17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023.

SpaceOps-2023, ID # 165

How does the CNES Multimission network adapt to the needs of New Space?

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Abstract

The CNES multimission network (so called MUM network, later on) is a highly reliable and efficient network of ground stations and centralized systems. It provides TT&C and data acquisition services for routine operations or on-demand supports such as LEOP or emergency operations. Missions can be either scientific or institutional missions

The emergence of innovative missions from the New Space has led CNES to reflect on its multimission network roadmap and to start the development of a new ground stations network, coupled with the implementation of new service proposal, to meet new constraints of responsiveness, flexibility and agility and reduced cost. The future MiniMUM network aims at fulfilling these specific requirements while remaining compatible with the legacy missions carried out by the MUM network. This new network will complete step by step the MUM network, which therefore will be better adapted to diversified mission' needs.

This article presents the approach that has led to the development of this new network of stations, as well as the objectives set and the results obtained so far. A medium-term projection also presents what the MiniMUM network will offer when the new service access proposal is available.

Keywords: MiniMuM, ground station, experiment, ACM, service proposal

Acronyms/Abbreviations

ACM	Adaptive Coding and Modulation
CNES	Centre National d'Etudes Spatiales (French Space Agency)
GSN	Ground Station Network
LAN	Local Area Network
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
MUM	CNES Multimission network
NOC	Network Operation Centre
SDR	Software Defined Radio
SLA	Service Layer Agreement
TT&C	Telecommand, Tracking & Commanding
VCM	Variable Coding and Modulation
WAN	Wide Area Network

1. Introduction

For several years now, the global space ecosystem has been undergoing profound changes with the arrival of new needs arising from the New Space. This change is disrupting the operating methods established for decades and forcing the historical players to adapt to these new constraints. The future in-flight missions resulting from the New Space are largely based on nanosat-type platforms or rely on constellations of satellites of greatly reduced size. These mission profiles require an increased flexibility in the ground segments, but also lower supports costs compared to large institutional or scientific missions.

This paper first presents the technical elements and the strategic reasons that have led CNES to develop the MiniMUM network, as a complement to the existing MUM ground stations network (GSN). The second part focuses on the MiniMUM GSN and its technical characteristics. Afterwards, the third part discusses one of the experiments carried out on the demonstration station (the first station of the MiniMUM network). This experiment aims at both characterizing new operational concepts, and testing technologies not currently implemented in the CNES MUM GSN. Finally, a last section introduces the Web interface and the definition of a diversified service proposal, which will be at a medium-term proposed to the subscribers of the CNES network (MUM and MiniMUM ground stations).

2. Why MiniMUM?

As French Space Agency, the role of the CNES is to support the French space ecosystem. The CNES multimission network (MUM) contributes to this objective by offering its services to French institutional missions, but also to French or international scientific missions most of these missions being so far operated by CNES.

The CNES MUM consists of 8 tracking stations distributed in 6 sites around the world [see Fig. 1]. This network of antennas provides Tracking, Telemetry and Command (TT&C), localization services and also Payload Telemetry services for all missions under CNES responsibility and during all stages of the satellite's space life, from Launch and Early Orbit Phase (LEOP) phases to End-Of-Life (EOL) operations, in S and X bands and for Low Earth Orbit (LEO) to Geosynchronous Equatorial Orbit (GEO) orbits. The network services can also be requested by other space agencies or industry major actors, to support LEOP phases or for emergency purposes.

Fig. 1. CNES MUM network

The CNES MUM GSN is managed 24/7 from the Network Operations Centre (NOC), located at the Toulouse Space Centre. NOC is in charge of ground stations scheduling, remote monitoring and control of the network (ground stations and distributed software), and monitoring the connections and data flows. For routine operations, the process is fully automated. To fulfil these requirements, NOC is composed of the main following entities:

- OCP ("Outil Central de Planification" in French), for station scheduling according to both the network workload and the various constraints of each mission
- The Orbit Computation Centre (OCC), for orbit calculation and predictions generation (station acquisition data, pointing elements, visibilities, interferences, collision risk assessment)
- ICARE, for data transmission control between ground stations and control centres,
- IDEFIX, for X-band telemetry processing and distribution to mission centres
- REGATES/CADOR, for remote monitoring and control the ground stations, and routine pass automation.

- WAN infrastructures (CORAIL3/HDX) supporting the data flow exchanges between the ground stations and CNES NOC.

Since 1984, more than 200 missions have been supported.
In 2022, the network handled more than 40,000 satellite passes for 15 missions, with a success rate over 99.3%.

The CNES MUM network has been designed to meet the needs of missions requiring a strong service availability and reliability, for positioning, routine, or emergency supports. The emergence of new space actors comes with a new deal in term of service requirement: easy and quick access to ground station services, and low costs.

The new challenge the CNES MUM GSN has to adapt in a flexible and more attractive way to the needs and requests of different class of customers, which subscribe to the GSN services: major institutional or scientific missions, student projects, nanosat demonstrators, etc…

Therefore, CNES has enforced its "Multi-Mission Network Roadmap" with the objectives of responding to this strong needs, to adapt to the requests of various users customers in terms of reliability, availability, flexibility, and cost optimization. The MiniMUM project, started three years ago, aims at contributing significantly to these objectives.

