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## 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 model-based approach 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...). Beyond, they improve the situation awareness of the controller by providing a long-term (a full week) perspective on recent-past and future operations.

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

### Acronyms/Abbreviations

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

operations scheduling. In parallel to these evolutions of the nature of operations, the skills, knowledge, and expertise of controllers are also evolving. Their profile evolves being less technical and with less knowledge in 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 evolutions of the nature of operations as well as the evolutions 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...). Beyond, it improves the

### 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

situation awareness of the controller by providing a long-term (a full week) perspective on recent-past and future operations.

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 present the approach applied to study the usability of the SWOT Command and Control Center (CCC). In the fourth section, we present an exhaustive description of the tasks that the controllers have to perform to operate the SWOT satellite. These models are the cornerstone of our study and enable us to recommend adding an interactive visualization to increase the situation awareness of the controllers. This is presented in section 5. Section 6 presents two prototypes that have been designed following this study. Section 7 presents preliminary results of user evaluation of these prototypes. Finally, Section 8 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).

The mission ground segment comprises (see Fig. 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 defines 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.

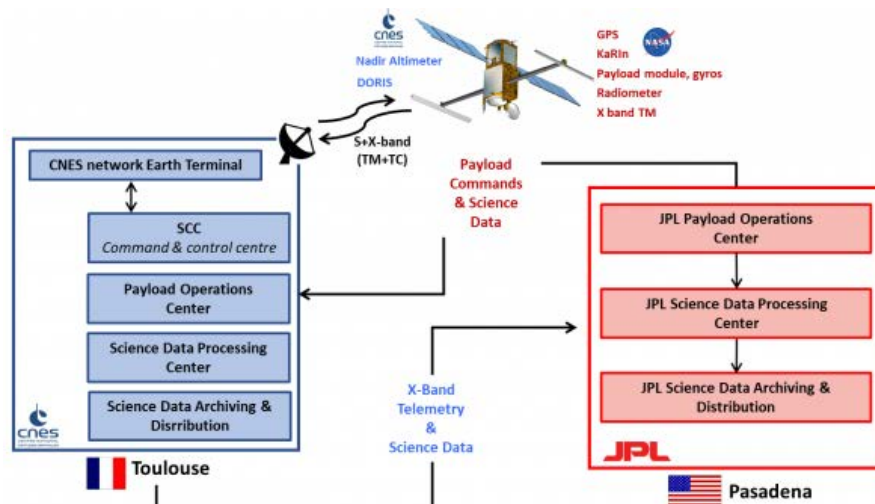


Fig. 1. Simplified SWOT ground segment architecture

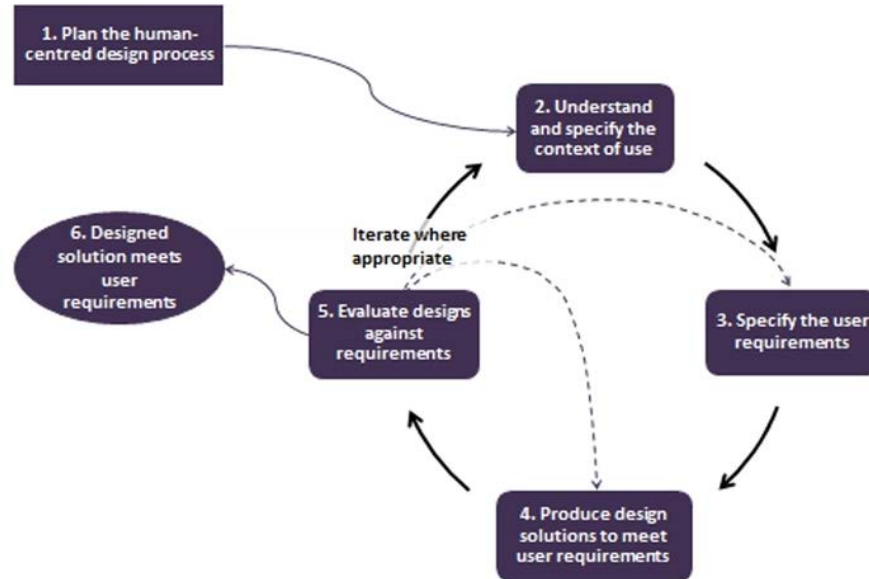


Fig. 2. User-Centered Process [4]

- *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. A User-Centered and Model-Based Approach to Assess Usability of the SWOT Command and Control Applications

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 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. Third, it presents how the approach was applied. Finally, it presents the results through an exhaustive description of the controller's tasks.

