# COLLABORATIVE, TAILORED, ANONYMOUS SURVEYS IDENTIFY SOURCES OF ERRORS IN UNMANNED SPACE FLIGHT CONTROL ENVIRONMENTS

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**ABSTRACT**

Since many aerospace accidents have been caused by organizational and socio-technical problems, it is crucial to identify and eliminate as many of these problems as possible. The question is how to do so early on, *before* an accident results. One approach is to survey individuals in the organization, using their perceptions to identify problems. Unfortunately, most surveys in aerospace have not been designed to do this. They have not focused on areas which have contributed to past aerospace accidents, nor have these surveys been specific enough in identifying problems so that the problems can be addressed. We describe a type of survey which accomplishes these goals. We give examples of how such surveys have successfully identified problems in unmanned and manned space operations, and how the results were used to address these problems and reduce risk. Finally, we suggest that safety oversight groups address organizational and socio-technical problems as well as purely technical problems.

## 1. INTRODUCTION

Organizational and socio-technical factors can affect system risk. In aviation, many aircraft accidents have been attributed in part to such factors as lack of training, time pressure, over-scheduling (and resulting fatigue), policies on resource management (fuel use), and faulty procedures (e.g., shift handovers in maintenance, check list procedures in the cockpit) [1,2].

Organizational and socio-technical factors have also contributed to spacecraft accidents. Some of these factors have been the lack of coordination between NASA and a non co-located contractor (Mars Climate Orbiter) [3]; lack of clearly defined roles and responsibilities (Titan IV/Milstar) [4]; inadequate documentation practices (Ariane 5) [5]; and the lack of communication channels for engineers who strongly hold a minority opinion (Challenger) [6]. Organizational factors were cited in the Columbia Accident Investigation Board (CAIB) Report [7] as contributing to the Columbia accident. The board recommended that

> . . .organizations committed to effective communication [to] seek avenues through which unidentified concerns and dissenting insights can be raised, so that weak signals are not lost in background noise. . . [These avenues] must mitigate the fear of retribution, and management and technical staff must pay attention. (p. 192)

One avenue that immediately comes to mind is anonymous surveys. Surveys can elicit perceptions of problems before they cause an accident. Further, they can provide communication channels for anonymous input. However, the type of surveys that have been typically administered in aerospace environments have failed to do this.

## 2. SAFETY CULTURE SURVEYS

Many different types of surveys exist to address many different goals. One type of survey often used to assess risk due to organizational and socio-technical factors is a safety culture survey.

### 2.1. Focus on Worker Safety

Safety culture surveys were originally developed to assess the extent that *worker safety* was a high priority in an organization. These surveys therefore typically include such questions as the perception of unsafe acts on the part of co-workers. The focus is not on factors most relevant to a failed space mission, such as the quality of decision making. In space flight operations, the safety concerns do not involve physical safety of co-workers, but of others—the astronauts, in manned missions, and in unmanned missions, the costly loss of scientific data.

### 2.2. Goal of Comparing Safety Cultures

Not only are the types of survey items found on a safety culture survey frequently not relevant for problems in space organizations, but these items are typically couched in very general terms. One reason for this is that the goal of many safety culture surveys is to *compare* safety cultures in different industries, and therefore survey items need to apply to many different domains. A price is paid in making survey items general, since the results are also general and often fail to produce an actionable agenda for improvement. One reason that the US Naval Aviation surveys of organizational safety climate are successful is that their items are specific enough to give meaningful information. The items *can* be specific because the Navy is comparing similar organizations (air crew units with their Command Assessment Survey and similar maintenance units with their Maintenance Climate Assessment Survey) [8]. Space flight control environments are unique. The benefits from comparing their safety climate to the climates of other industries is unclear. There are benefits, however, in comparing specifically designed safety climate measures *within* a space flight control environment over time in order to assess trends.

### 2.3. Development of Scales

Finally, leading to even further generality in typical safety culture surveys is the tendency to develop scales such as "upward communication," and "downward communication" which include many survey items grouped together. Although this may aid in a global understanding and statement of the problem, the more that details are blurred so as to contribute to a scale, the less concrete information people have to make constructive changes. The type of survey administered to NASA personnel by Behavioral Science Technology (BST) after the Columbia Accident Investigation Report was published, was a worker safety culture survey consisting of many scales and used in many organizations [9]. Although perhaps useful in other domains to compare cultures regarding worker safety, it is not the type of survey designed to uncover specific organizational and socio-technical problems which contribute to risk in a space environment.

