. The CSMC is a distributed system comprising at least 5 local nodes in the Kiruna G/S and other 4 remote nodes at the ESTRACK control centre (ECC) in ESOC. Having the new system deployed in physical nodes would have implied very tough and cumbersome swap and roll-back processes that would have prevented the use for testing of many of the short availability slots naturally available in Kiruna during gaps between nominal operation supports.

4.2 Incremental Validation

Having in mind the challenging circumstances under which the system had to be developed and deployed, an incremental implementation was thoroughly defined, proposed and agreed with ESA. The success of the new SW operational validation depended on the fine-tuning planning of every activity. Thus, it was undertook as expected by producing incremental SW releases that were coping with the requirements' set from bottom to top. Three main steps were conceived:

- V0: The first step was the replacement (in QNX) of the inter-process communication (IPC) layer (QNET) dependencies, prior to the porting to LINUX: As the QNET services was replaced by TCP/IP-based socket-services, it was implemented and validate it first in QNX. This produced an intermediate CSMC version, QNET-free or Linux-ready, that ran under QNX, and at the same time compatible with SLES-15. That is, all dependencies of QNX-native features were removed. Having this preliminary version provided the following advantages:
  - It allowed to anticipate tests of the internal communication mechanisms among CSMC processes (i.e., commanding and data processing flows, parameter subscription and broadcasting, alarm and event notifications, etc.), as they were the mechanisms affected by the replacement of the QNX-native services by POSIX-SLES compatible ones. Those tests enabled the early detection of any problem related to these internal mechanisms that are the core of the CSMC distributed architecture.
  - Once CSMC V0 was validated, porting activities of the modules that did not have any specific HMI was quite straight forward, as they consisted mainly in recompilation and thorough unit testing of each ported module.
  - This version eased the deployment and validation activities, thanks to the compatibility among QNX and Linux CSMC nodes: It enabled a gradual deployment approach, as new nodes were introduced by replacing QNX nodes one by one.
  - Furthermore, operations could be supported by a combination of QNX and Linux nodes (e.g., nodes with QNX HMI were used with LINUX nodes). This was a very smart and useful feature for the deployment phase, as the CSMC V0 QNX nodes could have be used as backup of the final SLES ones.

  V0 was extensively validated in the GSRF in an in-Factory Acceptance Test campaign (FAT) and, but not in the final environment as (Kiruna), and it was not conceived to be left operational after the validation.

- V1: The first version in SLES-15 aimed at testing all the CSMC M&C kernel and external interfaces (acquisition tasks, OCC I/F) already migrated (i.e., the MASTER and ACQ nodes). It included all the basic M&C HMI (i.e., mimics, AND displays, alarm handling, ...) already running in Qt/SLES-15 and an initial implementation of the automation tools. Therefore, this version served to validate the performance of the new system in operations. As the adapted QNX nodes were compatible with the new SLES-15-base nodes, the not-ready HMI utilities ran in QNX USER nodes. Therefore, this version could have been operational, if need be, although the initial idea was to revert to the QNX CSMC after the tests. This next step provided a high-level of confidence aiming at the final system which had to be operational but lowering the testing hours needed to cope with all the features.
- V2: This was the final version of the CSMC under SLES-15, with the full functionality and the improvements that might had been agreed during the project. This last release focused on the system integration phase and operational validation under real circumstances with no station downtime. Its purpose was to verify the CSMC M&C kernel with the new tailoring (synchronized with the last CSMC QNX), external interfaces already validated (i.e., the functionality of the MASTER and ACQ nodes), and the new graphical applications, including the HMI Console. It included the final implementation of the automation tools. Therefore, this version was planned to be the one to validate the performance of the new CSMC kernel in operations. The V0 USER kept being used to support the HMI Console validation for comparison purposes. Although this version was intended to be operational, the CSMC QNX version acted as back-up to roll back in case the CSMC Linux would have not achieved the major objectives. This degree of flexibility was one of the main keys of the success of the porting activity.

Although the deployment and testing of intermediate versions could bring some overheads compared to a single deployment and testing campaign at the end of the project, it's worth to do it, since, as it was learnt from other porting activities, early detection of problems is one of the keys for the success. Moreover, the compatibility between QNX and SLES-15 nodes provided a backup solution that was used temporarily in case that unexpected problems were found with any of the new HMI utilities.

