Jessica Kuleshov and Henry Manelski
Aerospace Human Factors Engineering

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Final Report

An Improved Design for the Communications of the *Mercury* Spacecraft

Abstract

In this paper we introduce a redesign of the communications system on the Mercury Spacecraft which powered America's first crewed steps into space. We discuss the issues with the original communications design and our solutions. The most glaring problem with the original system was its failure to notify astronauts when the next loss of signal (LOS) and acquisition of signal (AOS) was scheduled to occur. Our redesign solved this with a simple countdown to the next LOS. Astronauts were also unable to switch the audio transmitter off or even determine if audio was currently being sent in the original design - these issues could be solved with simple indicator lights and a SPST switch. This culminated in a working prototype of our display - created using tkinter and python - which allowed us to get feedback from four participants as part of an experiment we conducted. We received positive feedback from our test subjects (written about in section V), but included potential further improvements to the system at the end of this paper.

I. Introduction

The *Mercury* spacecraft was part of NASA's "Project Mercury", the United States' first human spaceflight program. The capsule itself was designed by McDonnell Aircraft, and even for the time the systems inside left much to be desired. 57 years after the end of the program, there have been plenty of updates on technology as well as advancements in our general knowledge of human factors design.

For this project, we decided to focus specifically on redesigning the displays for the communications subsystem. We begin this paper by discussing the current display we intend to improve upon, we present a human factors analysis of the old design, and then we will present a new design with an accompanying experiment to test the effectiveness of our changes. We will conclude by discussing the results of this experiment and potential changes that can be made in the future.

II: An Overview of the Communication Systems on the *Mercury* Spacecraft

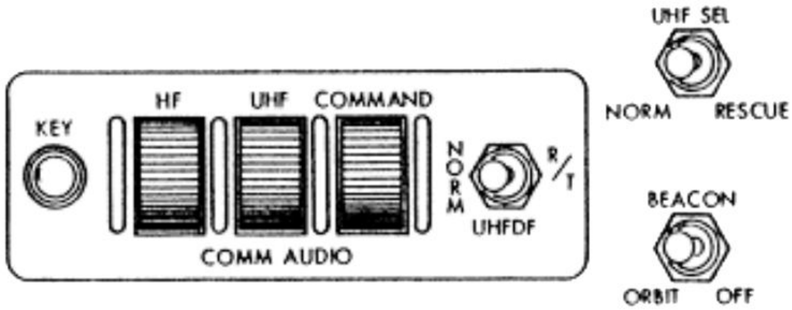

Fig. 1 - A picture of the comms interface from page 283 of "PROJECT MERCURY FAMILIARIZATION MANUAL" (NASA/MCDONNELL 1962)

The communications system, or "comms", is central to allowing astronauts to communicate with each other and ground control, and vice versa. It also allows for the relay of telemetry from the spacecraft, so that ground control can make more informed decisions, and a beacon system for accurate recovery. Without comms, astronauts may not have the guidance they need in order to complete their mission successfully and safely.

The system is based off of several antennae and beacons located underneath the capsule, which accept HF, UHF, and Command frequencies from the ground, the first two of which can be two-way (NASA/McDonnell 1962, 12-2). The control panel on the spacecraft amplifies the signal to an "audio center" located within each astronaut's headset, which then amplifies the signal further to the earphones (NASA/McDonnell 1962, 12-2).

The interface for the comms system is primarily located on the front panel, where there are dials for the volume for HF and UHF, as well as a channel dial for Command. The "Key" button serves as an emergency Push-To-Talk button (NASA/McDonnell 1962, 12-2). The "beacon" switch allows the user to turn on the beacon when in orbit, and the UHF switch is usually set to normal, unless it is during recovery in which case the settings change.

This system requires the most attention during takeoff and landing/recovery, because these are the riskiest maneuvers in any flight. For takeoff, the astronauts must be able to relay any information about the overall state of the spacecraft and telemetry readings during this time are especially important so that ground control can signal appropriate actions if necessary. For landing and recovery, the astronauts must be able to tell ground control conditions as they are coming back to Earth as well as where they landed.

Astronauts need to hear voice audio coming from the command center and be able to see the status of various streams of telemetry and communications coming to and from the spacecraft. They need to be able to easily read off the frequency and volumes from all audio channels. Warning lights are needed if any key communication systems have failed or are malfunctioning. All of this information is conveyed visually in the *Mercury* spacecraft, with warning lights and using the dials and switches on the communication section on the lower right of the control panel.