## 3. RELEVANT FOCUS FOR SPACE ENVIRONMENT SURVEYS

In space environment surveys, emphasis has to be placed on the adequacy of specific decision-making processes, specific group meetings, specific documentation, specific training, boundaries between specific group roles, and the ease of elevating specific issues through the appropriate channels. Especially in the manned space program, it is also necessary to take into consideration factors such as schedule and budget pressures, launch fever, and the impact of public opinion via media pressure.

## 4. THE IMPORTANCE OF OPERATIONS

Many of those who have studied high-reliability organizations such as nuclear power and aircraft carriers have stressed the importance of operations. It is in operations, the sharp end of the organization, where problems become obvious that have heretofore been unobserved. Procedures, training, software, hardware—all are put to the test in operations. Hence operations is the first and most important part of the organization to survey in a space environment. In unmanned space flight, operations personnel consist of the link controllers; in manned space flight, operations personnel consist of the flight controllers and the astronauts. Other parts of the organization can be surveyed later, depending on the problems found in operations.

## 5. SURVEYS DESIGNED FOR IDENTIFYING RISK IN SPACE OPERATIONS

Special surveys have been designed which have successfully identified organizational and socio-technical risk in space operation environments, including the International Space Station (ISS), the Shuttle, the ISS Vehicle, Integration, Performance and Environmental Resource (VIPER) Team, surface operations for the Mars Exploration Rover Mission (MER), and the Deep Space Network (DSN) [10,11]. These surveys utilize a modern systems approach: Individual and team performance and errors are understood in the context of how the overall organization and technical system operate. The results of two of these surveys will be discussed later in detail: the DSN Survey for unmanned missions and the ISS Survey for manned missions. All of the surveys have the following features.

### 5.1. Based on Organizational Risk Literature

Many of the risk factors found in the organizational risk literature apply to space environments and can be used to develop survey items. (See especially the literature regarding High-Reliability Organizations—HROs) [12,13], Generative Organizations [14], and Learning Organizations [15].)

### 5.2. Supported and Administered by Knowledgeable Outsiders

Experts from outside a domain are more likely to be free from internal alignments, which enables the survey and findings to be accepted more readily by all parties. For example, the authors of this paper are experts in aerospace system safety and, although they are affiliated with NASA, they are not from operational centers. Personnel from the operational domains should play an important role in developing the survey, however, as discussed later.

### 5.3. Scientifically Valid

Constructing a scientifically valid survey requires specialized knowledge. For example, one needs to know how to select participants, organize topics, phrase questions, examine response consistency, and choose and use appropriate analysis techniques. Such a survey can provide valid and reliable results on which decisions can be based.

**5.4. Collaborative**

Since a goal is to identify specific risk factors, as well as what works well, it is necessary to design a survey in close collaboration with those within the space organization. First, it is important to learn what decisions are facing managers and what information would be helpful to them. Second, it is important to discover what it is that operations personnel perceive as problems and what they wish to communicate to managers. This necessitates many hours of interviews and anthropological field work to become familiar with the domain. It is helpful to have operations personnel be involved in an iterative development of the survey. This not only increases the relevance of items included in the survey, but increases response rate, since those who will be responding to the survey have helped create it.

**5.5. Tailored**

The more the survey is tailored to the specific domain, the more useful the information it will yield. For example, inadequate documentation has been implicated in previous aerospace accidents (e.g., Ariane 5 [5]). Therefore, survey items request information on the adequacy of *specific* documents within a space domain.

**5.6. Enables New Issues to Emerge**

It is important to ask respondents to state in their own words what they perceive as the most important problems in their environment, what the consequences might be, and what they would suggest to remedy these problems. There are two advantages to including these questions on a survey. First, they allow new concerns to percolate up, concerns that might not have been tapped by the interviews used to develop the survey. Second, they enable one to assess the relative importance of the problems that have been rated earlier in the survey.

Another way to enable other issues to emerge is by providing space in the survey for free text comments after the rating statements. Doing so also contributes to a fuller understanding of what the ratings mean. Although it increases the time for analysis, space for such comments is provided in every section.

**5.7. Provides a Communication Channel for Safety of Flight Issues**

The supreme example of allowing for other issues to emerge, especially just before a flight, is to include a question as to whether there are any safety of flight issues for the current mission. A question of this type provides an opportunity for direct, immediate, and anonymous communication between those closest to the spacecraft and those in management positions.

