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Axel Carayon, Camille Fayollas, Clément Hubin-Andrieu, Emilie Tortel, Célia Martinie, et al.. Information visualization for supporting short-term and long-term situation awareness in ground segments monitoring: application to SWOT command and control operations. *Acta Astronautica*, 2026, 238 (Part A), pp.657-67. <10.1016/j.actaastro.2025.09.015>. <hal-05261344>

HAL Id: hal-05261344

<https://hal.science/hal-05261344v1>

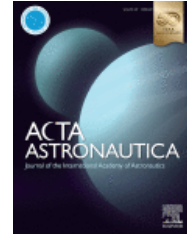
Submitted on 23 Mar 2026

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International Astronautical Congress (IAC 2024)

Information visualization for supporting short-term and long-term situation awareness in ground segments monitoring: application to SWOT command and control operations

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Abstract

The CNES-funded project called STRECCC (STudy and Recommendations for the Ergonomics of Command and Control Centers) studies ground segment interactive applications, their user interfaces, and how the controllers interact with them, to identify solutions ensuring the usability of future, more automated command and control centers. The nature of the operations evolves, along with the skills, knowledge, and expertise of controllers. Their profile evolves being less technical and with less knowledge in the underlying systems or telecommunications. The STRECCC project addresses these evolutions by designing advanced user interfaces improving performance and situation awareness of the controller. The designs deeply exploit knowledge and research contributions in the area of information visualization and Human-Computer Interaction. In this paper, we present the approach, based on task models, we applied to investigate the usability of the SWOT Control and Command Center (CCC). Based on the study we performed, we present two prototypes of interactive visualizations to enhance operations by improving the perception and understanding of numerous information while performing different types of tasks (e.g., identifying a disconnected antenna, comparing the processing state of two telecommands...). From the results of a predictive evaluation and preliminary empirical feedback, they improve the situation awareness of the controllers by providing a long-term (a full week) perspective on recent-past and future operations.

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Keywords: user-center design; task modelling; situation awareness; operations; command-control center

Nomenclature	
CCC	Command-Control Center
CNES	Centre National d'Etudes Spatiales
ISIS	Initiative for Space Innovative Standards
NASA JPL	National Aeronautics and Space Administration Jet Propulsion Laboratory
STRECCC	STudy and Recommendations for the Ergonomics of Command-and- Control Centres
SWOT	Surface Water and Ocean Topography
TC	Telecommand
TM	Telemetry
UCD	User-Centered Design
UX	User eXperience

1. Introduction

As the nature and complexity of ground segment operations increase, controllers' work is required to evolve in nature. Mostly manual, interactive operations performed by one single controller on a single satellite have been partially automated to allow a few controllers to monitor and manage a constellation of satellites. This increase in automation transformed the main controllers' tasks from the monitoring of satellites' passes to the high-level supervision of flight phases and operations scheduling [19]. In parallel to these evolutions of the nature of operations, the skills, knowledge, and expertise of controllers are also evolving. Their profile evolves to be less technical and with less knowledge of the underlying systems or telecommunications.

The CNES-funded project called STRECCC (STudy and Recommendations for the Ergonomics of Command and Control Centers) studies ground segment interactive applications, their user interfaces, and how the controllers interact with them, to identify solutions ensuring the usability of future, more automated command and control centers. The STRECCC project addresses the evolution of the nature of operations as well as the evolution of the skills, knowledge, and expertise of controllers. Its purpose is to design advanced user interfaces, improving performance and situation awareness of the controller. The designs deeply exploit knowledge and research contributions in the area of information visualization and Human-Computer Interaction. The proposed interactive system enhances operations by improving the perception and understanding of numerous pieces of information while performing different types of tasks (e.g., identifying a disconnected antenna, and comparing the processing state of two telecommands...).

There is a growing need to develop predictive tools that support ground controllers in performing higher-level supervision tasks and enhancing their overall performance[22]. Yet, this topic remains underexplored in the current literature. Slaney and Stecko [20] produced an interactive dashboard to enhance telemetry visualization for ground station operators. The dashboard is informationally dense and relevant for satellite engineers and ground station operators. Its main page displays several features such as spacecraft locations, alert status, telemetry packets, or average data rates. Those have been designed consciously, using for instance, stoplight-color coding or replacing the satellite's current location viewed as plain text with a global flight path

map. The authors reviewed their mock-ups with experts to produce the final dashboard. De Padova et al. [21] proposed a visualization that provides an overview of the status of each mission's ground segment on a dashboard. They used color-coding to represent the current operational state and displayed key information for each ground segment using the law of common regions. On a different view, they displayed an overview of the ground station's equipment and connectivity on the main and redundant chains, using color-coding again to indicate failures, warnings, and nominal status. While these studies align with the general scope of our study, some tasks supported differ from those required by STRECCC (they support input tasks such as modification of alert rules, whereas the visualisations we designed aim to be output only). Nonetheless, additional contributions from other domains address more generic task types in other application domains relevant to our study. In the health field, Widanagamaachchi et al. [23] introduced a tracking graph showing patient progression over time. In the business process management field, Suntinger et al. [24] presented the Event Tunnel framework to display the relationships between events. Across application domains, Mansmann et al. [25] proposed a visualization technique for dynamic event data streams that fosters traceability through animation and predictable positions. These contributions provide interesting visualisation solutions that we analysed for the study.

In this paper, we present the results of the project. In the second section, we introduce the context of the study: the operations of the SWOT (Surface Water and Ocean Topography) satellite, the ISIS product line that is used to operate the satellite, and the STRECCC project. In the third section, we describe the approach applied to study the usability of the SWOT Command and Control Center (CCC). The fourth section presents the results of the application of this approach. These results include an exhaustive description of the tasks that the controllers have to perform to operate the SWOT satellite. These task models are the cornerstone of our study: their analysis enable us to identify recommendations to increase the system's usability, such as adding a new interactive visualization to increase the situation awareness of the controllers. Finally, the results of the approach include two prototypes that have been designed following this study. Section 5 presents preliminary results of user evaluation of these prototypes. Finally, Section 6 concludes the paper.

2. Context: SWOT operations

The context of this study is the SWOT mission command-control center. This section first describes the SWOT mission. Second, it describes the ISIS Product Line. Finally, it presents the STRECCC projet (STudy and Recommendations for the Ergonomics of Command-and-Control Centers) and its objectives.

2.1. The SWOT mission

The French, U.S., U.K. and Canada joint SWOT mission is to measure the heights of Earth's rivers, lakes, and oceans waters [1]. The SWOT satellite was sent into orbit on the 16th of December 2022. It offers two acquisition modes that cover different purposes:

- High-Resolution mode enables to precisely identify fine (rivers) and small (lakes) features through very high spatial resolution.
- Low-resolution mode enables measuring water elevation with a very high accuracy (way better than previous satellites, thus much lower than High-Resolution mode).