3. How MiniMUM?

The development of the MiniMUM network consists in 3 phases:

- One station demonstrator,
- Two additional stations, early 2024 and early 2026
- Two optional additional stations to complete the worldwide coverage for an optimal orbital follow-up

The first step of the project is to develop a demonstration station. The key elements that have guided the definition of this demonstration station are:

- Antenna adapted to the small satellite market in low earth orbit
- S-band transmit/receive capability
- X-band reception capability
- Ka-band reception scalability
- Optimization of maintenance
- Complementary station to the existing MUM network
- Controlled acquisition and operating costs

This demonstration station is also intended to carry out experiments:

- Support for new generation on-board demonstrators: qualification of on-board/ground interface on in-flight system, ACM/VCM, Ka band
- Evaluations of new architectures as part of the continuous improvement of the MUM network as a whole:
  - Evolution of baseband technologies (SDR, digitization)
  - Evolution of front-end or ingestion systems
  - Evolution of service management (planning, programming, automation)

After the installation of this demonstration station at the end of 2022, the phase 2 started. The design of the two additional ground stations is based on the feedback from the development of the demonstration station, which has enabled the characteristics of these two new stations to be consolidated.

3.1 MiniMUM sites

In parallel with the development of the demonstration station, stations visibility studies were performed to identify the best target sites for hosting the MiniMUM network antennas.

These studies were based on the following assumptions:

- Demonstration station installed on the Aussaguel site (Toulouse, France)
- 4 additional stations to be deployed between 2024 and 2029
- An homogeneous coverage of LEO orbits (in order for future target missions to be able to rely almost exclusively on MiniMUM)
- National areas preferred:
  - Avoid the risks/complexities of obtaining operating licenses
  - Avoid risks/complexities related to administrative and geopolitical aspects
- Avoid polar areas
  - Limiting interference, especially in the North
    - Many constellations intersect at the poles
    - Risk inversely proportional to the size of the antennas
  - Physical and telecom accessibility problems, especially in the South
- To complete the MUM network

Following the analysis of all these criteria, the MiniMUM network has been defined as follows:

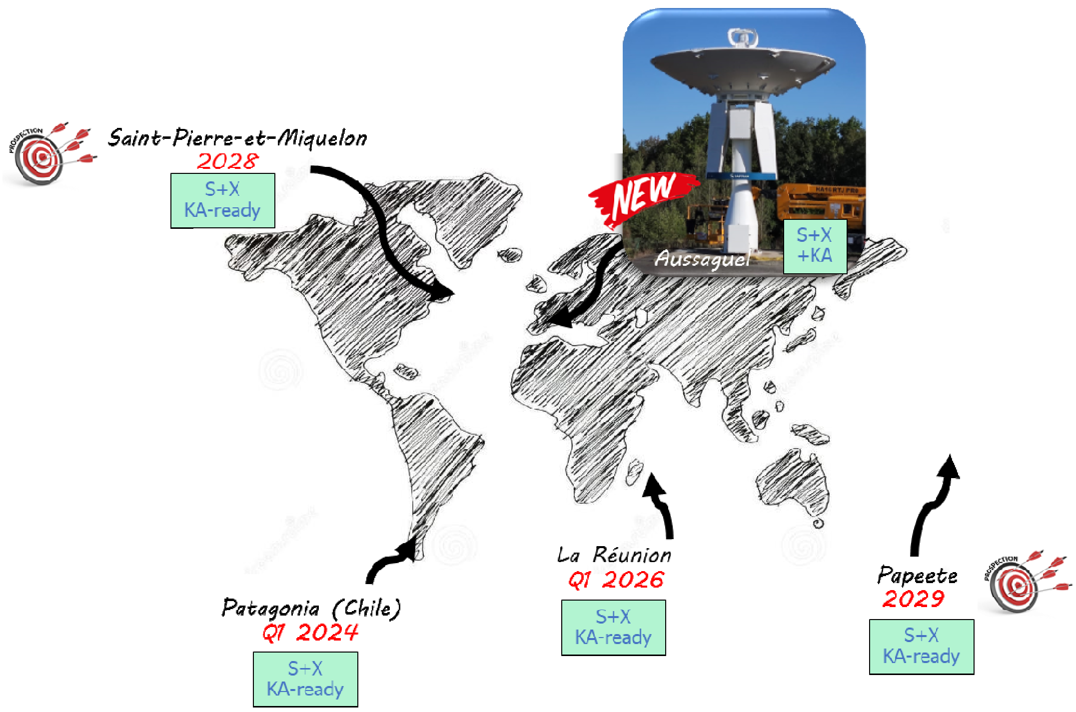

Fig. 2. Foreseen MiniMUM network

The analysis of the station visibilities within this network shows that the station visibilities are well distributed over the day, with sometimes gaps in between rarely exceeding 1 orbit but never 2 orbits.

Figure 3 shows an example of the visibilities of the MiniMUM network stations for a satellite on a SSO at 600km over a time horizon slightly longer than 1 month (x-axis: day in the month // y-axis: hour in the day). We can observe a periodic visibility gap of one orbit on the 16h00-19h00 time slot (blue ellipses) as well as a gap of one orbit on the 06h00-08h00 time slot but in a punctual way.