### 3.1. User-Centered-Design

The ISO 9241-210 standard [4] defines the User-Centered Design Process. This process is depicted in Fig. 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.

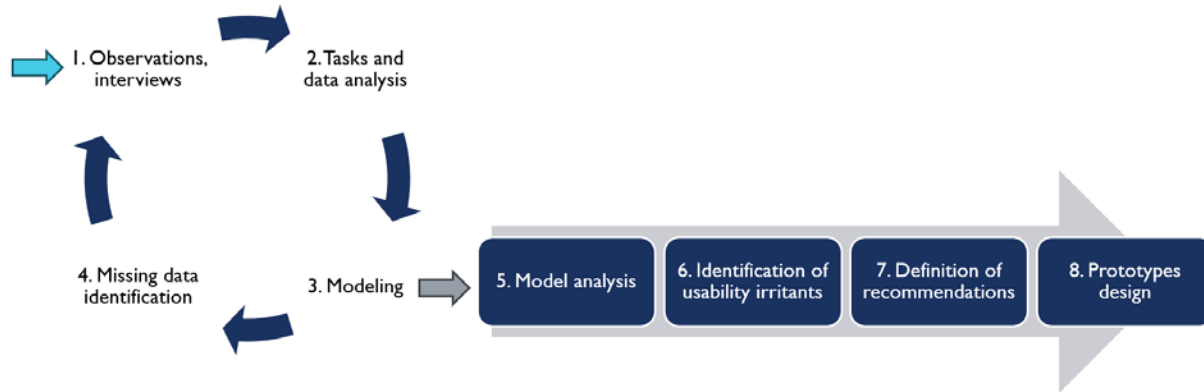


Fig. 3. Applied approach

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.

### 3.2. Overview of the Applied Approach

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

#### 3.2.1. Observations and interviews

During this first step, 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.

#### 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.

#### 3.2.3. Modeling

This step consists in modeling the user tasks and the data manipulated to perform these tasks exhaustively. For that purpose, we use the HAMSTERS-XL notation [5] 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 [6] [7] enables the editing and simulation of task models. The tool can be used to ensure consistency, coherence, and conformity between assumed or prescribed user tasks and the sequence of actions necessary to operate interactive systems.

Section 4 presents examples of the task models that have been produced during the STRECCC project. This task modeling step leads 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 tools to interact with to perform the tasks.

#### 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 model is complete and consistent, it is 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 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 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 [8]. For the heuristic usability evaluation, we used the Bastien and Scapin's heuristics [9] and the Nielsen's heuristics [10] that, coupled together, are the most generic and enable to cover a maximum of all the HMI facets.

### 3.2.7. Definition of recommendations

Both previous steps (the task models analysis and the heuristic usability evaluation) led to 43 recommendations. These recommendations concern

generic purposes or are specific to 6 different tools. They are classified into four categories:

- Provide support to the most frequent tasks.
- Speed up the understanding of the operations state.
- Avoid errors and confusion.
- Ease the interaction with the HMIs.

We do not detail here these recommendations; however, the paper will focus in a generic way on how to speed up the understanding of the operations state for the controllers. This implies increasing the situational awareness of the controllers and is detailed in Section 0.

### 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.

It is described in Fig. 4 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 [11] and Bertin's visual variables [12] in order to check if all the aspects