**5.8. Involves Multiple Levels**

Risk factors can be identified at multiple levels of an organization and can exert their effects at higher or lower levels. It is important to address organization-wide, team-level, and individual-level risks in a survey. Obviously, management decisions made at the organizational level influence the operational effectiveness of both teams and individuals.

**5.9 Assesses Quality of Meetings**

High quality meetings contribute to good decision making. The following survey items are used to assess *specific* decision-making meetings.

- My input is considered.
- People feel free to disagree.
- Different opinions are respected.
- Decisions are made by one with group input.
- Decisions are made by the group.
- Decisions are made by one.
- There is a lot of disagreement in this group.
- Almost everyone there participates.
- This is an effective group.
- Actions are followed up by this group.

Additional survey items for meetings of primary work groups include

- My group supports me.
- Group members respect those who spot and elevate problems.

**5.10. Assesses Decision Factors**

Especially relevant to manned space flight, factors such as schedule, cost, and pressure from governmental bodies have been shown to play an important role in decisions that have contributed to spacecraft accidents. In both the Challenger and Columbia investigations, it was determined that schedule concerns overrode safety concerns. One way to ascertain the prevalence of this pattern in ongoing missions is to ask respondents to rate how often they think various factors play a role in upper management decisions, as shown in Figure 1. Later in the survey, respondents can be asked to rate how often these factors play a role in their own decisions and recommendations. These data can be used to measure the extent to which schedule and other factors are perceived as playing a role at different organizational levels, how these factors change with time, and whether they are in alignment with management goals and safety considerations.

*When upper management makes decisions about the mission, how often do you think the following factors play a role?*

| | Never | - | - | - | Always |
|---|---|---|---|---|---|
| Crew safety | ☐ | ☐ | ☐ | ☐ | ☐ |
| Vehicle safety | ☐ | ☐ | ☐ | ☐ | ☐ |
| Science output | ☐ | ☐ | ☐ | ☐ | ☐ |
| Cost | ☐ | ☐ | ☐ | ☐ | ☐ |
| Schedule | ☐ | ☐ | ☐ | ☐ | ☐ |
| Contract negotiations | ☐ | ☐ | ☐ | ☐ | ☐ |
| Public opinion and support | ☐ | ☐ | ☐ | ☐ | ☐ |
| International cooperation | ☐ | ☐ | ☐ | ☐ | ☐ |
| Interpersonal conflict | ☐ | ☐ | ☐ | ☐ | ☐ |
| Influence from other governmental bodies | ☐ | ☐ | ☐ | ☐ | ☐ |

*Figure 1. Possible survey format for assessing the perceived frequency of various factors in decision making.*

## 6. SURVEY EXAMPLE #1: THE DEEP SPACE NETWORK LINK CONTROLLER SURVEY

The DSN has centers in California, Australia, and Spain, as shown in Figure 2, and supports about 24 spacecraft for NASA, ESA, and JAXA, e.g. the Mars Exploration Rovers, Voyagers 1 & 2, SoHo, Dawn, and the Mars Reconnaissance Orbiter (MRO).


*Figure 2. The three DSN Centers*

Figure 3 shows one of the many antennae at each DSN center that are used to receive data from spacecraft.

*Figure 3. A 70M antenna at Goldstone, CA.*

A DSN control room, shown in Figure 4, is very similar to control rooms for manned missions.

*Figure 4. A DSN Control Room*

In July, 2007, 60 link controllers from all three centers took an online survey as described above. Management wanted to know how to increase efficiency of operations so as to keep up with increasing demands for tracking spacecraft. Specifically, management wanted to know whether link controller setup times could be reduced, and whether controllers could monitor two antennae stations at once.

### 6.1. DSN Operational Strengths

The survey results revealed many areas of strength in DSN operations as well as some areas in which operational efficiency could be improved. Areas of strength include excellent teamwork among link controllers and good communication with their supervisors, a shown in a section of the results in Figure 5.