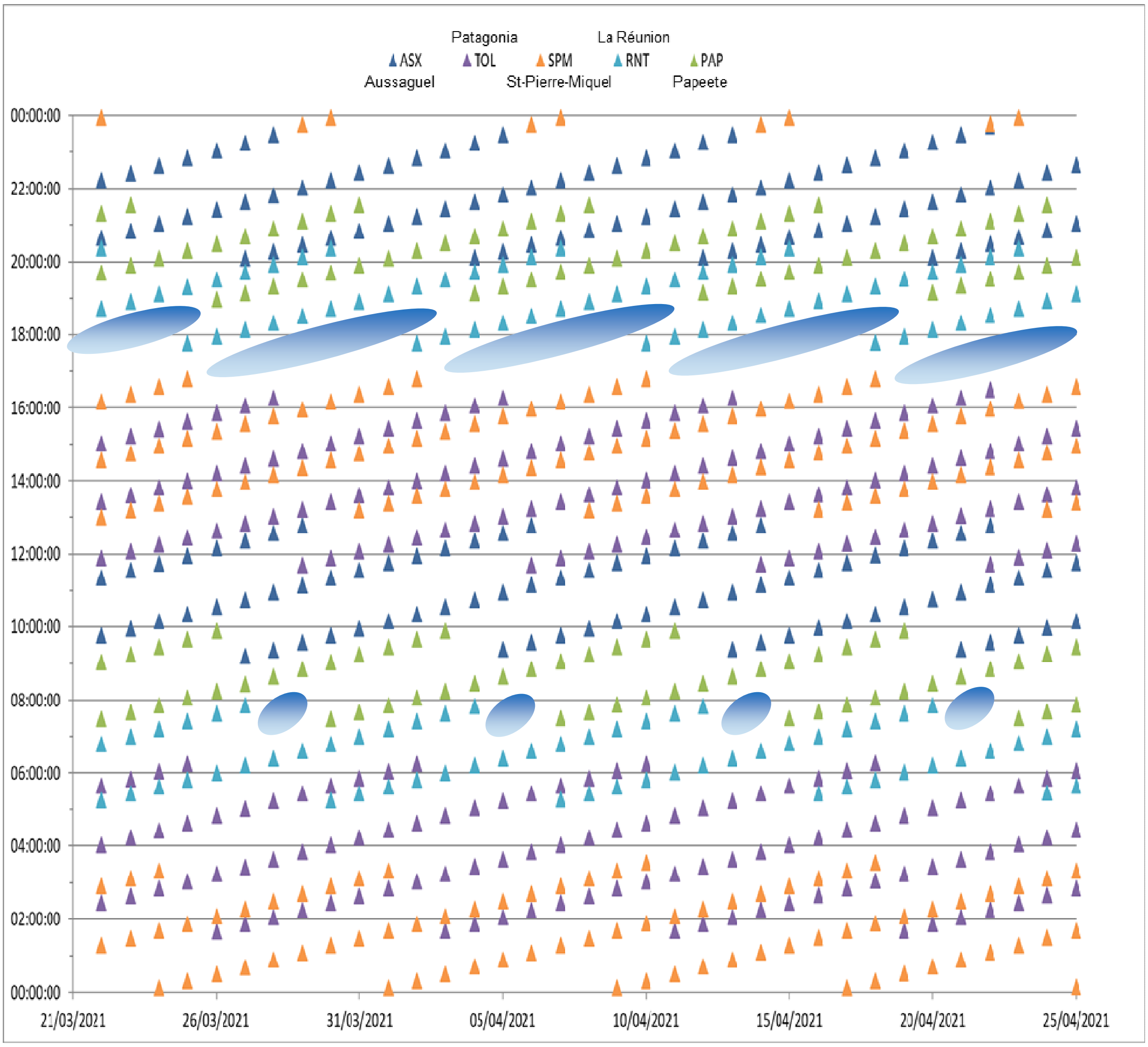

Fig. 3. MiniMUM network visibility analysis

The result of this hosting areas survey shows that the proposed areas are in line with the requirement:

Objectives	Results
Homogeneous coverage for LEO orbits	**OK**, visibility hole limited to 1 orbit
Sovereign Network	**OK**, French territories except Patagonia
Avoid polar latitudes	**OK**, only low/medium latitudes
MUM network complement	**OK**

Table 1. MiniMUM stations location criteria

3.2 MiniMUM Stations characteristics

Fig. 4. MiniMUM Ground Station

The demonstration station enables the technical and operational aspects of the system to be validated. The choice has been made to supply identical stations for the next two stations (Patagonia and La Reunion).

Therefore, the first phase of deployment of the MiniMUM network is made up of small antennas (5.5m/6.1m), which will enable the system to meet the requirements of the target missions in low earth orbit and meet the constraints of optimizing installation and operating costs.

The first three stations are Vision systems supplied by Safran Data Systems, selected after an Invitation to Tender.