4.3 Remote testing

The incremental validation strategy described above implies a significant number of test campaigns to be conducted in-factory (at TTI premises), in the GSRF (at ESOC), and in the real environment (Kiruna and ESOC). Nevertheless, simulation environments at the developer's test bench and even at ESA's Ground Station Reference Facility (GSRF) are not representative enough to ensure smooth and fast site acceptance testing activities and therefore fully support the operational validation phases. Thus, several remote testing campaigns, also during operational slots (i.e., between passes), were performed. Remote access provided the flexibility required to take advantage of short time intervals that, besides, frequently happened out of nominal working hours. Moreover, the upgrade was carried out in 2020 and 2021, under the severe restrictions imposed by the COVID-19 pandemic. Under this peculiar situation the remote validation played a key role in the success. Full operational validation and final deployment of the new system was successfully carried out remotely, implying a significant coordination effort among all actors located across different European locations: Kiruna station, ESOC and TTI; all working together to achieve the same objective. Although the initial project plan already included remote testing, combined with some on-site test campaigns, as a key element for the project success, the travel restrictions resulting from the COVID-19 pandemic, declared just before the start of the deployment and testing phase, made remote testing the only feasible alternative to carry out all the planned testing campaigns.

Remote testing was feasible because TTI is authorised to use a VPN (only enabled upon request) to access the CSMC systems in ESOC (GSRF and ECC) and Kiruna for maintenance purposes. This VPN is a critical element in the system support, as it allows to conduct remote installations and tests in a very efficient way, resulting in a very significant reduction of travel costs. So this VPN access was extensively used during the porting activities, for tests at the GSRF, ECC and Kiruna. The travels foreseen in the initial plan were completely eliminated by making use of this remote access facility. This elimination allowed to move that effort and cost to new improvements that enhanced the system to cope with the new Copernicus' missions support.

Remote tests were thoroughly agreed and coordinated with the customer and the G/S M&O team at the station, considering the operational constraints of the station. They revealed as very important to anticipate problems in the acquisition interfaces with the station devices and in the overall performance of the system.

So, in order to reduce the impact on operations, a gradual approach for the deployment on site was proposed (at Kiruna and the ECC) of the first SLES version of the CSMC (V1). It took advantage of the following features:

- The new CSMC system had to be deployed in a different hardware platform. This made this upgrade different to previous major CSMC upgrades, as it was possible to have both systems running at the same time, although only one of them would be connected to the external interfaces.
- The CSMC remote workstation interface (RWS I/F), i.e., the interface between the local system in Kiruna and the nodes in the ECC at ESOC, was already platform independent and was not changed in the upgrade.
- The tailoring version was the same in both CSMC systems. Modifications on the tailoring that were required during the project were implemented in both systems to keep their tailoring data synchronized.
- Consequently, CSMC SLES nodes in the ECC could connect to the QNX nodes in Kiruna. Moreover, the CSMC already supported a redundant connection between Kiruna and the ECC. Thus, it was possible to have both sets of nodes (SLES and QNX) running in parallel at the ECC, and all connected to the CSMC in Kiruna.

4.4 Deployment and validation strategy (Ground station splitting)

Based in the above facts, a deployment and validation approach in two steps was proposed:

- STEP 1:
  - Deployment of the remote nodes at the ECC (see Fig. 2):
    - As explained above, the CSMC under QNX provided two communication channels between the local nodes in Kiruna and the remote nodes at the ECC.
      MASTER <-> R-MASTER
      USR1 <-> R-USR1
    - It was planned to replace the remote user node, R-USR1 by the new SLES R-USR1.
    - Another new remote USR was connected to that node, so the new subscription mechanisms could be tested with a minimum impact on the operational system.
    - This approach would allow tests being done firstly out of operations, but they could continue during operations, as the new nodes can run in parallel without interfering with operations.