A task summary of the communications system for the typical *Mercury* flight is as follows:

Time	**Task**
Entire Mission Duration	Provide telemetry to the command center
Entire Mission Duration	Send audio back and forth to command center
After water landing	Send Beacon signals for recovery teams

Fig. 2 - Communications system task summary.

Certain tasks are automated within this system. Telemetry is automatically sent from the spacecraft to the command center throughout the mission. The beacon is also automatically turned on upon touchdown in the water. The operational plan of this system is to facilitate communication between the ground and the ship while providing useful data on the spacecraft's inner workings to help diagnose potential problems.

III. Human Factors Analysis of the *Mercury* Spacecraft

The following is an overview of the current system's structure, its ease of use, and tasks that may be difficult physically or mentally for users on the spacecraft.

Overall, information is conveyed to the astronaut through an audio headset that amplifies a radio signal from an audio center that communicates with the main control panel. Because humans have fairly good auditory perception, they can typically decipher the audio signals very well. However, garbled transmissions may be difficult to process during takeoff and landing.

The tasks required for the astronaut are to be able to listen to audio and transmit audio, as well as press buttons. Communication does not require significant cognitive abilities and requires no physical ability other than a good sense of hearing, so there are no significant cognitive or physical limitations.

The tasks that are most crucial to the system are using the push-to-talk button properly, sending telemetry data, and deploying the recovery beacon upon landing. Push-to-talk allows them to communicate with the ground, sending telemetry messages allows ground control to know what is going on in orbit, and deploying the recovery beacon helps pinpoint where the vehicle is located upon touchdown.

Astronaut performance with respect to effectively communicating should not be too affected by the environment of space, although astronauts are likely to have their judgement impeded by spatial disorientation especially upon launch and reentry. Due to these factors, it can cause them to potentially misinterpret directions if they are not clear or flip the wrong switch, or otherwise make a decision regarding communication that they should not have made.

One potential human error is failing to key before talking, which would prevent ground control from hearing the astronauts. Another is deploying the emergency recovery beacon at the wrong time. Having the volume too loud or too quiet within the headset is also a potential problem. In all of these cases there is no safeguard to prevent this because the errors have little consequence. If the contingency recovery beacon is deployed in space, it will be evidently clear to ground control this was an error, as they have not landed yet. Similarly if the communications haven't been keyed before a transmission, upon not receiving a response from ground control the astronaut would simply double check the display and it would be clear that the communications have not been keyed yet.

For the automated systems, there are a myriad of different sources of failure. The communication system relies on UF and UHF radio receivers and transmitters, along with a significant amount of wiring behind the control panel (NASA/McDonnell 1962, 12-2). If any of these subsystems failed (wires became frayed and split, the radio broke, etc.) there was a full backup radio system. The most important moment from a communications perspective is landing and recovery. An astronaut is well trained and can generally manage most systems on orbit - but the coordinates of landing need to be known by ground crews so they can bring the astronauts back safely. Because of this the emergency recovery beacon is available for landing, along with the usual HF and UHF band radios (NASA/McDonnell 1962, 12-5).

From a human factors perspective the most vulnerable points of the system relate to timing of communications and the awareness of communications settings. In the 1960's communications were made through ground stations, meaning that it could only occur at certain times during the mission (NASA/McDonnell 1962, 12-9). If an astronaut simply forgot to open up communications it could lead to dire consequences, as communication windows were typically packed with important dialogue with ground crews. It is also unclear for the user when there is a blackout or not, or when telemetry stops sending. These are the most vulnerable parts of the system from a human factors perspective.

Given the technological advances of the time there is surprisingly little that could or should be done to automate more in regards to the communications system. The most notable thing that actually can be changed with the communications system is rather than using ground stations for radio connections, crewed flights can use satellites in geostationary orbit ("The Space

Network" or the TDRS constellation) so that comms are maintained throughout the entire mission as opposed to dropping out as the spacecraft goes beyond the horizon (Dunbar). Because of this displays should be added showing when transitions between connections to various geostationary satellites are made (as it is on the ISS) so that astronauts can see when momentary blackouts might occur. The controls and displays for communications are remarkably simple and don't require precision measurements, readouts or switching between screens. Because of this digital displays are not required.