The MiniMUM Demonstration Station is the first of this product range, and CNES has fully played its role in supporting the French space ecosystem by assisting Safran Data Systems in the technical qualification of this first of a series in a difficult global context. Indeed, the project took place at the height of the COVID pandemic, and, then, in a complicated global economic context linked to numerous shortages and delays in the delivery of raw materials. These severe constraints led to some delays in development. The station has been installed at the operational centre in Aussaguel (near Toulouse, France) at the end of 2022.

During the preparation phase of the installation, the optimizations relating to the deployment of such a system were verified:

- Lightweight civil engineering: as the antenna system is relatively light (6 to 7 tons), the infrastructure for hosting the antenna is limited.
- Simplified site interfaces: the site interfaces are limited to the supply of one to two electrical lines (uninterruptible and non-interruptible depending on the configuration) by the site and a grounding connection. All the RF/data link links are made via a fiber optic link supplied by Safran Data Systems. This link has a standard length of 200m and can be extended on customer request.
- Limited indoor space: most of the equipment are integrated on the positioner, inside the arms or in boxes positioned at the base of the positioner and on top of the pedestal. For the demonstration station, a single 36U rack is required indoors to house the equipment: optical transceivers (RFoverIP and data link), time-frequency generator, baseband, test equipment, front-end station.

It has be noted that, except for the Demonstration Station located on a CNES site, a second rack is required to host the LAN/WAN equipment.

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The installation phase has proved the simplicity and the quick assembly of the system, which is delivered pre-assembled. For example, the positioner takes less than half a day to install. The assembly and installation of the carbon reflector takes less than a day. The antenna is therefore installed and wired in less than a week.

15h50
Positioner unloading

16h08
Crane to anchor

16h20
Placing the positioner on its anchor

In terms of operation, the stations have been designed to minimize the preventive maintenance. Station unavailability due to preventive maintenance is limited to 10 hours/year. Such a duration represents a significant gain compared to the maintenance duration of the MUM ground stations network, which is approximately 70 hours/year long. This difference can be explained by the fact that no mechanical maintenance is required: no lubrication or oil change is necessary.

The simplification of the hardware architecture (e.g. absence of frequency converter except for the Ka-band) allows faster investigations in case of a fault due to the limited number of subsystems. The choice to limit redundancies in order to optimize costs also contributes to this simplification of the architecture.

Finally, all the subsystems are remotely accessible and RF test points are available at different levels of the transmission/reception chains. This allows a very high level of remote investigations for finding the root causes of the issues, which limits the need for on-site support Such an on-site support is mainly requested to replace the equipment identified as faulty.

Post-installation Ka-band scalability was a strong requirement of the project. Indeed, the MiniMUM network is deployed at a time when CNES does not have any Ka-band missions in flight. However, the evolution of needs in terms of TM data rate suggests that Ka-band support will most certainly be necessary in the medium term. The demonstration station is therefore equipped with Ka-band reception and tracking capabilities, as it is intended to be used to conduct various experiments covering Ka-band requirements. This technological choice also allows the Vision system to be qualified in a complete tri-band S/X/Ka configuration. The Patagonia and La Reunion antennas will be deployed in a dual-band S/X configuration in a first time. The implementation of the Ka-band will be carried out afterwards as soon as candidate missions have been identified. It was therefore essential to have stations that could be upgraded to a tri-band S/X/Ka version while limiting the material impact and station unavailability once the need would be established.

From a financial optimization view, some technical choices have been made during the development of the demonstration station. Among these choices, we can mention:

- **No automatic tracking in X-band**: the antenna's pointing performance being compatible with programmed tracking in X-band, it was decided not to exercise this option. In addition, it is possible to consider tracking in S-band during an X-band dump if the mission is transmitting simultaneously in these two bands (which is very often the case). Moreover, the concentric source proposed by Safran Data Systems makes it possible to eliminate mechanical misalignment of the sources.
- **Strong limitation of redundancy in the station**: contrary to the MUM network stations on which all the equipment are in hot redundancy, the MiniMUM stations only benefit from a minimum of redundancy on the equipment considered critical: the basebands and the network equipment are thus the only equipment in hot redundancy in the station. It should be noted that in order to limit long periods of unavailability of the stations on distant sites, a complete spare batch will be available on site.
- **Change of baseband equipment compared to the MUM network**: the high-end basebands used in the MUM network stations represent a significant investment cost. The choice of baseband was made in favour of the Satcore Direct equipment from Safran Data Systems, which offers a wideband TM receiver (payload TM receiver) and a TT&C modem in a single 2U equipment. Therefore, such equipment saves on physical space in the rack and on acquisition costs. On the other hand, there is a few limitations, such as the absence of a TM combination and the absence of ranging, but these have been considered acceptable for operations on the MiniMUM network.

3.3 Experiments

First MiniMUM station was developed with the objective to perform some technical experiments. Among the experiments of interest for the MiniMUM network, we can mention the followings:

- Ka band propagation for LEO satellites
- Ka band signal tracking without need of autotrack
- Variable Coding and Modulation in X band
- Virtualization : digitizer on the antenna, then SDR hardware
- SDR products evaluation
- ACM (Adaptive Coding and Modulation) operational concept
- …

Concerning ACM, studies and tests are ongoing aiming at defining the operational concept of the ACM protocol. Indeed, ACM makes sense on the MiniMUM network, which is composed of small antennas (5.5m/6.1m), at a time when there is significant increase in on-board data rates. The implementation of the ACM on future missions therefore seems to be an efficient way to gain dumping capacity while limiting the impact on board and on the ground.