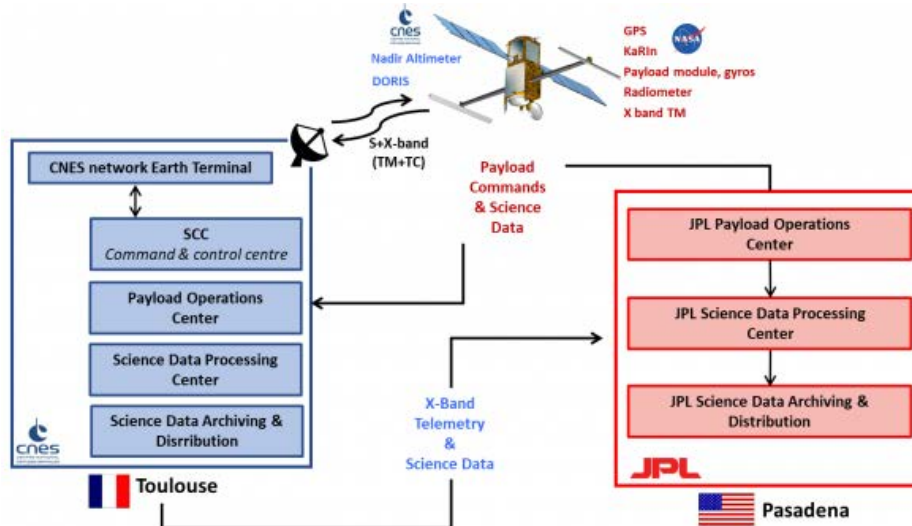


Figure 1: Simplified SWOT ground segment architecture

The mission ground segment comprises (see Figure 1):

- A Command-Control Center (CCC), provided by CNES in Toulouse that handles satellite command-control and operations. Its role is to communicate with the satellite to send telecommands (TC) and to receive telemetry (TM), and to ensure that the satellite is working correctly.
- Two mission centers (at NASA JPL and CNES) that define the missions of the satellite and process the scientific data sent by the satellite.
- A network of S-band and X-band stations provided by CNES's multi-mission ground segment. It comprises Inuvik and Kiruna ground stations, with additional passes over Aussaguel, Hartebeesthoek and Kourou ground stations.

The CCC in Toulouse gather several occupations to operate the SWOT satellite:

- *Flight Director*: they are responsible for the right execution of the mission.
- *Controllers*: they are responsible for handling all routine operations while constantly monitoring the entire system
- *Flight control engineers*: they are responsible for maintaining the satellite in operation and controlling its orbit and attitude.
- *Ground segment engineers*: they are responsible for the ground segment system.
- *Mission engineers*: they are responsible for payload monitoring and workplan processing.
- *Orbit engineers*: they are responsible for defining and optimizing the satellite trajectory.

2.2. ISIS product line

In the early 2010's, the CNES published an internal standard aiming at rationalizing the CNES mission operation systems. By standardizing together, the CNES mission platforms, and the mission operating systems. This standard is named ISIS (Initiative for Space Innovative Standards) [2]. The ISIS Product Line [3] is the implementation of the ISIS standard and can be instantiated, for instance, as a command-control center, a main control room, or a satellite experts and on-call controllers' workstations. SWOT is the second mission to be operated by an ISIS-based CCC.

2.3. The STRECCC project

The CNES-funded project called STRECCC studies ground segment interactive applications, their user interfaces and how the controllers interact with them.

The objectives of this project are two-fold:

- Identify solutions ensuring the usability of future, more automated command and control centers.
- Address the fact that the profile of the controllers is evolving, being less technical and with less knowledge on the underlying systems or telecommunications. This implies the evolution of the nature of operations and of the skills, knowledge, and expertise of controllers.

The STRECCC project addresses these evolutions by studying the current CCC user interfaces, focusing more particularly on controllers' work. The goal of the project is, based on the controllers' work study, to design advanced user interfaces that improve the performance and situation awareness of the controller.

3. Overall approach description

To propose new user interfaces to take into account the challenges raised by the evolution of the controllers' background and tasks, we applied a user-centered and task model-based approach to assess the usability of the SWOT command-control center. This section first presents the principles of user-centered design. Second, it described the approach we applied.

3.1. User-centered-design

The ISO 9241-210 standard [4] defines the User-Centered Design Process. This process is depicted in Figure 2 and is divided in the following steps:

1. Plan the human-centered design process. This step consists in planning how to roll out the whole process.
2. Understand and specify the context of use. This step consists in understanding and specifying:
 - the user and the other stakeholders' groups,
 - the users' or groups of users' characteristics,
 - the users' tasks and goals,
 - the environment(s) of the system.
3. Specify the user requirements. This step consists in identifying users and other stakeholders' needs to derive them in user requirements. An important aspect to take into account here are to resolve trade-offs between user requirements and to ensure the quality of the user requirements specifications.
4. Produce design solutions to meet user requirements. This step consists in designing user-tasks, user-system interaction and user interface to meet user requirement and designing the tasks and interaction between user and system.
5. Evaluate designs against requirements. This step consists in evaluation the propose design with respect to the user requirements. If the design needs to be improved, the process is iterated from step 2 to step 5. Otherwise, if the designed solution meets user requirements, the design process ends.

The approach we applied is based on these principles and is presented in next section.

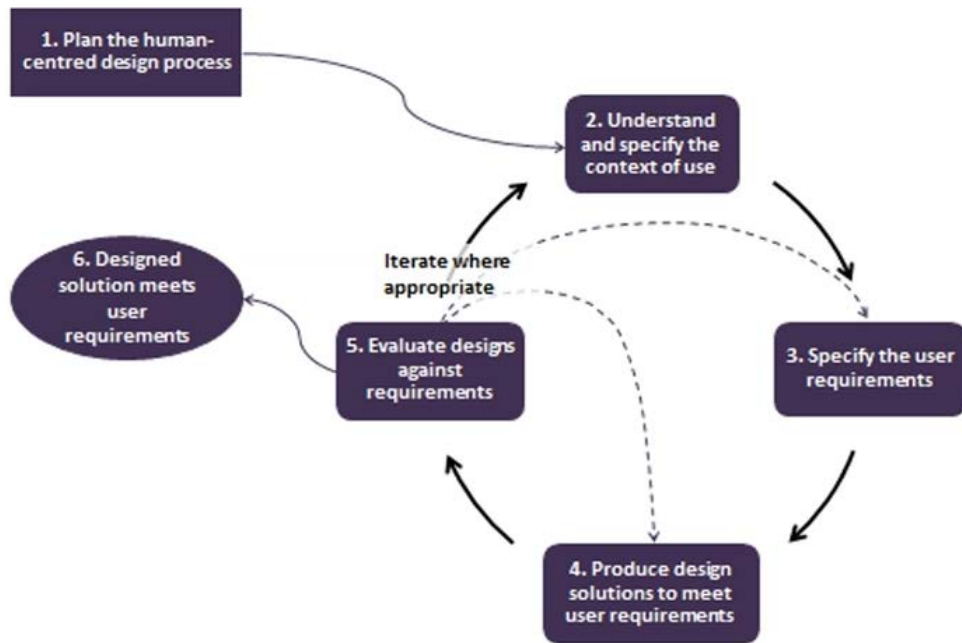


Figure 2. User-Centered Process (adapted from [4])

3.2. Overview of the applied approach

The applied approach is depicted in Figure 3 and is divided in several steps that are detailed below.