IV. Proposed Design Changes

i. General design and experiment overview

The main problems of the *Mercury* communications display are that there was no way to tell if or when there is a loss-of-signal, as well as not knowing if it is a scheduled loss or due to a system failure. There is also no way to shut the audio transmission off on the operator's side, or any indicator of the status of telemetry transmission. The result is that the operator has no awareness of the status of their communication, which although it is often merely inconvenient, it can cause unnecessary stress in difficult situations where directions from ground control need to be relayed in an effective manner. The simulation described in section IV.iii discusses in more detail our solutions to these issues.

Instead of focusing on the recovery beacon deployment issues, which cannot be adequately fixed by modifying a display, our new design aims to fix the issues of not knowing when the communications cut out due to switching stations, helps make the user more aware of the state of telemetry transmission, allows for a clearer push-to-talk system, and allows the user more privacy in terms of communications.

The components of the system that will be changed in the new display are the push-to-talk system and telemetry display systems, as well as including a countdown until loss-of-signal (LOS) and acquiring-of-signal (AOS) during the switching between TDRS satellites. The components that will stay the same are the recovery antenna controls and audio center connections to the headsets. The main control included in the simulation is a clear button to shut off communications. The previously-included volume/channel dials, antenna switches, and telemetry keying buttons will not change from the previous design, and the goal of this simulation is to create a new panel entirely of status indicators.

For this experiment, the awareness of changes in the status of communications will be monitored as a metric of user performance. One simulation of the redesigned system will be employed while the test subject will be taking directions to attempt to draw a picture. The percentage correctness of the status of each subsystem should give a rough idea of the success of the design. A survey will also be conducted afterwards to gauge user satisfaction with the system.

ii. Design concepts

The display shown in the simulation has no equivalent on the *Mercury* spacecraft, as it did not have any visual transmission status indicators or on/off audio switch, which leaves a lot of room for necessary design improvements. The concepts being implemented improve the awareness of the user and make for a less-stressful user experience. The following design concepts are taken into account as follows:

- Legibility is improved through the implementation of readable and well-placed labels.
- Redundancy is also used between circular color indicators and label changes for both audio status and telemetry status.
- The system is not overly complicated, and does not make status-checking more difficult than checking color and a countdown, minimizing information access cost.
- The dynamic countdown display also alerts the operator in real-time to when the system is scheduled to shut off due to LOS and how long after LOS it will turn on.
- The visual split between the Audio Status, Telemetry Status, and the Blackout Monitoring System allows for more discriminability between the different indicators.

Through the implementation of these design concepts, the overall usability of the system is greatly improved.

iii. Simulation overview

The simulation for the redesigned *Mercury* communications display is made in Python using the tkinter and Pillow packages. The displays included are the audio status display, telemetry status display, and loss-of-signal/acquiring-of-signal countdowns. The controls included in this simulation is solely for switching between turning the audio on or off. The design works as follows:

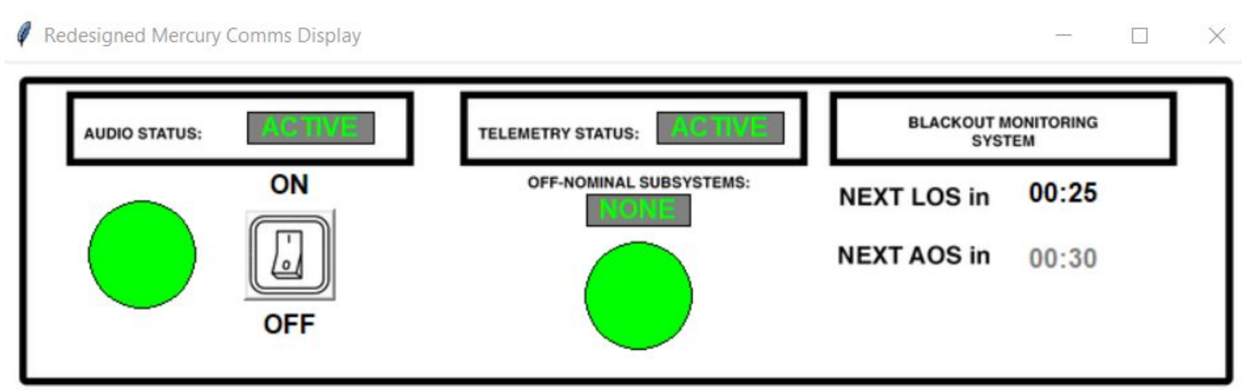

Fig. 3 - When audio/telemetry is being transmitted, the status indicators should be green, and the AOS countdown should be grayed out.