CNES has therefore started a study to define the optimal system architecture for implementing the ACM protocol on its network.

3.3.1 Study logic

This study aims at investigating the usage of ACM modulation & coding techniques for board/ground communication links. Standardized within ETSI, CCSDS and SCCC, this standard introduced a dynamic configurability of the modulation & coding schemes to adapt to changes in the physical path (RF or optical). This study analyzed the standards, the state of the art of the usage of such technology, the impact on Ground and Space architectures and drive a trade-off through the analysis of elementary use-cases.

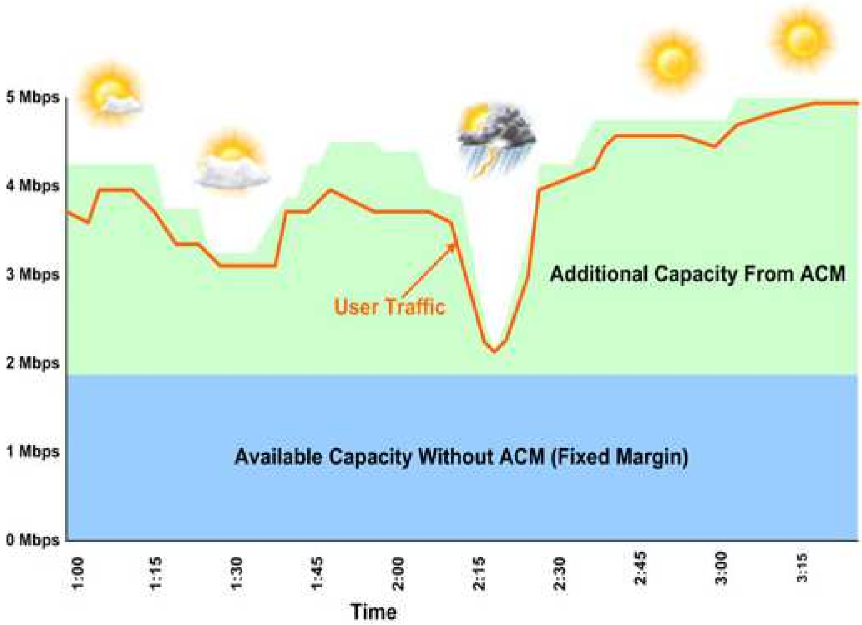


Fig. 5. ACM adaptation principles

3.3.2 Synthesis of the ACM protocol analysis

Since there is no capability at MODCOD & Frame layer to command a return signal (only signaling of local link is available), the only way to perform a closed-loop system is to go through the Packet layer, which requires specific implementations of PUS services to enable the ACM programming. Since the MODCOD programming of the return channel is performed at packet level, when a cyphering engine is used on the TC link, this programming is also protected.

3.3.3 Ground segment studied scenarios

3 mains scenarios were studied including some alternatives to consider crypto subject.

- Scenario 1a and 1b (S&X local loop) considers an advanced hybrid Ground Station, capable to handle both the Payload and the Platform communications and manage locally the insertion of commands within the TC plan with specific priority management. The Control Center defines the overall TC plan and monitors the Ground Station through an SLE interface, but is not required in the MODCOD selection process.
  This architecture is optimal for scenarios involving a feedback between the downlink and the uplink (ACM feedback). In this scenario, the ACM selection engine is preferably implemented in the hybrid Ground Station to enable fast locked loops. Scenario 1b is very similar to scenario 1a, with an additional encryption module within the hybrid Ground Station. This encryption module is performing specific uplink authentication or cyphering, but since it is implemented at the level of the hybrid Ground Station, it does not affect the implementation of the ACM mechanisms.

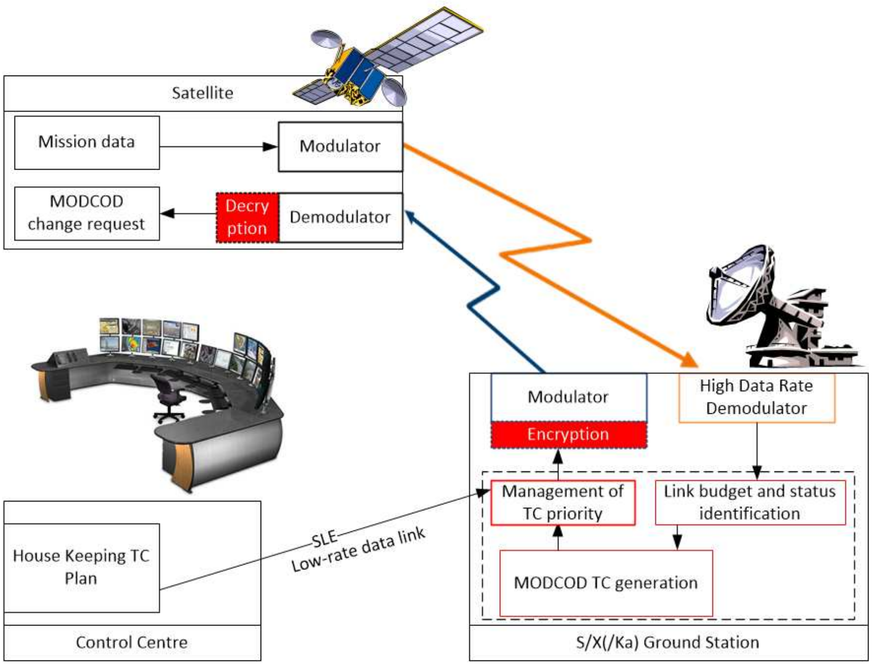


Fig. 6. ACM architecture scenario 1a/1b
Scenario 1b → Encryption added (red boxes)