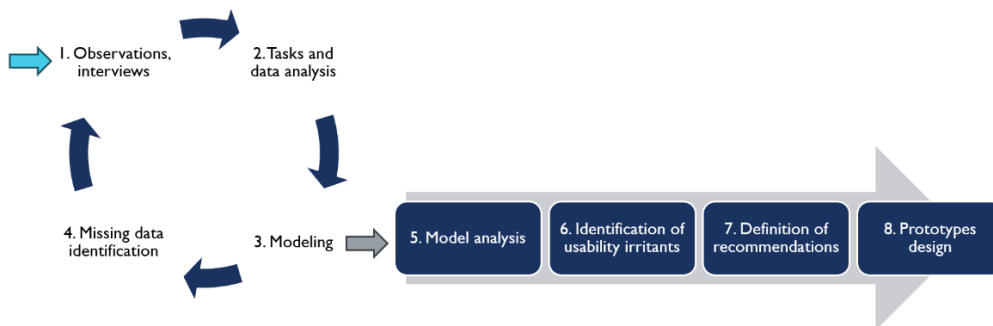


Figure 3. Applied approach

3.2.1. Observations and interviews

This first step consists in conducting several observations of different controllers and ground-segment engineers performing their work and interviewed them about the tasks they are performing (both during a satellite pass and during the whole day), the data they needed to perform their tasks and what are the tools they are using and how they use them.

For the observations, we applied the Spradley's nine dimensions observation framework [5] to gather data about:

- Physical space,
- Actors,
- Activities performed by the actors,

- Objects that are relevant and present, or used by the actors,
- Specific individual actions carried out by the actor,
- Particular occasions that surface from the research,
- Sequence of events,
- Actors' goals, what are they trying to accomplish,
- How the actors feel.

For the interviews, we led semi-structured interviews, following the Lazar et al. "Interviews and focus groups" guidelines [5]. Examples of questions we asked during these interviews are:

- What a typical day is like?
- What a typical week is like?
- Are there priority tasks?
- What are the tools?
- How of them is used for?
- Which tools are the most used?
- What can be a problem?
- How do you handle problems?
- What modifications would you like to see?

It's important to note that both techniques are complementary and allowed us to cross-check the information.

3.2.2. *Tasks and data analysis*

This second step entails to the analysis of the observations and interview results to define the user tasks and the data needed to be able to model them. Task Analysis is a cornerstone of User Centered Design approaches, aiming to collect information from users about the work they are doing and the way they perform it. According to Johnson [7] "any Task Analysis is comprised of three major activities; first, the collection of data; second, the analysis of that data; and third, the modelling of the task domain" (p.165).

3.2.3. *Modeling*

This step consists in modeling exhaustively the user tasks and the data manipulated to perform these tasks. For that purpose, we use the HAMSTERS-XL notation [8] that makes it possible to structure users' goals and sub-goals into hierarchical task trees. The notation is tool-supported and the HAMSTERS-XLE tool [9] [10] enables the editing and simulation of task models. The tool is used to ensure consistency, coherence, and conformity between assumed or prescribed user tasks and the sequence of actions necessary to operate interactive systems. As users' tasks may be numerous and complicated, HAMSTERS-XLE supports editing, refining and structuring task models that embed a large number of tasks. It provides elements of notation and tool support to split task models into several files, as well as to reuse part of them. The HAMSTERS-XLE software tool also supports the simulation of task models and the production of scenarios from the task models.

3.2.4. *Missing data identification*

This step entails evaluating the task models to verify if all the user tasks are described and if they are described correctly (for instance, including all the data that is needed by the controllers to perform their tasks). If some missing data is identified, the process starts again from step 1, otherwise, the process continues with step 5.

3.2.5. *Model analysis*

When the task models are complete and consistent, they are analyzed to evaluate the system usability through the effectiveness and efficiency factors and to evaluate the tasks complexity.

The effectiveness factor can be studied by checking if the final goal of the user is achievable when using the system. The efficiency factor can be studied by analyzing the number of tasks, the number of input and output devices used when performing the tasks, the number of information needed to perform the tasks, ... This data can give information about the user task difficulty. The task model analysis allows also to identify redundant tasks, error prone tasks (or way to perform the task), lack of procedure...

3.2.6. Identification of usability irritants

The task model analysis step enables to identify usability irritants. For instance, which user tasks are difficult or lack of information availability.

Furthermore, we also study the tools used by the controllers when performing these tasks through a systematic analysis of the information displayed to the user and through heuristic usability evaluation [11]. For the heuristic usability evaluation, we used the Bastien and Scapin's heuristics [12] and the Nielsen's heuristics [13] that, coupled together, are the most generic and enable to cover a maximum of all the HMI facets.

3.2.7. Definition of recommendations

This step entails identifying recommendations to improve the usability of the system, taking into account the results of both previous steps (the task models analysis and the identification of usability irritants).

3.2.8. Prototype design

This final step consists of designing one or several prototypes to answer the recommendations that have been given in the previous step. This step is also an iterative one.

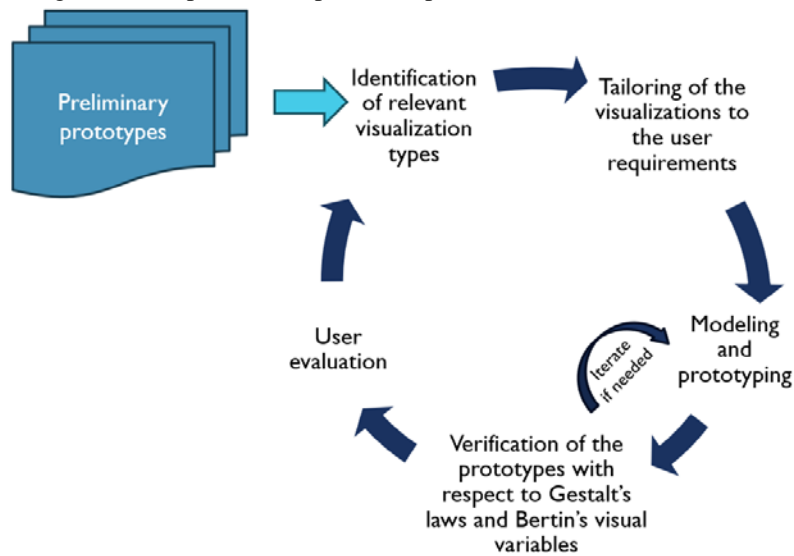


Figure 4. Applied approach for the prototypes design

Figure 4 presents the prototype design process as follows:

- First, we identify the data needed to be displayed, the interaction necessary, and the tasks that will be performed using the HMI in order to design preliminary prototypes.
- Second, these preliminary prototypes enable the identification of relevant visualization types for the data that need to be displayed.
- Third, we tailor these relevant visualizations to the user requirements and needs.
- Fourth, we design new prototypes using these tailored visualizations.

- Fifth, we verify and inspect the prototypes with respect to Gestalt’s laws [14] and Bertin’s visual variables [15] in order to check if all the aspects of the visualizations are correct and easily understandable. If this is not the case, the prototypes are reworked.
- Finally, the prototypes are evaluated by the users to determine if they are suitable for the tasks the users will have to perform with them. If some missing data or some issues are identified, the process is iterated, else the prototypes can be implemented in a more high-fidelity version.

4. Results of the application of the approach

In this section, we present the results of the application of the approach described above. First, we present the observations and interviews we conducted. Second, we present the results of the iterative steps leading to the definition of the task model. Third, we present the task modeling analysis and identification of usability irritants steps results. Fourth, we present the definition of the recommendations step results. Finally, we present the two prototypes that were designed to answer the recommendations.