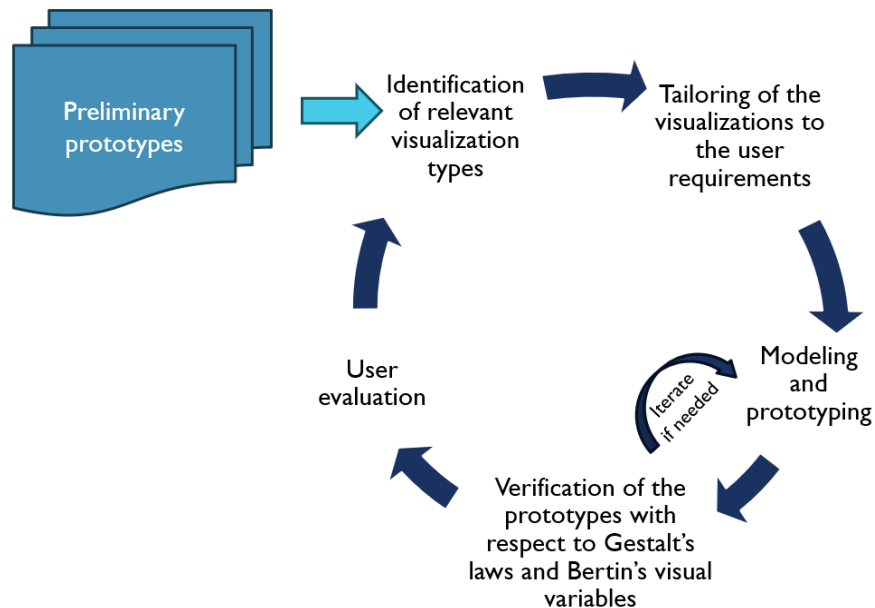


Fig. 4. Applied approach for the prototypes design



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.

Two examples of prototypes designed to increase the situational awareness of the controllers are presented in Section 6. The HAMSTERS-XLE software tool supports the editing and simulation of the execution of task models [6],[7]. 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.

#### 4. Exhaustive Description of Controllers' Tasks as the Cornerstone of the Approach

Fig. 5 shows the task model of the goal “Handle satellite operation routine” which is the main goal of the controllers' work when handling the satellite operation routine. The “[>]” icon under 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 gray 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 operations” 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

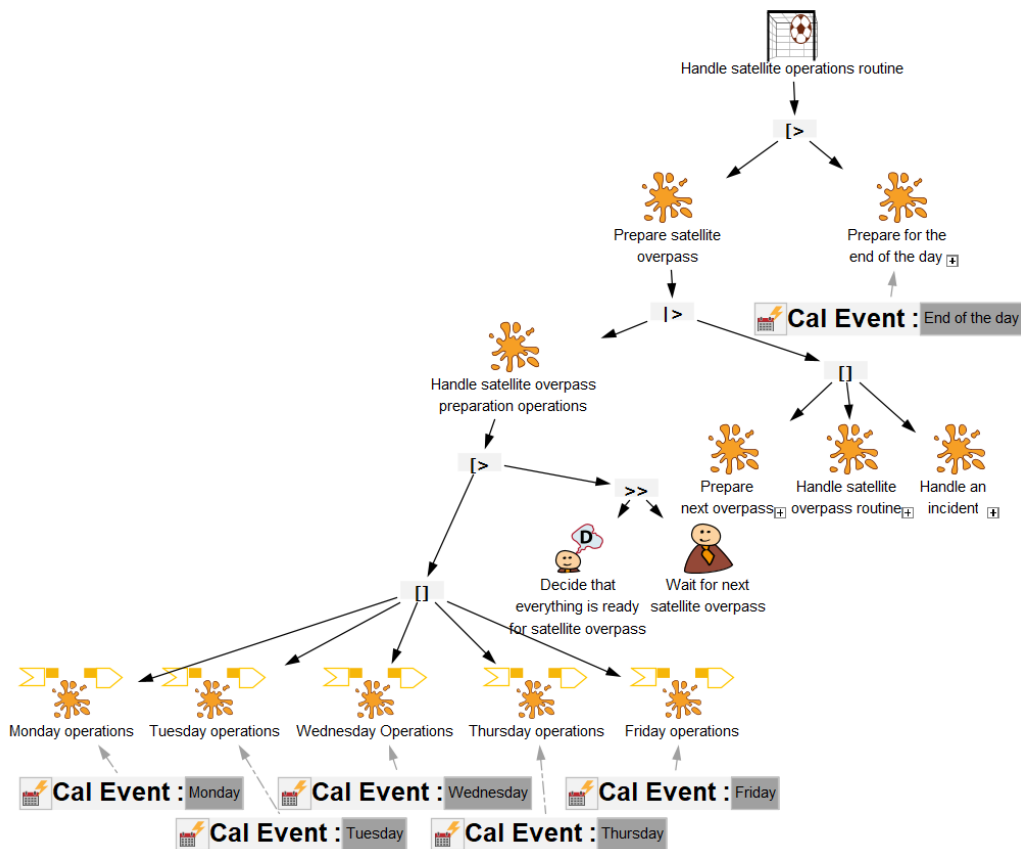


Fig. 5. Task model of the goal “Handle satellite operation routine”