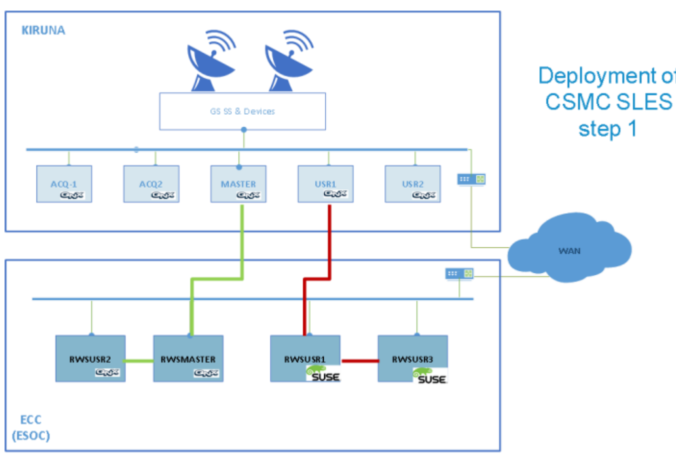

Fig. 2. Deployment Phase: Step 1

- STEP 2:
  - Deployment of the local nodes in Kiruna (see Fig. 2):
    - New CSMC SLES nodes then were installed in Kiruna. The new system became operational just by stopping the QNX ACQ node and starting the new SLES one
    - Two sets of CSMC nodes ran in parallel, only one of them in operation, to enable easy swapping from the operational version to the new one

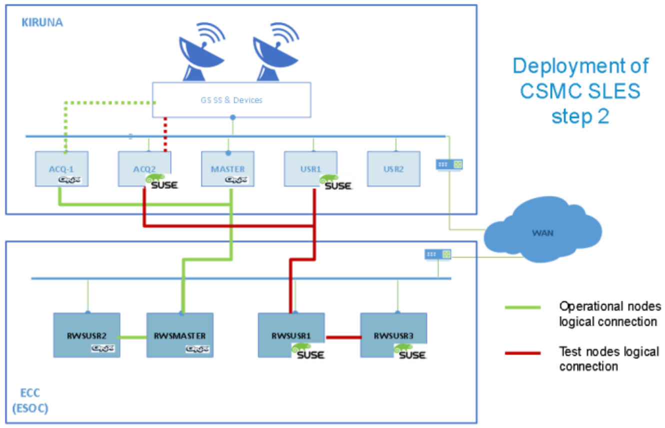

Fig. 2. Deployment Phase: Step 2

Last but not least, the good achievement of the goals couldn't have been possible if the relevant stakeholders were not involved in the porting activities from the very beginning. ESA, as the final customer, was consulted continuously, and the NOC personnel and the Kiruna M&O Teams played a crucial role. The latter provided support in the ground station engineering aspects, more precisely on:

- Analyse and contribute to the proposed solutions considering not only technical but also operational aspects.
- Contribute with the expertise in ESTRACK ground stations.
- Support during the validation activities, with special attention to the automation tailoring for Copernicus, the so-called jobs.
- Contribute with the expertise in other non-ESA similar systems (ground stations and M&C).
- Provide support during the on-site activities at the ground station during the Site Acceptance Tests (SAT).
- Coordinate the work performed in this project with the daily tasks at the station and the required support from the M&O.
- Coordinate with the activities for the planned Kiruna front-end upgrade.

5. Results and current status

The results were achieved gradually as the different SW versions (V0, V1 and V2) were produced, deployed and tested. As explained before, the objectives of each version were different but incremental, so the next version relied on the results of the previous one. Consequently, as a summary:

- V0: It was successfully tested in the GSRF's ESA environment, supported by expert key personnel. The testing environment was composed of a VMWare vSphere ESXi 6.5 platform (same as the final one) and 5 virtual machines. Those virtual machines ran simulators of the most complex subsystems that compose the Kiruna G/S (FEC, Cortex-XL, IFMS, TMTCS…).
- V1: A FAT campaign and a SAT campaign were conducted in this phase. For this paper, the SAT campaign results are the most relevant ones as it was driven in the real environment. V1 was the first CSMC version running SLES-15. It included an initial implementation of the automation tools, so, it already served to validate the performance of the new CSMC kernel in operations. A mix infrastructure composed of CSMC QNX and CSMC Linux nodes was established, benefiting of the outcomes from V0. In the beginning, two days of pre-SAT and 5 days of SAT were planned. These days were selected to minimize the downtime needed and to work in parallel with real operations. Since the remote access (VPN) allowed to work at any time, the booked slots were agreed with different missions and a no operational impact was introduced. Even more, since this version was not intended to be operational, and the objective was to revert to the QNX CSMC after the tests, no risk was foreseen.
  The result was the expected: the CSMC Linux was executed successfully in the real environment for the first time and the main SAT objectives were fully achieved low-level and automation tools successfully validated. In addition, the performance observed of the new CSMC kernel in operations was really good: average load was about 0,6 and queues load were not significant.
  It is worth mention that this version was able to shadow track several passes of CRYOSAT mission.
- V2: Since planned as the final version to be put in operation, it consolidated the CSMC version running in SLES-15. The result was a smooth validation through several testing campaigns avoiding impact the ongoing operations.