- Scenarios 2 (S&X station; loop with CC) introduces a major modification with respects to scenario 1 with a hybrid Ground Station without local capability to manage the TM/TC stream. Since this management is being performed at the level of the Control Center, the ACM command feedback needs to account for a specific SNR measurement performed at the level of the Ground Station demodulator and transferred through the SLE link (~2s latency). This will typically affect the reactivity of the ACM closed-loop and the overall performance.

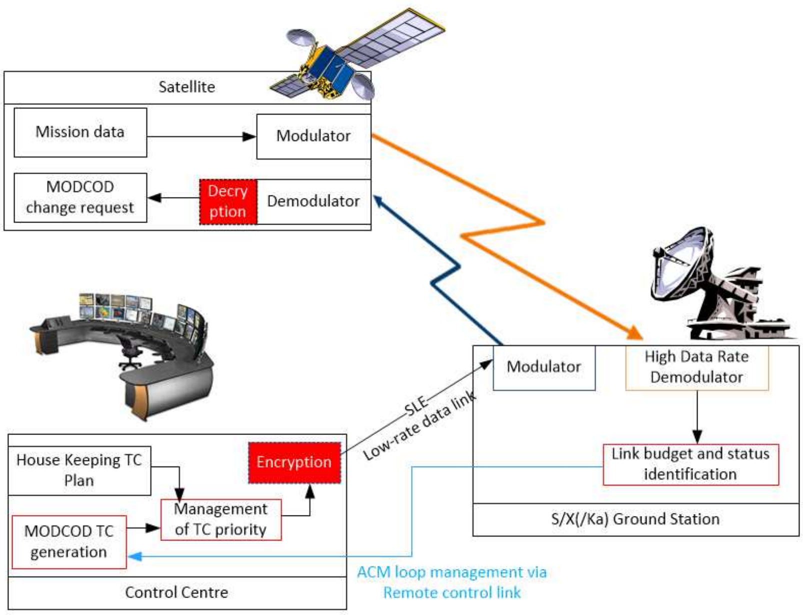


Fig. 7. ACM architecture scenario 2

- Scenario 3 (S station; X station; Loop with CC) can be considered as an extension to scenario 2. Since the TC stream management is located within the Control Center, the ACM command feedback needs to account for a specific SNR measurement performed at the level of the TMHD Ground Station demodulator and transferred through the SLE link (~2s latency) to the Control Center that generates the TC stream to feed the S-Band operating Ground Station. As for scenario 2, this will typically affect the reactivity of the ACM closed-loop and the overall performance. This scenario presents a major drawback in case both stations are not co-located, since ACM requires immediate feedbacks to be driven.