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

## 5. Study of the Situation Awareness for the SWOT Operations

As explained in Section 3.2.7, the study we

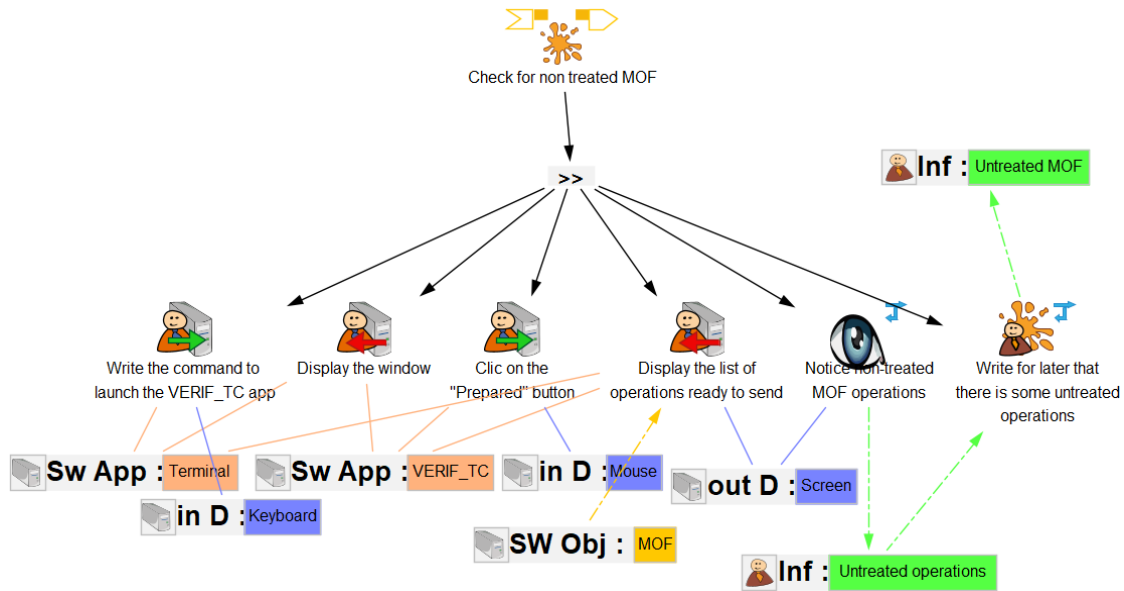


Fig. 6. Task model of the subroutine “Check for non-treated MOF”

task “Wait for the next satellite overpass”.

A subroutine is a sub-model that can be reused in different parts of a task model. Fig. 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”), 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”.

conducted lead to the identification of 43 recommendations, classified into 4 categories. In this paper, we will focus on the category “Speed up the understanding of the operations state”. More particularly, we found that we could add to the current systems a visualization allowing 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.

The situation awareness and its role in the decision-making process have been modeled by M. R. Endsley [13] and are pictured in Fig. 11. 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).

Taking into account that model, we can define the tasks that the user will have to perform with this visualization. The main goal is to become aware of the