Despite the fact that the real environment (with the new virtualization platform completely deployed) was the main testing realm, the TTI's testbench and the GSRF were extensively used for problems assessment and resolution during period of time that the station was not available. In both sides, a virtualization environment existed attempting to be as close as possible to the real one.

The testing approach was incremental as the whole station was available only for a few slots. During the rest of the slots, only one terminal or the other (KIR1 or KIR2) was available, or some devices were needed to support a particular mission (usually CRYOSAT). Furthermore, the objective was to carry out the verification and validation tests with the minimum risk for the mission's operations. This fact implied to split the CSMC system in two main chains: one running CSMC QNX and another one running CSMC Linux. It guaranteed the full operational validation with only the available slots to not impact the operations. 38 slots were used for testing and onsite acceptance during limited access to the station. 11 slots for operational validation (around 161 hours) were used whereas only in one session the system had to be rolled back to the backup one before leaving it fully operational. It is worth mention that the system validation (from partial to total) started on 25th January and ended on 13th May, where the system completely replaced the legacy one.

6. Discussion and lessons learnt

In view of the testing campaign's flow and its outcomes, and applying a retrospective analysis to how the tests were planned and executed, we may comment a set of lessons learnt:

- The V2 SAT was split into two campaigns to deal with possible bugs and performance deviation that could not be detected during FAT at TTI or GSRF infrastructures. This was a good strategy even when three phases were needed in the end.
- The adopted strategy revealed as successful at this stage as well, as it permitted the end-user to verify and validate the GUI in advance during several operational validation phases.
- Some high-level end-to-end-tests were conducted too early during the first SAT phase. Although it is very useful to perform these tests, in earlier stages it is counter-productive as root cause for high-level errors cannot be easily determined. It's better to face the system integration tests from bottom to top, addressing the end-to-end tests only once all the lower-level functionality has been successfully verified.
- The system split granted the operational usage of the station as different subsystems were verified with the new version. However, some long duration test slots with the complete station were still necessary, as there were performance issues that can only be fully verified with all the subsystems connected during a significant time period.
- The system scalability and testing approach allowed us to face the deployment infrastructure modifications with guarantees (e.g., the VM infrastructure was slightly changed during SAT so it was necessary to re-test some kernel functions).
- Operational validation was spread out in several 24- and 48-hours sessions along a full month. This approach aimed to minimize operational risks, but it made long-term problems arise later.
- The mechanisms established to address a fully remote deployment and validation were defined in the course of the project, deviating from the original baseline (deemed unfeasible under the stringent constraints imposed by the COVID-19 crisis).

7. Conclusions

The new CSMC was operationally deployed on May 17th, and it is continuously running 24/7 since then. A highly innovative approach was selected for the deployment and validation activities to overcome the severe environmental limitations, the basis being a highly flexible system allowing the coexistence of both the old and the new systems, a full remote access to the ground station and an extensive coordination among the different parties involved (TTI, ESOC and Kiruna station).

The CSMC SW evolved significantly from the preliminary version tested during the first SAT campaign. A gradual validation approach was undertaken, allocating most of the testing time to be conducted under hybrid configurations, combining simultaneous use of the old and the new system (modular validation).

Regarding the functional completeness of the new CSMC system, it was fully verified that it included all the functions that were provided by the old QNX CSMC system.

As for the operability aspects of the new GUI, the resemblance of the new development compared to the legacy one allowed the end-users to get into grips with the new system faster, minimizing the learning curve. Moreover, early validation and live comparison between the two systems (old and new) thanks to the two systems running in parallel (splitting the station), boosted the GUI acceptance since sometimes this is a cornerstone for operations key personnel.

Regarding the performance and reliability of the new system, during the Operational Validation phase the system was left in operation for long periods during which these two aspects were thoroughly assessed. Detailed records of the performance and system resources consumption were obtained for all the nodes.

To conclude, it is necessary to remark that this upgrade is not just an upgrade of the station's "brain", but it also brings another very significant breakthrough: the new CSMC system is now running in a fully virtualized environment, both at the station (Kiruna) and at the remote control centre (NOC), becoming the first virtualized G/S M&C system in ESTRACK. Virtualization also implied a new concept for the user access and interaction with system (via the use of non-dedicated terminals, "thin clients") significantly different to that used in the previous system. Therefore, the CSMC migration project served not only to solve the hardware obsolescence issues in the previous system, but also to enhance the overall system capabilities, defining new innovative deployment procedures and paving the ground for future evolutions.

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