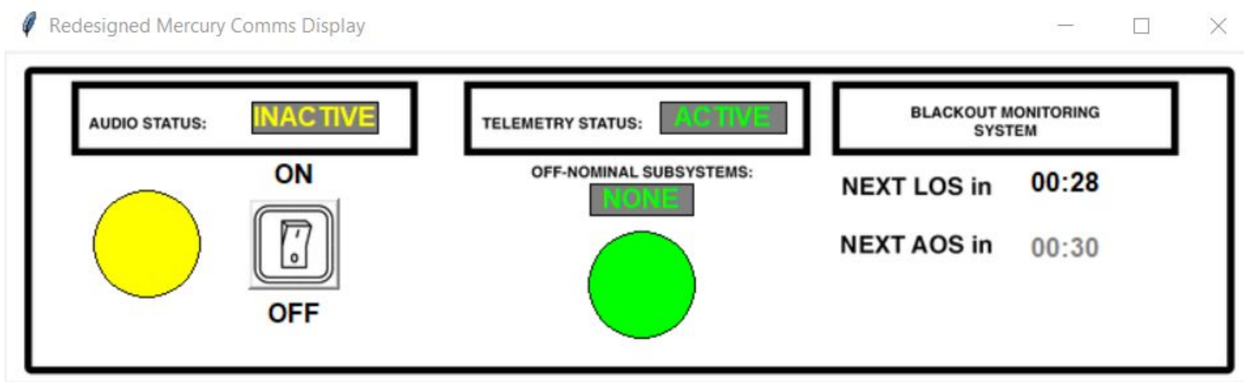

Fig. 4 - When audio is switched off during normal operation, the audio status indicator should be yellow.

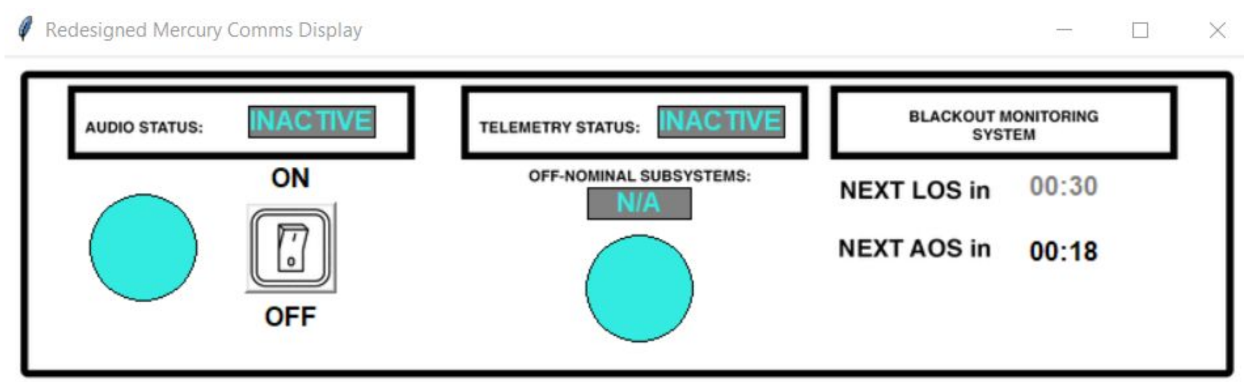

Fig. 5 - During LOS, all displays should be turquoise and the AOS countdown should start, with the LOS countdown grayed out. The audio switch cannot be flipped. When the signal is acquired again, the status of all of the systems goes back to what it was pre-LOS.