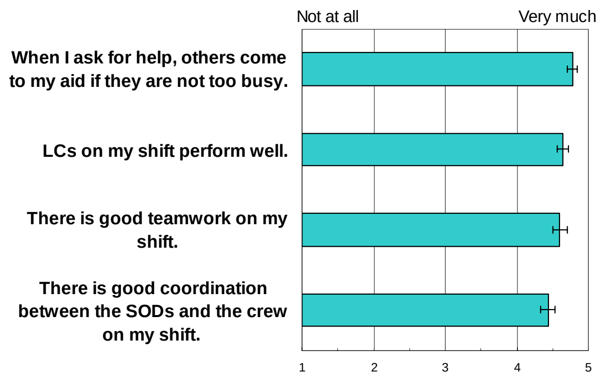


*Figure 5. Ratings of teamwork and coordination with other Link Controllers (LCs) and Supervisors-on-Duty (SODs) within the DSN*

On-site observations and comments also revealed excellent teamwork. One link controller wrote, "All I have to say is 'Uh-oh' and someone shows up!" Operations personnel are satisfied with and take pride in their jobs. They have also increased the efficiency of the DSN by implementing higher levels of automation and by improving procedures.

### 6.2. DSN Areas Needing Improvement

Among the areas identified as needing improvement were

- maintenance during off-hours,
- the number of workarounds and access to them,
- software,
- consideration of the system causes of human errors, and
- undocumented problems during pre-calibration.

The survey results showed that without improvement in these and other areas, shortening setup time and having link controllers monitor more than one antenna station at a time, would lead to an increase in errors and data loss.

### 6.3. Examples of DSN Improvements

Efforts have been made to improve in all of the areas listed above. For example, the software interface and displays are currently being redesigned. Also, the Manager of DSN Operations, in collaboration with the authors, designed a new reporting form for human errors called the "DSN Human Factors/Error Report," which enables identification of system and human factors contributions to human error.[1] Without identifying, classifying. and monitoring these contributions to human errors, one cannot judge their impact, address them, or ascertain whether they have been addressed. The new form follows the Aviation Safety Reporting System (ASRS) format of requesting a narrative description of the error, followed by a list of system and human factor contributions to the error which can be checked off. Two questions follow:

1. Sometimes errors are caught before they cause problems. Why was the error not caught in this case?

2. Describe any changes that might be made to reduce the likelihood of this type of error reoccurring.

A third example of responses to the survey results has been the effort to identify undocumented pre-calibration problems which are typically overcome by excellent link controller teamwork. The link controllers themselves have responded to this challenge by developing an e-survey to document these problems after each pass. The e-survey asks two main questions.

1. "Did you have any [non-reportable] problems during the pass?"

This question is followed by a check list of five various hardware and software problems broken down by phase of pass: "pre-track, in-track, post-track."

2. "Did the pass require any change/communications below?"

This question is followed by a check list of six possible changes and communications that were required.

It should be noted that this type of survey is especially effective when those who have taken the survey –who have the best understanding of the technical issues involved—also actively participate on the teams assigned to address identified problems. This collaboration between management and controllers is generally beneficial in promoting a team spirit and raising the morale of all involved.

## 7. SURVEY EXAMPLE #2: THE ISS FLIGHT CONTROLLER SURVEY

Key findings of the ISS Survey will be described briefly since details can be found elsewhere [11]. In 2003, 191 ISS flight controllers in ISS Mission Command and Control (MCC) completed an online

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[1] The authors also appreciate Dr. Alan Hobbs' assistance in designing this form.

survey, similar to those described earlier in this paper, entitled "Organizational Risk and Tool Development Survey." The purpose was to identify organizational risks that could endanger the program and to generate tools to reduce these risks and facilitate tasks.

### 7.1. ISS MCC Strengths

As with the DSN controllers, the flight controllers had positive attitudes towards their work, pride in their jobs, and good relationships with their supervisors. Flight teams were seen as performing very well. Individual discipline groups had many excellent, risk-reducing characteristics. Group members respected those who spotted and elevated problems, supported each other, and flight controllers reported good collaborations within their group and between groups.

### 7.2. ISS MCC Area Most Needing Improvement

The survey results revealed one area of critical vulnerability, along with several areas which needed improvement.

The critical vulnerability was an over-reliance on human operators to work around malfunctioning software. At the time of the survey there were over 1,000 written workarounds (called Station Program Notes, or SPNs) to software problems, and flight controllers reported difficulties in remembering them. Flight controllers rated software issues as compromising ISS safety. When flight controllers were asked to list the three most serious organizational vulnerabilities, software workaround issues were listed most frequently and rated as being the most serious. This vulnerability was compounded by a structural difficulty in communication, since the boards which have responsibility for making decisions on software (the Avionics group) are in a different directorate than the flight controllers, as shown in Figure 6.