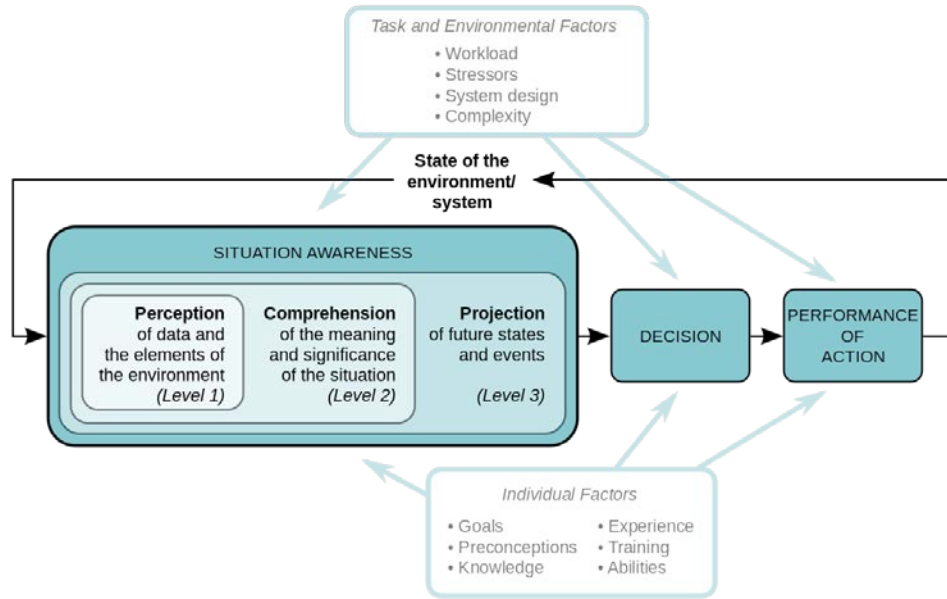


Fig. 7. Model of situation awareness in dynamic decision-making from [13]

SWOT satellite and its operations. To do this, the controllers will need (for example):

- Find out about the next SWOT overpass (when will it be and how much time is left until then).
- Find out about the next significant events of the day.
- Find out about the availability of the other actors (mission centers, ground stations, ...).
- Find out about how to contact the people in charge of the SWOT satellite (ground segment engineer, controller, ...).
- Find out about the state of the files that have to be sent to the SWOT satellite.
- ...

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.

## 6. Prototypes of Interactive Visualizations to Support Situation Awareness

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 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 displayed in Appendix A, Fig. 11.

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 3<sup>rd</sup> 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.

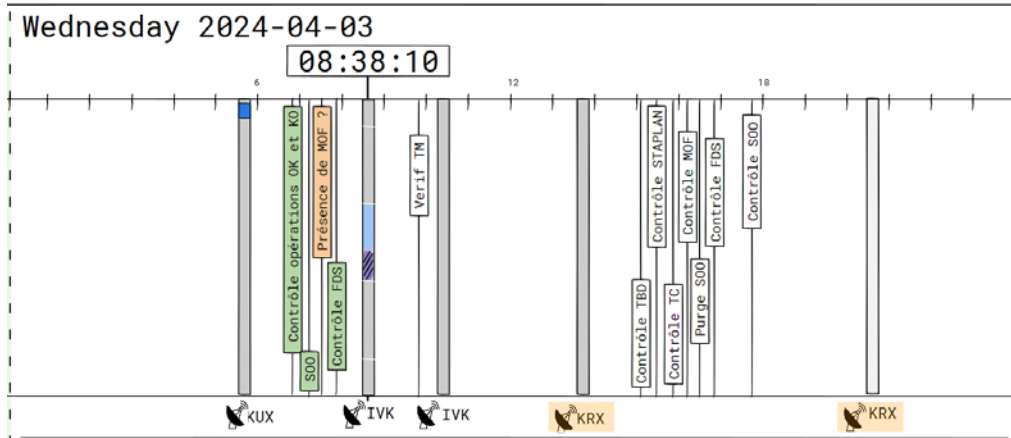


Fig. 8. Excerpt of the “classical view” prototype: timeline for the current day.

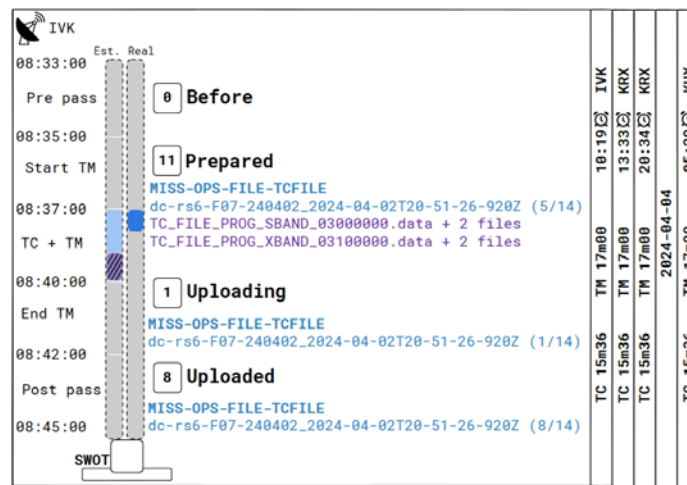


Fig. 9. Excerpt of the “classical view” prototype: state of the files being send to the SWOT satellite.