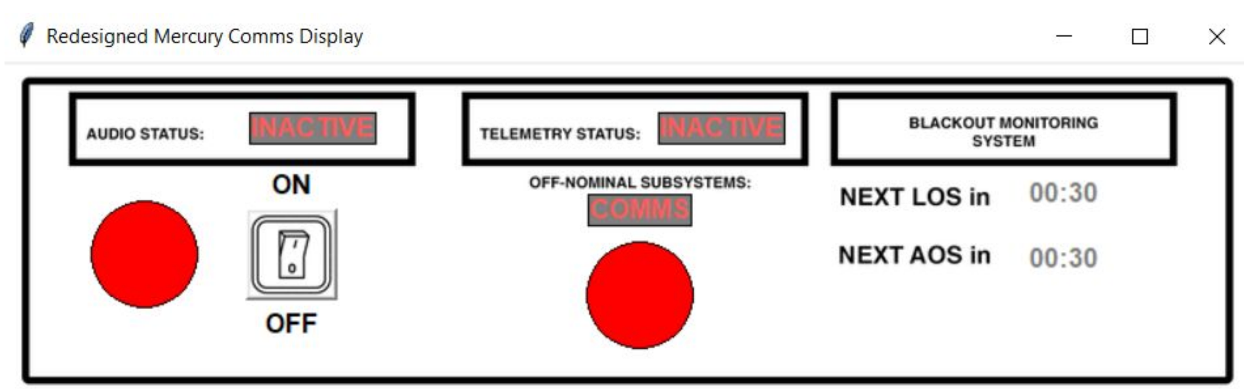

Fig. 6 - In case of a comms system malfunction, all audio and telemetry indicators should turn red, the telemetry indicator should show "COMMS" as an off-nominal system, and both countdowns should be grayed out.

During the simulation, the user should be able to turn the audio on and off and be able to say at any given moment the status of not only audio and telemetry transmission but also when there is a comms shutdown outside of standard procedures. Data that will be collected through this simulation will be qualitative data regarding the ease of checking the status of the system.

v. Simulation testing

In order to test our display we are going to create a virtual display of the system used on Mercury and run test subjects through a communications scenario using both systems and have them compare. For our system we found that quantitative metrics like reaction time are likely not the best way to gauge the success of a system. Instead we will run them through a scenario that requires them to communicate with ground control (us). We will guide them through a task that requires two way communication - once for each system. Their situational awareness will be challenged throughout the simulation as they try to handle managing their task and noting when the next blackout will occur. The results of the two tests will be found by asking participants afterwards for their opinion on both systems as well as passive observations that we will make throughout the runtime of the simulation. We will be constantly monitoring performance of the test subjects and recording results.

vi. Simulation limitations

There are several limitations of our simulation that need to be taken into account. For one, communications is a largely passive subsystem on a spacecraft. When you are communicating with the ground you are likely going to be engaged in a slew of other important tasks that warrant your attention in the capsule. Our simulation is going to have participants engaged in one other task - but it will likely not come close to approximating the stress involved when astronauts are faced with real situations on orbit.

vii. Other improvements

There are many other improvements that could be added to the communications system more broadly, but we feel that the current status of the display is likely final for our project. It conveys all of the necessary information about communications and omits the interesting but less relevant information that would otherwise cause the system to be difficult to use in an emergency situation.

V. Experiment Results and Analysis

The results of the experiment were that overall, there was a high success rate across the tests of the experiment, and overall test subjects stated the state of each subsystem (audio, telemetry, and blackout) with 86.7% accuracy. This is what was expected, as we assumed that the majority of the test subjects would have no issue with it and that an outlier may have missed a direction that skewed the results (which is what occurred with someone not switching on the audio switch in their simulation, accounting for a drop from about 90% to 86.7%). No results were particularly surprising.

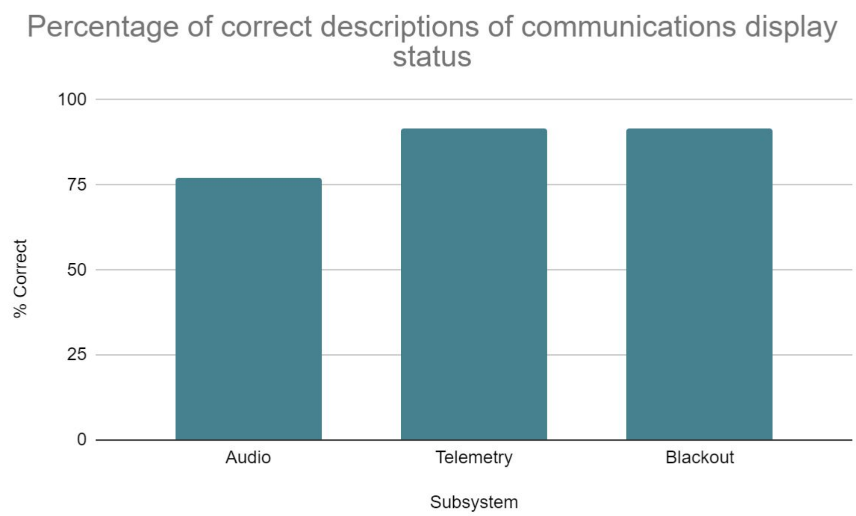

Fig. 7. Graph of simulation experiment results.