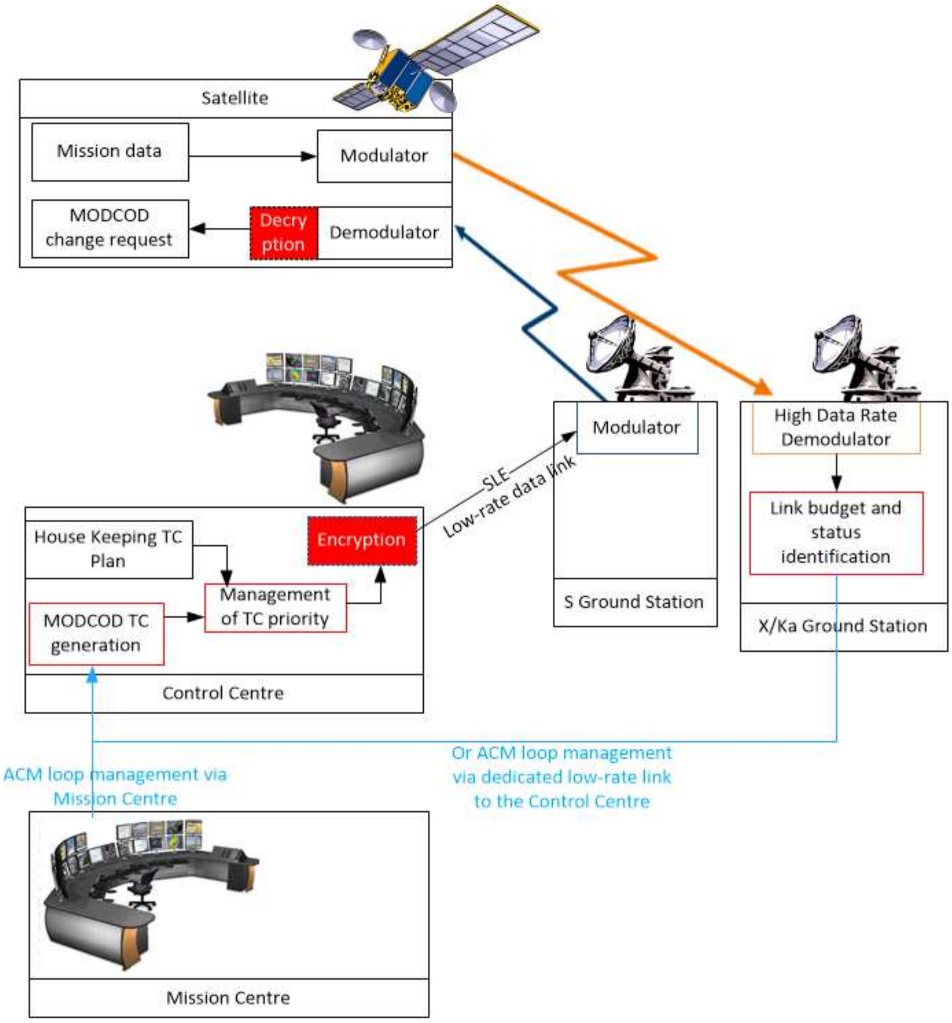


Fig. 8. ACM architecture scenario 3

3.3.4 Problematics of architectures & ground stations with the reference scenarios

The analysis of ACM implementation requires an investigation on the communication channel properties including the atmospheric attenuations in the bands of interest. The analysis has focused on Kourou, Kiruna and Aussaguel sites to identify the useful level of granularity to be defined for the MODCODs for ACM, and the sizing of the closed-loop duration for ACM commands.

Statistical analysis have been performed to characterize the Ka link budget variation due to atmospheric effects over different periods of the year. These analysis have concluded that the link budget variation over short duration (1 to 10 seconds) is limited.

	Availability of the link (%)	Kourou	Kiruna	Aussaguel
Peak to peak variation (dB) over 10s	**99.9**	1.50	1.33	1.02
	99	0.80	0.64	0.63
	98	0.58	0.52	0.52
	97	0.50	0.46	0.46
	95	0.35	0.34	0.33
Peak to peak variation (dB) over 5s	**99.9**	0.80	0.71	0.54
	99	0.45	0.36	0.36
	98	0.35	0.31	0.32
	97	0.25	0.23	0.23
	95	0.20	0.20	0.19
Peak to peak variation (dB) over 1s	**99.9**	0.39	0.34	0.26
	99	0.10	0.08	0.08
	98	0.06	0.06	0.06
	97	0.05	0.05	0.05
	95	0.04	0.04	0.04

The dependency to the delay in ACM configuration is then considered. The average MODCOD step in terms of energy threshold between two consecutive MODCODs in a given modulation is 0.85dB, meaning that if we also consider that it is acceptable to lose some frames on a MODCOD transition according to a statistical approach, this resolution fits well with the Ground Station properties as follows:

- With 1s ACM closed-loops: no frame loss expected on MODCOD transition in ACM
- With 5s ACM closed-loops: 0.1% frame loss can be encountered on MODCOD transition in ACM for Kourou and Kiruna (no loss in Aussaguel)
- With 10s ACM closed-loops: 1% frame loss can be encountered on MODCOD transition in ACM for all stations

This frame loss can be limited to 0.1% in all cases if the ACM algorithm is driven with a margin with respects to the signal recovery threshold by using the maximal variation encountered at 0.1% of time, for instance using for Kiruna:

- 0.34dB in 1s closed-loops
- 0.71dB in 5s closed-loops
- 1.33dB in 10s closed-loops

The interesting outcome of this analysis, is that the trade-off is actually a matter of finding the referent setting to fit the available architecture, and that even with 10s close-loops, ACM could be operated.

4. Perspectives

The development of the MiniMUM network is not limited to the deployment of new ground stations. A diversified service proposal is under analysis in order to meet the needs of different types of missions. Four tentative levels of services (SLA) are under consideration so far: Basic, Essential, Serenity and Critical.

4.1 Diversified Services proposal overview

It is intended that all the MUM and MiniMUM ground stations could be used whatever the subscribed service is. However, the Basic service is mainly intended to be provided by the MiniMUM ground stations.

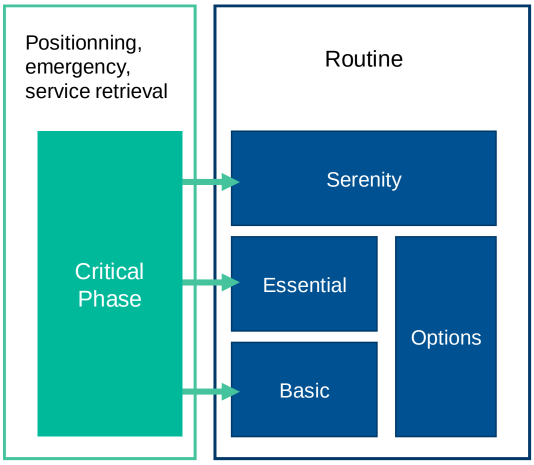


Fig. 9. A diversified services proposal

- "Critical" SLA, will be used during specific critical operation phases such as LEOP. It could also be triggered at any time during routine supports, in case of emergency or a specific mission activity.
- "Serenity" SLA, is planned to be an all-inclusive service.
- "Basic" SLA, will be considered as a "low cost" service.
- "Essential" SLA, will then be the intermediate service.