4.1. Observations and interviews

During the first step of the process, we conducted several observations of different controllers and ground-segment engineers performing their work and interviewed them about the tasks they are performing (both during a satellite pass and during the whole day), the data they needed to perform their tasks and what are the tools they are using and how they use them. For the STRECCC project, we conducted:

- Observations and interviews of 3 controllers and 1 ground segment engineer operating the SWOT satellite.
- Observations and interviews of 1 ground segment engineer operating another satellite.
- Observations and interviews of 2 teams operating other satellites.

We present below some examples of results from the observations and interviews.

Hereafter are some examples of results from the observations for the dimension “Actors” of Spradley’s observation framework [5]:

- the controller in charge changes every week,
- the controllers communicate dates and times using universal time
- the controllers got support from an on-call crew composed of on-board engineer, ground segment engineer and orbit engineer.

Hereafter is an example of answer to the question “Are there priority tasks?”:

“There are priority tasks in the checklist depending on the time before the pass (for example checking flow connections). Other tasks can be done after the pass (TM recovery). Purge is best done when you’re more relaxed, when all the passes are over.”.

4.2. Tasks and data analysis and modeling

The iterations of the first four steps of the approach led us to the definition of 34 task models (1 describing the main goal and 33 enabling the decomposition of the work performed by the controllers). These task models contain in total 458 tasks, 32 kinds of information to handle (to remember, to analyze), 23 knowledge data to master, and 16 different interactive tools to perform the tasks. In this section, we present excerpts of the task models produced. The first one presents an overview of the main controllers’ tasks and the second one is the detailed description of a specific task led with dedicated tools.

The main goal of the controllers’ work when handling the satellite operation routine is to

handle the satellite operation routine. Figure 5 presents the task model corresponding to this goal, which is represented by the top-level goal “Handle satellite operations routine”, on top of the figure. The “[>” icon below it is a disabled operator, this means that the left task “Prepare satellite overpass” is performed, and that at any time, the left task “Prepare for the end of the day” will occur and stop it. The grey part “Cal Event: End of the day” linked to this task means that this event will happen at the end of the day. In the “Prepare satellite overpass” task, the “[>” icon is a suspend-resume operator, where the task “Handle satellite preparation operations” is performed until one of the three tasks “Prepare next overpass”, “Handle satellite overpass routine” or “Handle an incident” on the right (represented by the “[]” operator) is performed, then the task is resumed. The “Handle satellite preparation operation” will perform one of the five subroutines: “Monday operations”, “Tuesday operations”, “Wednesday operations”, “Thursday operations” or “Friday operations” which occur on the corresponding day of the week (represented by the “Monday/Tuesday/Wednesday/Thursday/Friday Cal Event”). At any time, the operation can be stopped and do a sequence (represented by the “>>” operator) of tasks composed of the decision task “Decide that everything is ready for the next overpass” and the user task “Wait for the next satellite overpass”.

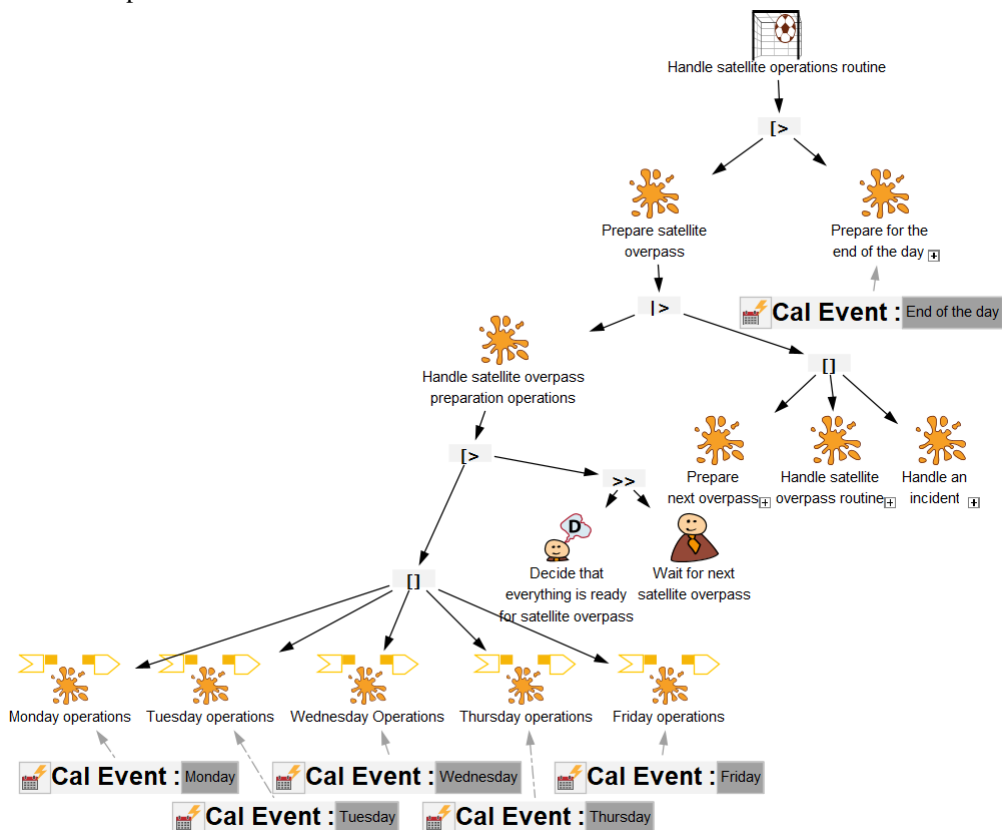


Figure 5. Task model of the goal “Handle satellite operation routine”

A subroutine is a sub-model that can be reused in different parts of a task model. Figure 6 presents an example of a subroutine, the subroutine “Check for non-treated MOF” which can occur several times in different operations. This subroutine is composed of a sequence of tasks (represented by the “>>” operator). First the input task “Write the command to launch the VEIRF_TC app” using the input device “Keyboard” (represented by the blue “in D: Keyboard bloc”), the output device “Screen” (represented by the blue block “out D: Screen”) and the

software “Terminal” (represented by the orange “Sw App : Terminal” bloc). Then the output task “Display the window” using the same “Terminal” software, the input task “Clic on the “Prepared button” using the input device “Mouse”, the output task “Display the list of operations ready to send using the output device “Screen”. The next vision task “Notice non-treated MOF operation” is optional (represented by the blue arrows) and will use the Screen and produce a piece of information “Untreated operation” represented by the green block “Inf : Intreated Operations”. The final abstract user task “Write for later that there is some untreated operations” is also optional, consumes the information “Untreated operations” and produce the information “Untreated MOF” represented by the green block “Inf : Untreated MOF”.