For qualitative data, we collected user responses to a Google form given to them immediately afterwards to get their immediate reaction to the system's design. Based on the nature of the experiment, gathering this qualitative data was critical in evaluating the design's performance.

What we understood from these results is that though all test subjects understood the general premise of the experiment, we should have given more time to explain how it functions. Nevertheless, we received mostly good feedback. Positive comments we received were that it was easy to quickly tell what mode the system was in and it was easy to tell how to switch the audio status on and off. Points of improvement could potentially be changing the color of the status indicators during blackout from turquoise to another color because it was unintuitive for some users, as well as potentially reducing redundancy as it seemed confusing for one test subject.

From these qualitative and quantitative results, our redesign appears to meet user requirements accurately. Whereas with the first model there were no indications whatsoever about the system state and LOS/AOS, testers were able to predict quite accurately the state of the system at any given time. There were no complaints regarding the overall design. We did get one user's feedback that suggested that not all of the features of the display were well understood, but that can be attributed to the lack of time we had to explain the design elements to our participants. In hindsight, more than 15 minutes was needed to complete the experiment and 20-30 minutes would have allowed us to have more time to brief participants on how to better understand the display. That being said, the users performed remarkably well for having so little training with our display system which gives us confidence in our redesign.

Given the limited training we gave our participants and the overall good situational awareness they exhibited based on both the qualitative and quantitative data we collected, we are confident that our results are positive. That being said, the limitations of our experiment were clear and the effectiveness of our design would be best determined by a second experiment with more users and a somewhat modified format. The way that our system redesign stands now, however, we would recommend that NASA adopts this system design, as it clearly shows that it is more effective than the old Mercury design in showing participants the status of the communications system.

Based on the feedback from the participants, other than changing the color of the blackout indicator, we do not know of any further improvements that could be made to the display. The problems users had was with the lack of understanding of certain features - which is ultimately a failure in the experimental design (by not explaining the interface thoroughly). We are confident that the design can be understood by anyone if sufficient time is put into learning the system's elements.

VI. Conclusion and Acknowledgements

Overall, we definitely improved awareness of communications system status from what the *Mercury* capsule had before. There is now a clear on/off switch, a clear indication of when comms would cut out, and a clear indication of which systems are on or off at any given time. Though more extensive experiments with more test subjects would be desirable to determine the effectiveness of the solution more accurately in the future, the experiment we ran for this paper showed a simple and effective design that was not distracting and did its job in relaying information quite well.

We would like to thank Professor Michael Massimino and Rosemarie Murray for coming up with this project and providing us with the knowledge necessary to evaluate this system and redesign it. We also would like to thank all of the students in the Aerospace Human Factors Engineering class as well for all of their feedback throughout the process, especially those who participated in our simulation experiment. The results and criticism we received were invaluable to our design process and evaluation.