	Basic	Essential	Serenity
Scheduling	• **Best Effort** (no requirement) • Scheduling by the subscriber through a Web Interface (booking request, cancellation request) • Available station slots according to the orbit elements provided	• **Long term scheduling (4 weeks) but not frozen, commitment 95% to 98%** • Pass cancellation by NOC accepted within the limits of the global availability • Scheduling modification by the subscriber through the Web Interface only	• Long term frozen scheduling (4 weeks), commitment ~100% • High priority for additional scheduling • Scheduling performed by CNES GSN
Global availability	No specific rate	>95%	98% to 99%
Localization Measurement	Not applicable	Optional	Yes
Real time transmission	Through the Web Interface API	Through the Web Interface API or CNES NOC interfaces	Through CNES NOC interface
Data files transmission	• Raw data distributed on a shared data exchange area (e.g. Cloud). • Hyperlink provided through a Web Interface	• Raw data distributed either on a shared or a dedicated data exchange area (e.g. Cloud) • Hyperlink provided through a Web Interface in case of shared solution • Subscriber in charge of the data transport in case of a dedicated solution	• Data distributed through a secure and high available network (redundant circuits) • External subscriber is in charge of the data transport between its premises and CNES NOC
Reporting	Pass status and pass accounting through a Web Interface	• Pass status, data distribution monitoring through a Web Interface • Troubleshooting during working hours depending on the anomalies • Annual review	• Montly report • Troubleshooting whatever the anomaly is • Intervention under 1 hour • Annual review

Fig. 10. Services proposal overview

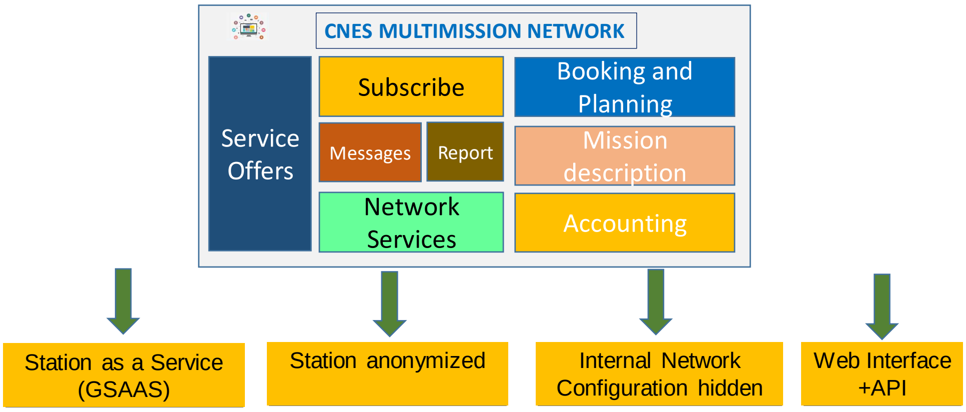
The medium-term objective is to provide users of the CNES GSN services, with an Internet Web Interface for subscribing and requesting services over the CNES MiniMUM ground stations, according to the Basic service level.

The longer-term objective aims at expending these accesses through the Web Interface to all services, in accordance with the selected Service Level Agreement, as well as making available an Application Programming Interface (API) allowing the subscribers to automate some processing.

4.2 Web Interface

The functional definition of the Web Interface is ongoing. The first version of this Interface aims at proposing the needed interfaces to support the Basic service:

- Subscribe (user details);
- Mission description (specific mission parameters);
- Network Services (required services, such as X-band Telemetry);
- Booking (contact slots available, scheduled passes, performed passes and hyperlinks for station connection or data);
- Accounting (performed passes, remaining passes);
- Report (pass status);
- Messages (mailing);



The ground stations are transparent to the subscribers who book visibility slots (no need to know which ground station is used, since only compatible slots with the provided orbit elements are displayed and can be booked).

5. Conclusions

Global space ecosystem undergoes profound changes with new needs arising from the New Space. These changes are disrupting the operating methods established for decades, and the mission profiles require increased flexibility in the ground segments, but also lower supports costs compared to large institutional or scientific missions.
The CNES MUM GSN has to adapt in a flexible and more attractive way to fulfil the needs of this different class of customers. Therefore, CNES has enforced its "Multi-Mission Network Roadmap" with the objectives of responding to this strong need in terms of reliability, availability and flexibility, and optimizing the costs. The MiniMUM project aims at contributing significantly to these objectives, by becoming in the future an essential complement to the CNES existing network.

The MiniMUM network establishment is ongoing and covers a perimeter from the ground stations to a future service proposal. The installation of the first ground station was completed by the end of last year. This first GS is under qualification. The next few years will see the advent of new antennas and the establishment of the service proposal, which should answer to the new space ecosystem needs.