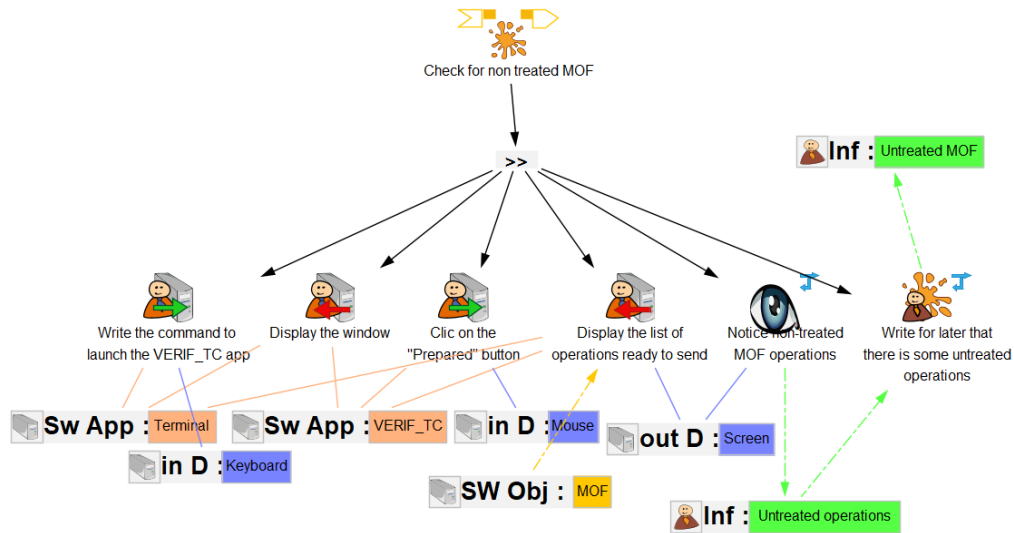


Figure 6. Task model of the subroutine “Check for non-treated MOF”

4.3. Task modeling analysis and identification of usability irritants

The task model analysis and the identification of usability irritants steps led to the identification of 43 irritants. These irritants concern or generic purposes or specific tools (6 tools studied). They are classified in four categories:

- Lack of support for the most frequent tasks.
- Lack of support to speed up the understanding of the operations’ state.
- Lack of support to avoid errors and confusion.
- Lack of support to ease interaction with the HMIs.

Table 1. Examples of usability irritants found during the study, from the “Lack of support to speed up the understanding of the operations state” category.

Irritant id	Irritant description
IRR#01	Information loss: after an operation, the only data displayed concerning its duration is the planned duration. There is a loss of the real operation duration.
IRR#02	Operation type confusion: all types of operations have the same representation.
IRR#03	Missing information: there is no data available about the availability of other actors (e.g., mission centers, ground stations, ...).
IRR#04	Target role confusion: the task checklist mixes all tasks without any means to distinguish the role concerned by the action.

Table 1 presents four irritants from the “Lack of support to speed up the understanding of the operations state” category. These irritants are presented here in a generic way, even if they might concern a unique tool, and their identification has been changed for the paper.

4.4. Definition of recommendations

The 43 irritants identified led us to the definition of 43 recommendations which concern or generic purposes or specific tools (6 tools studied). They are classified in four categories:

- Provide support to the most frequent tasks.
- Provide support to speed up the understanding of the operations’ state.
- Provide support to avoid errors and confusion.
- Provide support to ease the interaction with the HMIs.

Table 2 presents four recommendations corresponding to the irritants presented in Table 1. They are extracted from the recommendations of the “Provide support to speed up the understanding of the operations’ state” category. These recommendations are presented here in a generic way, even if they might concern a unique tool, and their identification has been changed for the paper.

Table 2. Examples of recommendations to correct the usability irritants

Recommendation id	Recommendation description
RECO#01	Both planned and real durations shall be displayed once an operation has been performed.
RECO#02	The different types of operations shall be displayed with different types of visual representations.
RECO#03	Availability status of other actors (e.g., mission centers, ground stations, ...) shall be displayed.
RECO#04	The role corresponding to the tasks in the checklist shall be identifiable.

Concerning the “Provide support to speed up the understanding of the operations’ state” recommendation category, we found a supplementary recommendation requiring the addition of a new visualization tool to the set of existing interactive tools. This visualization tool shall allow the controllers to have an overview of the operations’ state that would enable them to be aware of the situation in progress, analyze it, and predict what will happen next. This would greatly help the controllers when they arrive for an on-call duty, or when they arrive at their workstations after a break. The need for such a visualization is also increased by the fact that the profile of the controllers is evolving towards a less technical one with less knowledge of the underlying system or telecommunications.

This visualization would support the general understanding of operations’ state for the controllers and imply increasing their situation awareness. The situation awareness and its role in the decision-making process have been modeled by M. R. Endsley [16] and are pictured in Figure 7. To be able to make a decision, the user needs to be aware of the state of the system, this is the situation awareness. It is divided into three levels:

- Perception of data and the elements of the environment (level 1).
- Comprehension of the meaning and the significance of the situation (level 2).
- Projection of future states and events (level 3).

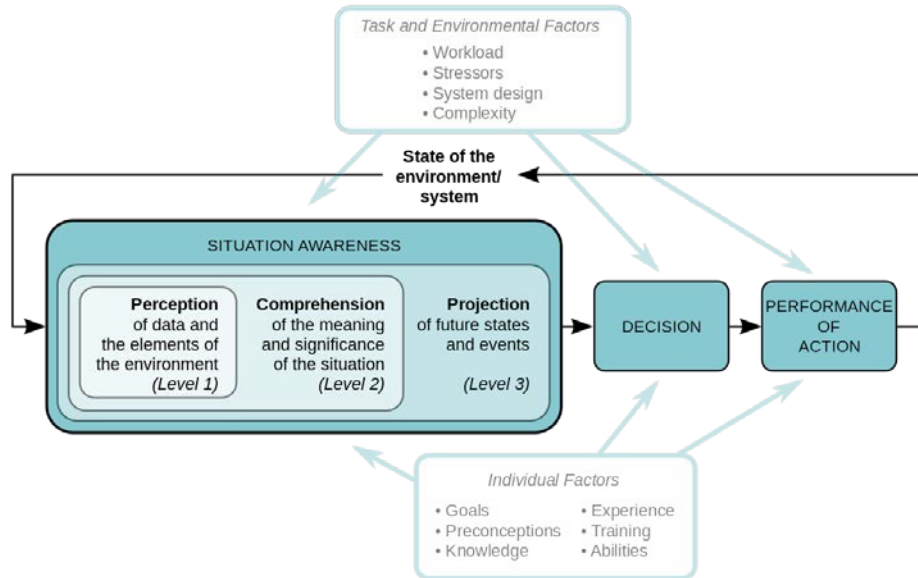


Figure 7. Model of situation awareness in dynamic decision-making from [13]

This model, coupled with the results of our analysis, enables us to define the tasks that the controllers will have to perform when interacting with this new visualization. These tasks are listed in Table 3.

Table 3. Controllers’ tasks for developing a better situation awareness

Task id	Task description
T1	Be aware of the current situation of the SWOT satellite and its operations
T2	Be aware of the time left to act until the next overpass (when it will be and how much time is left until then)
T3	Be aware of how much time is left to act before the end of the overpass
T4	Be aware of how much time is left before the next phase
T5	Be aware of important events on different days (overpasses, errors, presence of tasks to be performed)
T6	Be aware of other actors availability (mission centers, ground stations, ...)
T7	Be aware of the CNESMC availability status announced to other centers
T8	Be aware of internal availabilities and contact (for people in charge of the SWOT satellite, for instance, ground segment, engineer, controller, ...)
T9	Be aware of the status of the files that have to be sent to the SWOT satellite (uploaded, uploading, prepared, before)
T10	Be aware of the current date and time
T11	Be aware of the data of upcoming overpasses (TC, TM)
T12	Be aware of the notes left for a specific role
T13	Be aware of the notes left for everyone
T14	Be aware of the report from the previous day

The main goal is “T1 - Be aware of the current situation of the SWOT satellite and its

operations”, this goal is further detailed by the other 13 tasks. These tasks are written to represent all data that the controllers need to know to perform their job; this is why they all start by “be aware of”. If these tasks were further detailed, we would find the three levels of situation awareness previously presented (perception, comprehension, and projection).