- 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).
- Fig. 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.

The second prototype is also designed to support the situation awareness of the controllers about the operations state. Unlike the first one, 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” [14]. 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 [11] and Bertin’s visual variables [12] to ease the understanding of the data displayed. The whole prototype is displayed in Appendix A, Fig. 12.

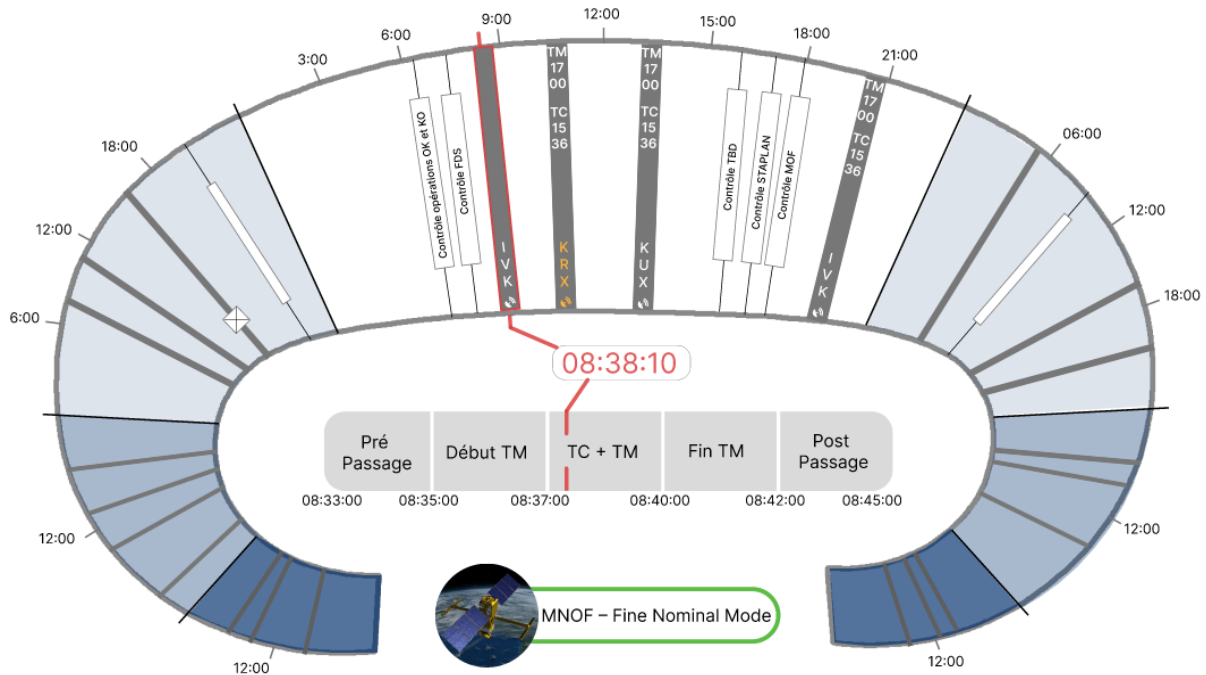


Fig. 10. Excerpt of the “breakaway view” prototype: timeline for the week.

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 more suitable to the data displayed.

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, 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 picture, the current SWOT overpass is depicted with its timeline.
- In the center-down of the figure is pictured the state of the SWOT satellite.

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

## 7. Preliminary Results from Evaluation with Controllers

The two preliminary prototypes were presented to 3 controllers to evaluate them. The controllers’ feelings with respect to these prototypes differ following the profile of the controller, yet, the overall feeling is that these two prototypes will help to increase the situation awareness of the controllers.

The more experienced controller preferred the “classical view” prototype to work with and suggested using 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.