Appendix

1. Cooper-Harper Scales for Displays

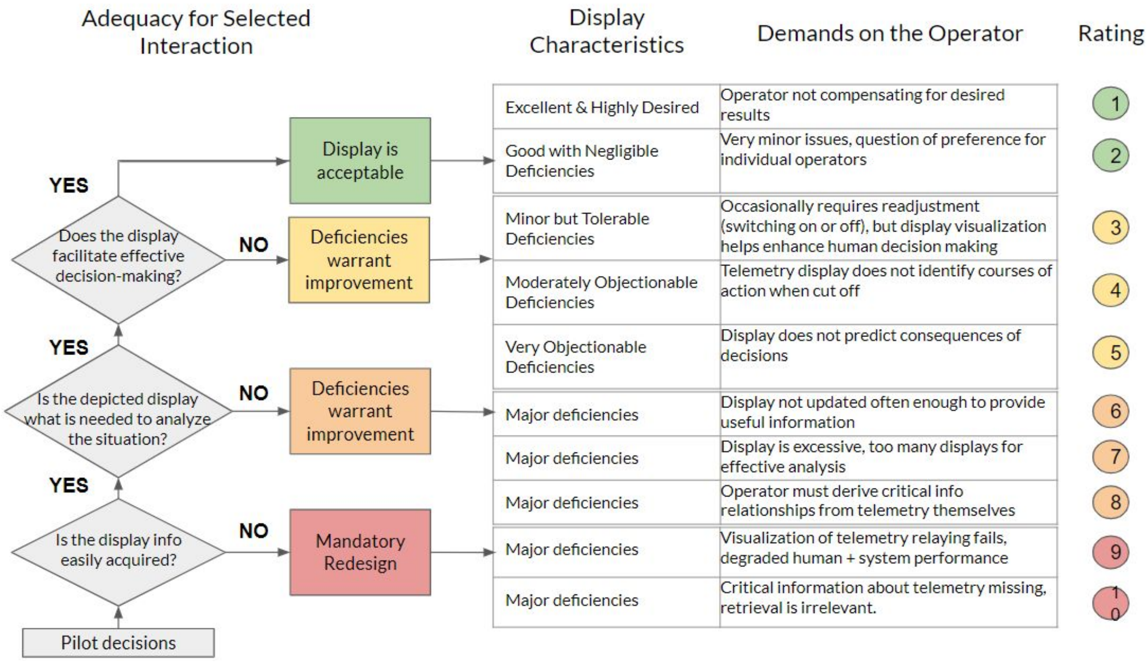

Fig. 1 - Cooper-Harper scale for the telemetry status display

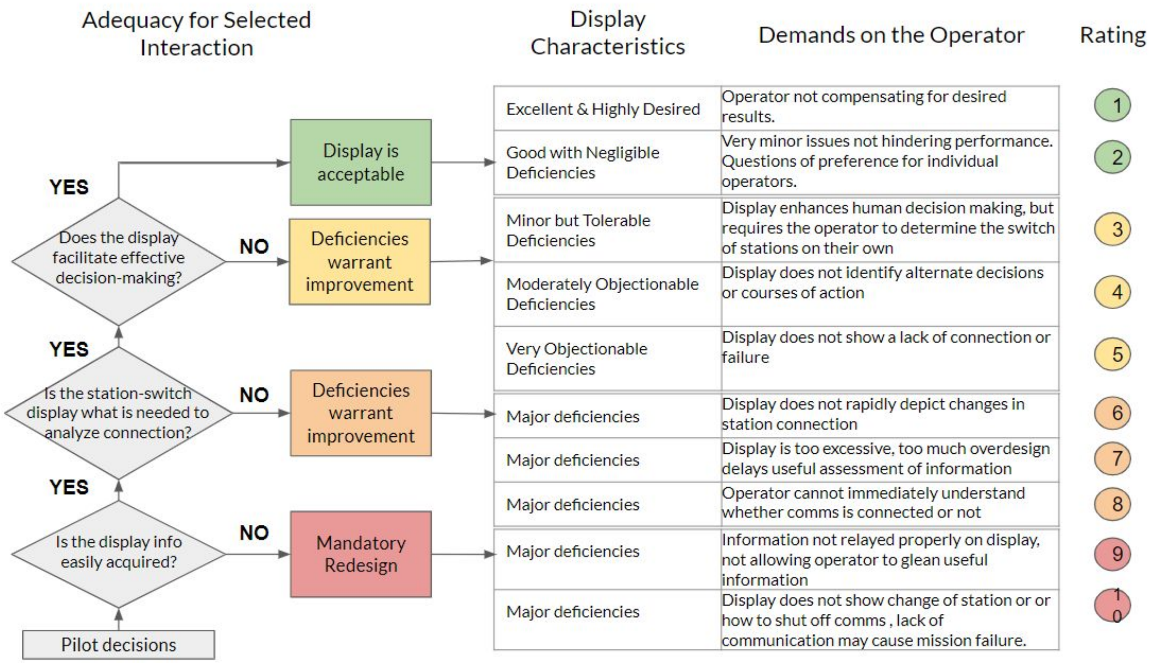

Fig. 2 - Cooper-Harper scale for the audio and blackout status displays

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