With these tasks in mind, we designed two prototypes of interactive visualizations to support the situation awareness of the controllers. They are presented in the next section.

4.5. Prototypes design

To increase the situation awareness of the controllers and enable them to perform the tasks described in the previous section, we designed two prototypes of interactive visualization. The first prototype (P1), presented in the first subsection, is designed to support the situation awareness of the controllers about the operations’ state and is designed as a “classical” view, similar to the other tools already used by the controllers. The second prototype (P2), presented in the second subsection, is also designed to support the situation awareness of the controllers about the operations’ state. It is also designed to increase the experience (UX) of the controllers and, for this, it is designed in a “breakaway” view.

4.5.1. First prototype: “classical” view

The first prototype (P1) is designed to support the situation awareness of the controllers about the operations’ state. It is designed to be similar to the tools that are currently used by the controllers. The whole prototype is presented in Appendix A, Figure 14.

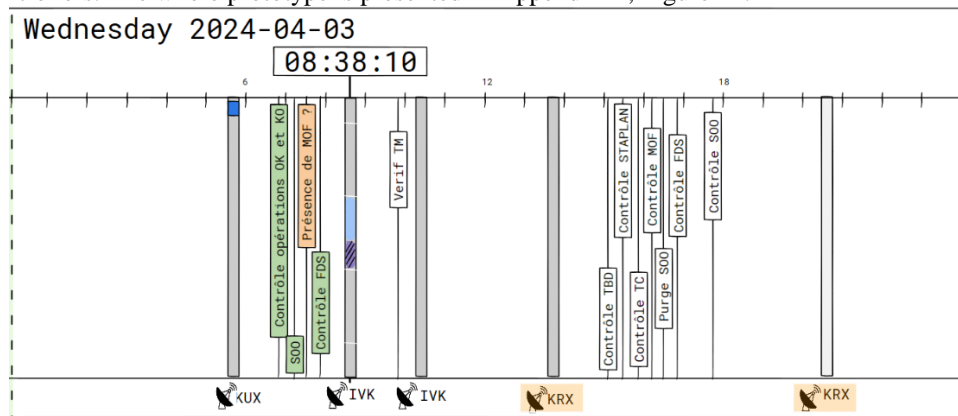


Figure 8. Excerpt of the “classical view” prototype (P1): timeline for the current day

Fig. 8 depicts an excerpt of the timeline part of this “classical view” prototype. On this figure, we can see the timeline for Wednesday, the 3rd of April 2024. This visualization presents to the controllers:

- The SWOT overpasses (grey vertical bars), when they are planned, and which ground station will be in contact with the satellite (for instance “KUX” indication below the first overpass which stands for Kourou ground station).
- To support the controllers’ projection of future states, we added in the next (or current) SWOT overpass the estimated planning for the sending of telecommands. This is done with the colors depicted inside the bar representing the overpass. For instance, on the second overpass, we can see in blue the estimated mission telecommands sending. The purple color stands for the estimated sending of the other telecommands, here it is striped to warn about the fact that these telecommands are likely not to be uploaded in the time left and may need another SWOT overpass to be sent completely.
- The availability of the ground stations is also depicted in this view. For instance, we can

see here that the KRX (which stands for Kiruna) ground station is currently not available; this is why its name is depicted over an orange background.

- The significant events of the day, with approximate planning. The events correspond to the vertical wires associated with boxes embedding the name of the corresponding event. These boxes are colored depending on the fact that the event was executed as planned (green boxes), was not executed yet while it should have been (orange boxes), or is not executed yet (white boxes).
- Figure 9 presents another excerpt of this prototype depicting the state of the files being sent to the SWOT satellite. In this view, we can see:
- The planning of the SWOT overpass is depicted on the left. The first bar presents the estimated view while the second bar presents the real state.
- The files and their states (before, prepared, uploading, or uploaded) are depicted in the middle.
- The next SWOT overpasses and their significant data are depicted on the right.
- Through all these data, this visualization fully supports the situation awareness of the controllers concerning the operation states.

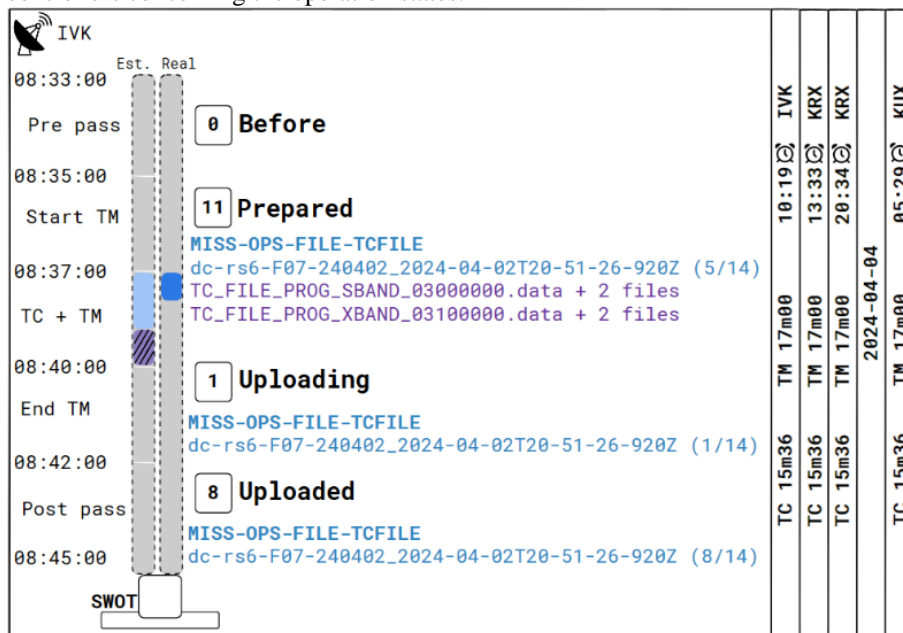


Figure 9. Excerpt of the “classical view” prototype (P2): state of the files being sent to the SWOT satellite

4.5.2. Second prototype: “breakaway” view

The second prototype (P2) is also designed to support the situation awareness of the controllers about the operations’ state. The whole prototype is presented in Appendix A, Figure 12. This prototype is, on purpose, designed with a “breakaway view”. We investigated several shapes for this prototype; the “croissant shape” was chosen to be the most suitable for the data displayed.

Unlike the first prototype, it is also designed to increase the user experience (UX) of the controllers. The user experience includes the “users’ perceptions and responses that result from the use and/or anticipated use of a system, product or service” [17].

A broad variety of dimensions are associated with user experience, among which Identification [18], which is defined as “self-expression, interaction with relevant others”. In other words, identification represents how much the operator will find the visualisation presentable, professional, tasteful, and if it brings the operator closer to others. We thus chose to

use the CNES corporate identity and style guide: Blue Pantone 294C and Arial font.