## 8. Conclusion

This paper has presented the findings of the STRECCC project funded by CNES. This project was dealing with the increase of situation awareness and take-over activities for ground segments controllers. To do so, we have applied a User Centered Design (UCD) approach augmented with a model-based representation of controllers’ tasks.

Controllers’ work and tasks on 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 evaluated with 3 controllers who provided feedback for improvements and suitability to

work and users. Feedback was positive on all aspects of usability including situation awareness.

While the proposed approach was applied on 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.

### Acknowledgments

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Appendix A. Prototypes of an interactive visualization of operations state

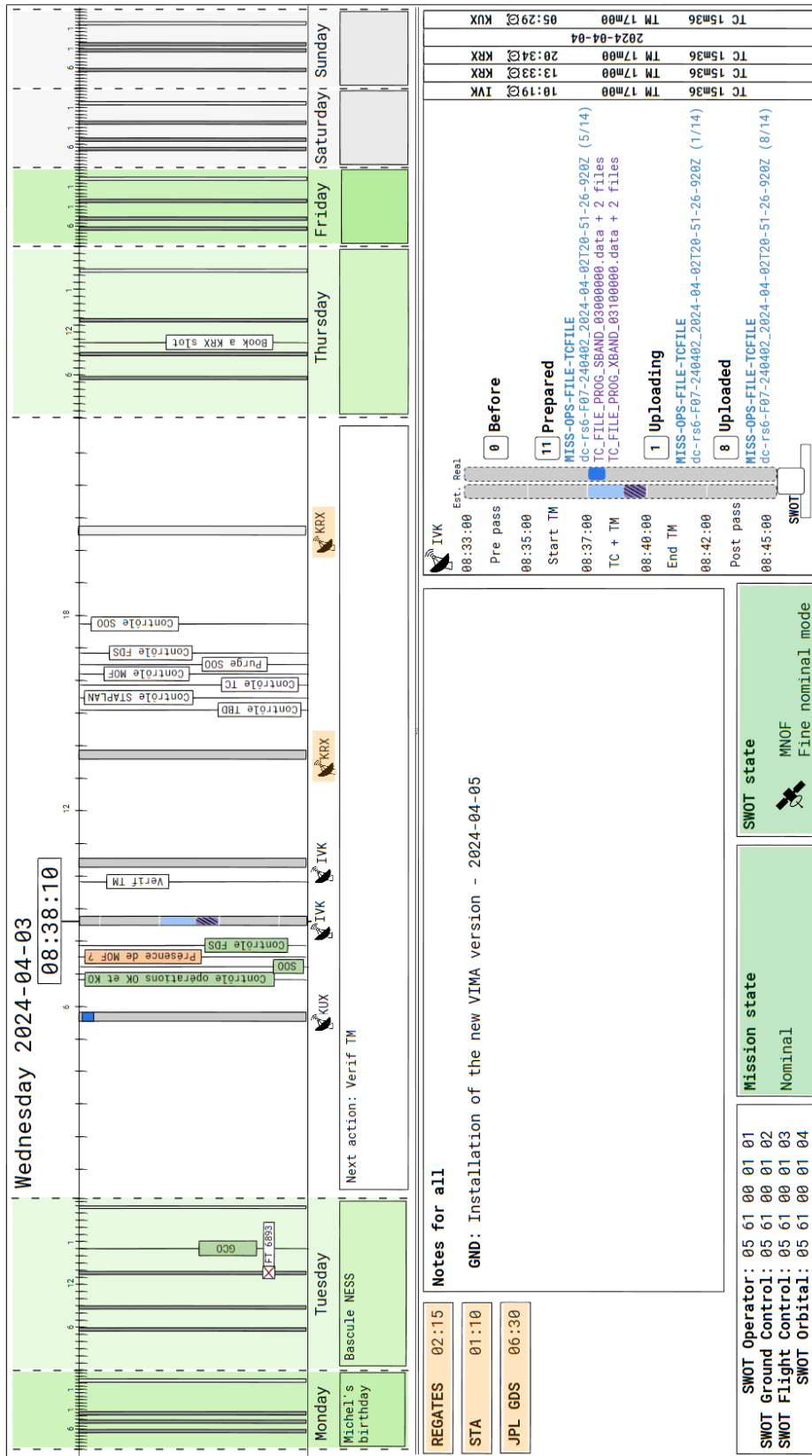


Fig. 11. Prototype of an interactive visualization of operations state - classical view