By increasing the UX, we wanted the users to perceive the prototype as attractive and that its use creates positive emotions. To improve the UX of this prototype, we evaluated it using Gestalt's laws [14] and Bertin's visual variables [15] to ease the understanding of the data displayed. The Gestalt's laws and Bertin's visual variables also supported the choice of the layout of the visualization. For instance, we used the Gestalt's law of uniform connectedness to associate the satellite overpass on the croissant to its different phases displayed in the center of the figure. Although the law of uniform connectedness was not directly addressed by Koffka et al. [26], it builds upon and extends their work. It was proposed by Palmer et al. [27] and states that "*a connected region of uniform visual properties –such as luminance or lightness, color, texture, motion, and possibly other properties as well- strongly tends to be organized as a single unit*" (example in Figure 10).

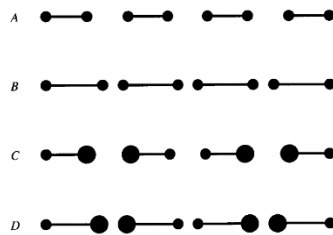


Figure 10. Demonstrations of uniform connectedness as a principle of perceptual organization (A) and of its ability to overcome such classical grouping factors as proximity of the dots (B), similarity in size (C), and their combination (D) extracted from [24]

Events such as tasks and satellite overpass are recognizable despite their sizes and orientation differing thanks to the Gestalt's principle of invariance. This principle addresses "*how the essential structural character of an object is recognized immediately and effortlessly when presented in a great variety of different aspects and viewing conditions*"[28] (example in Figure 11).



Figure 11. Demonstration of the principle of invariance extracted from [25] : the basic structural form of a simple object is recognized immediately, independent of rotation, translation, and scale.

Bertin [15] introduced the following retinal variables, also called visual variables: size, value (the various degrees between white and black), colour, shape, orientation, and texture. These are illustrated in Figure 12.

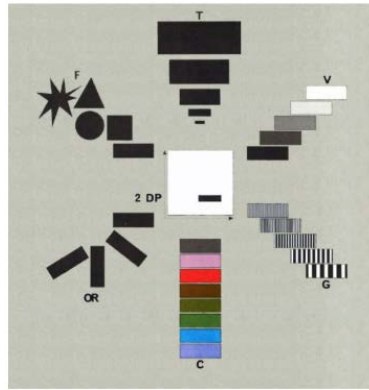


Figure 12. Representation of Bertin’s visual variables from [12]. At the top, in the middle, are the representations of rectangles of different sizes. Then, in a clockwise direction, are illustrations of the variables value, texture, color, orientation, and shape.

Fig. 10 depicts an excerpt of the “breakaway view” prototype. This excerpt corresponds to the whole week’s timeline:

- In the middle of the “croissant” shape, we can see in white the current day timeline. This timeline includes the significant events for the day as well as the SWOT overpass. The SWOT overpasses are associated with their more significant data (corresponding ground station and its state, timed data for TC and TM).
- In the center of the prototype, the current SWOT overpass is depicted with its timeline.
- In the center, at the bottom of the figure is pictured the state of the SWOT satellite.

In the “breakaway view”, we used the hue and size variables as markers of the temporality. The further an event is, the smaller and darker it becomes. We also used colour to highlight different types of information. We used the red color for information that requires attention (such as the current time in the croissant, and the current moment in time during a pass in Figure 13). The green color represents the nominal status for the satellite (such as the satellite banner at the bottom in the middle in Figure 13). We used the orange color for the potential warnings (such as the antenna name “KRX” in the grey vertical bar in the middle of the croissant in Figure 13).

Through all this data, this visualization fully supports the situation awareness of the controllers concerning the operational states.

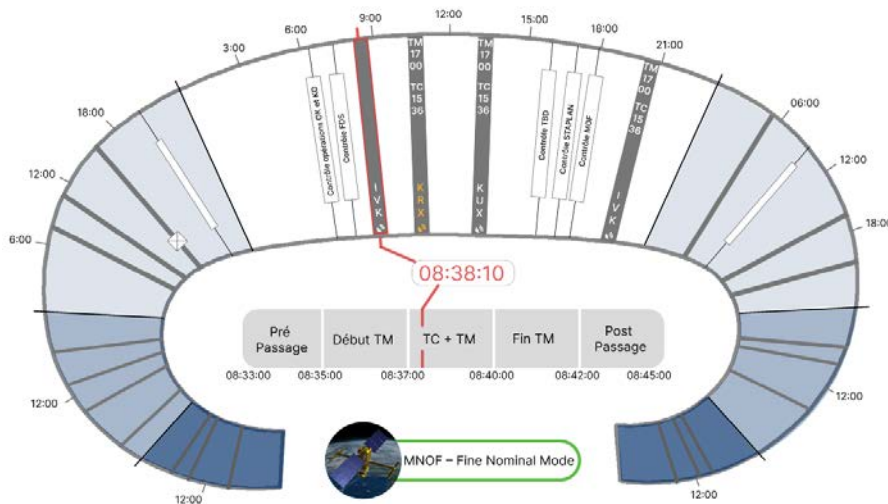


Figure 13. Excerpt of the “breakaway view” prototype (P2): timeline for the week

5. Prototypes' evaluation results

We performed two types of evaluation: a qualitative analysis of the effectiveness dimension of usability [17] and a preliminary empirical analysis with ground controllers.

5.1.1. Predictive evaluation

Both prototypes P1 and P2 were built to increase the situation awareness of the controllers. In section 4.4, we present a set of 14 tasks to support the situation awareness of the controllers. These tasks are designed to support the perception level, the comprehension level and the projection level of the situation awareness as modeled by M. R. Endsley [16]. Therefore, the predictive evaluation of the effectiveness of the prototypes with respect to these tasks enable to predict if the prototypes enable to support the situation awareness of the controllers.

Effectiveness is referred to as “*the accuracy and completeness with which specified users can achieve specified goals in particular environments*” [17]. We evaluated the effectiveness aspect of usability by measuring task coverage for both prototypes P1 and P2. These are reported in Table 4.

Table 4. Coverage of the controllers' tasks by the prototypes

Task id	Task description	P1	P2
T1	Be aware of the current situation of the SWOT satellite and its operations	✓	✓
T2	Be aware of the time left to act until the next overpass (when it will be and how much time is left until then)	✓	✓
T3	Be aware of how much time is left to act before the end of the overpass	✓	✓
T4	Be aware of how much time is left before the next phase	✓	✓
T5	Be aware of important events on different days (overpasses, errors, presence of tasks to be performed)	✓	✓
T6	Be aware of other actors availability (mission centers, ground stations, ...)	✓	✓
T7	Be aware of the CNESMC availability status announced to other centers	✓	✓
T8	Be aware of internal availabilities and contact (for people in charge of the SWOT satellite, for instance, ground segment, engineer, controller, ...)	✓	✓
T9	Be aware of the status of the files that have to be sent to the SWOT satellite (uploaded, uploading, prepared, before)	✓	✗
T10	Be aware of the current date and time	✓	✓
T11	Be aware of the data of upcoming overpasses (TC, TM)	✓	✓
T12	Be aware of the notes left for a specific role	✓	✓
T13	Be aware of the notes left for everyone	✓	✓
T14	Be aware of the report from the previous day	✓ (partial)	✓ (partial)

The prototype P1 supports one additional task (T9) compared to the second prototype P2. This choice was made to preserve the second prototype's aesthetics and increase its user experience by avoiding information overload on the croissant. Additionally, this tool is designed to provide an overview of the situation rather than replace existing ones. Controllers will continue using their usual tools, especially during critical moments like satellite overpasses, to gain a detailed understanding of the situation. Therefore, information about file status is considered more specific and is not essential for this overview prototype. For task T14, the status of operations from previous days can be seen on both prototypes thanks to a cross mark indicating that an error occurred. Nonetheless, controllers cannot see full reports recounting details about the type and cause of that error, this is why “partial” is indicated in the table for this task.