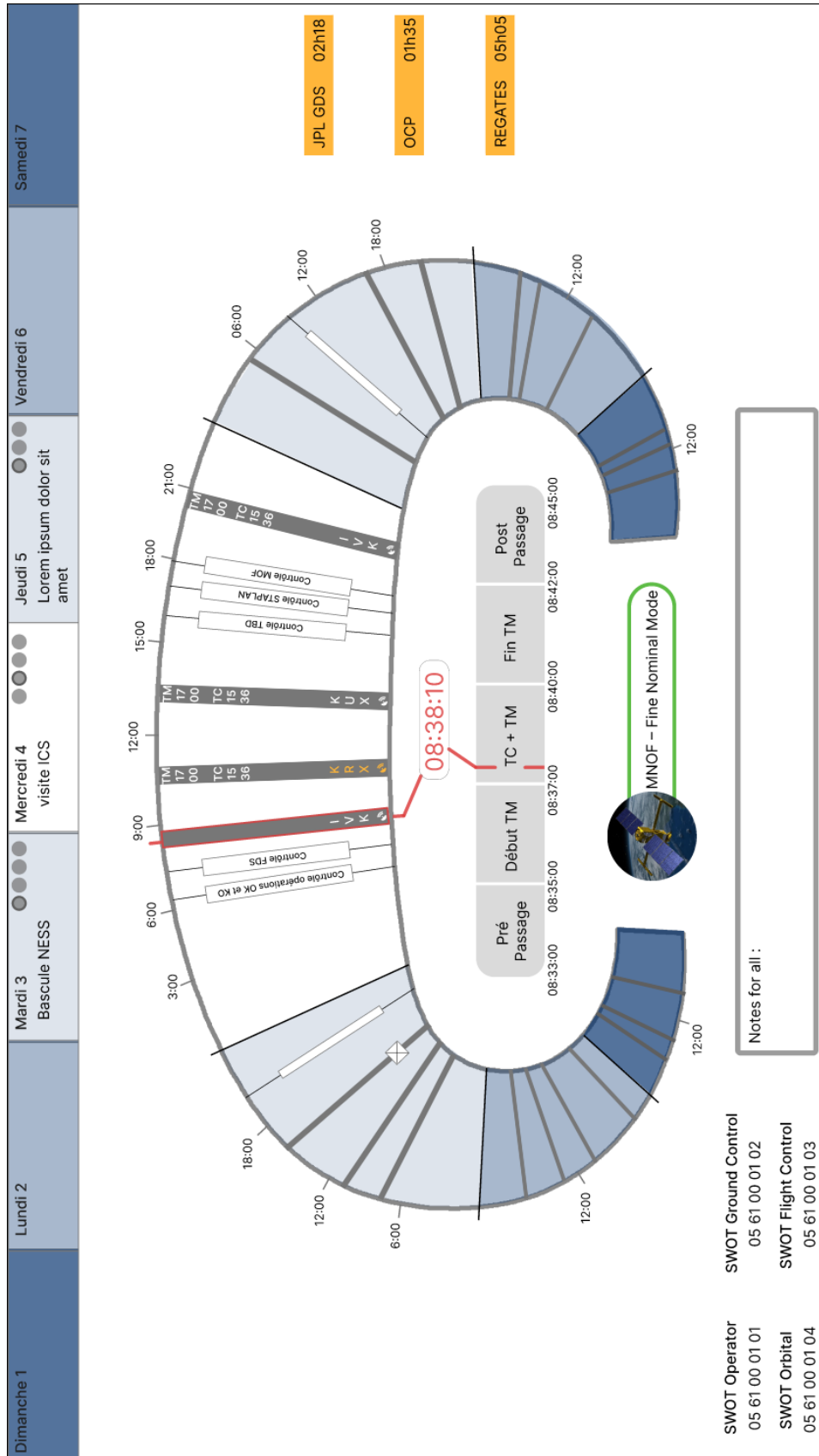


Fig. 12. Prototype of an interactive visualization of operations state - breakaway view