5.1.2. Empirical feedback

The two preliminary prototypes were presented to 3 controllers to evaluate them. The feedback session was prepared in the form of an unstructured interview [6] to let the controller express as much as possible on what they feel and to let them focus on the concerns they find important. First, we introduced to the controllers the main philosophy of the two prototypes we developed. We then presented the first prototype, let the controllers ask questions and express their opinions. Then, we presented the second prototype, let them ask questions and express their opinions as well.

Hereafter are some examples of what the controllers said during the unstructured interviews for each prototype:

- For prototype 1 (P1 - “Classical view”):
 - “Unavailability of other centers could be placed much lower than the timeline, it’s too close to the timeline.”
 - “Unavailability of centers could be useful. Last year, we got a sudden station unavailability due to a forest fire.”
 - “What is important is that we see if all the files could make it to the satellite.”
 - “The notes part takes too much space.”
- For prototype 2 (P2 – “Breakaway view”):
 - “The croissant shape is very nice.”
 - “The information about the status of the centers at the top of the view is not the most important information.”
 - “Only the centers that are unavailable should be displayed.”
 - “This view would not work for some other missions, for example, for the missions for which there are 14 passes a day... for SWOT we don’t use all of the passes, then it goes”

In the end, and to summarize, we notice that the controllers’ feelings concerning these prototypes differ following the profile of the controller:

- The more experimented controller preferred the “classical view” prototype to work with and made the following remark about both prototypes: “I have the impression that the classical view would be for the controllers and that the breakaway view would be for the visitors”, yet suggesting to use the “breakaway view” prototype for guests with less technical profile.
- The other controllers preferred the “breakaway view” prototype to work with as they find it more attractive and more beautiful. This finding shows that we partially meet the objectives of increasing the UX of the controllers and of being accessible to users with different technical backgrounds.

Yet, the overall feeling is that these two prototypes will help to increase the situation awareness of the controllers.

This empirical feedback helped us to confirm the findings we made during the predictive evaluation. When the controllers arrive for an on-call duty, or when they arrive at their workstations after a break, the visualization supports them in rapidly building a mental model of the operations state and increases their awareness of the situation in progress. They can analyze it, and predict what will happen next faster than without the visualization.

6. Conclusion

This paper has presented the findings of the STRECCC project funded by CNES. This project dealt with the increase of situation awareness and take-over hand-over activities for ground segment controllers. To do so, we have applied a User Centered Design (UCD) approach

augmented with a task model-based representation of controllers' tasks.

Controllers' work and tasks on the extant system have been represented exhaustively using the HAMSTERS-XL notation. Following the UCD approach, we produced several prototypes of the future system, and two of them (a classical one and a breakaway one) were presented in the paper. Those prototypes were checked for effectiveness against the task models to ensure that they were covering the controllers' work in its entirety.

In conformance with the UCD approach, the prototypes were iteratively produced with the feedback of several controllers. The last version of the prototypes was evaluated with 3 controllers (different from the controllers that were interviewed during the design iterations) who provided feedback for improvements and suitability for work and users. Feedback was positive on all aspects of usability, including situation awareness.

While the proposed approach was applied on the SWOT ground segment, the evaluation clearly shows that the approach, the findings, some aspects of the design, and some parts of the task models are generic enough to be applied to other satellites or other dashboards in the space domain or other domains. A perspective for this work is to apply the analysis and design process to user interfaces for engineers in charge of onboard operations, as well as for the monitoring and control of multi-mission satellites.

7. Acknowledgments

This work was funded by the project CNES 21055/00.

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Appendix A. Prototypes of an interactive visualization of operations state

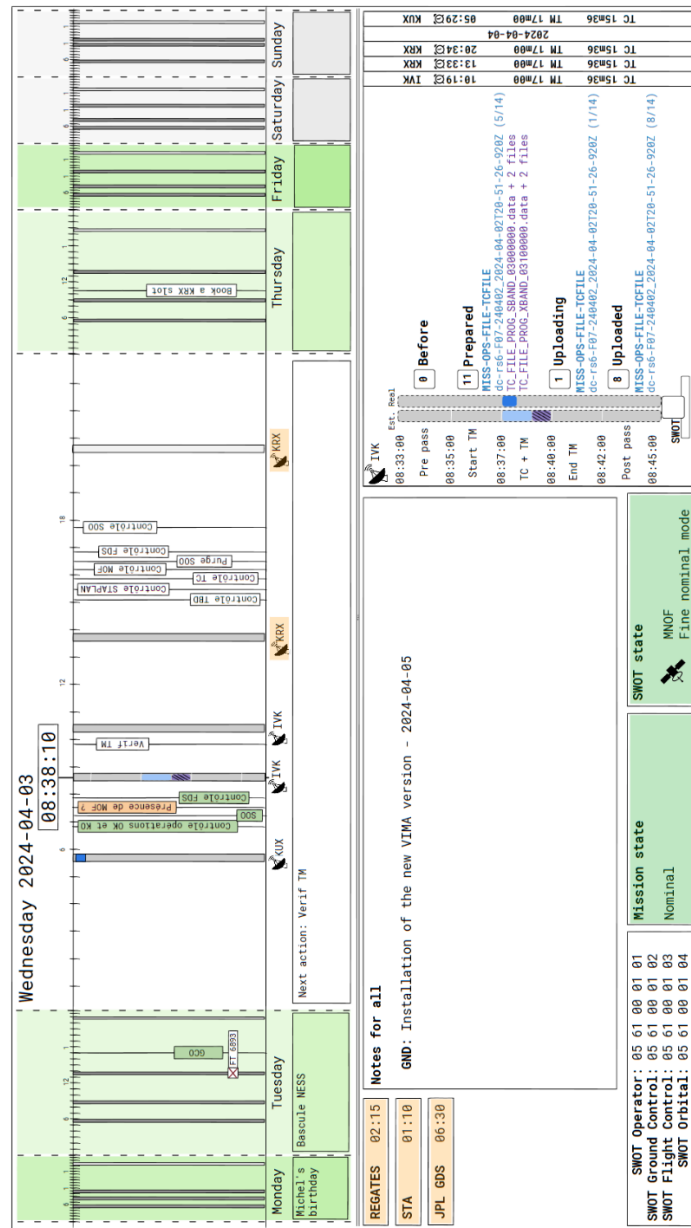


Figure 14. Prototype of an interactive visualization of operations state – P1 - “classical view”

Figure 15. Prototype of an interactive visualization of operations state – P2 - “breakaway view”