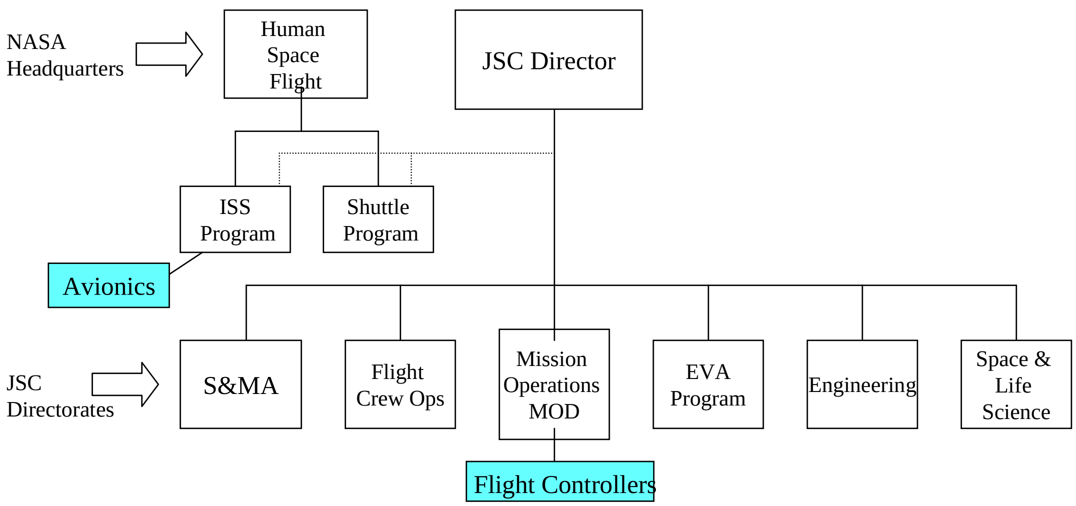


*Figure 6. Simplified Johnson Space Center organization chart. (Not shown are offices such as Human Resources, Legal, Center Operations, etc.) Avionics is in a different directorate than the flight controllers.*

### 7.3. ISS MCC Improvement Regarding Software Workarounds

As a result of the survey, the software workarounds have been reduced by almost half as of last year. Reducing the number of SPNs by this amount has required a concerted effort not only by Avionics, but also by the flight controllers in updating their procedures. Even so, this leaves many workarounds in existence which continue to be problematic for the flight controllers. Nonetheless, the trend is certainly in the right direction.

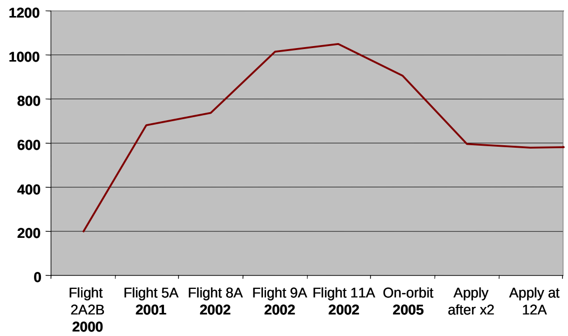


*Figure 7. Number of SPNs since beginning of the ISS.*

Second, steps have been taken to reduce the creation of SPNs. Avionics and MOD created additional interfaces on the software deployment timeline, including new design reviews, new uplink planning, and new meetings to collaborate on how SPNs are incorporated into Mission Operations Directorate (MOD) procedures. Additionally, the two organizations set up weekly meetings between representatives of MOD and Avionics, and strengthened flight controller representation on Avionics Boards

### 7.4. Benefit of MCC ISS Survey

The flight controllers worried about forgetting the large number of SPNs. When asked at the end of the survey, "What worries you the most today?" the most frequent response involved external factors (such as loss of funding), but the next most frequent was that they would forget a software workaround. Although flight controllers felt the burden of remembering these workarounds, they were unable to communicate the weight of this burden, the extent to which it was shared by other flight controllers, and the risk it entailed to the ISS. The survey results effectively communicated this to all parties involved. The head of MOD Systems Integration stated that

> The survey results brought us light years forward with regard to communicating and developing a working relationship between MOD and [Avionics].

It should be noted that despite attempts of the flight controllers to bring this issue to the attention of higher management, and despite the risk it involved to the Station, the safety organizations in charge of assessing risk to the Station were not involved in identifying or addressing this risk.

## 8. NEED FOR SAFETY OVERSISGHT GROUPS TO CONSIDER ORGANIZATIONAL AND SOCIO-TECHNICAL RISKS TO SPACE FLIGHT

Safety oversight groups have long focused on technical risks to missions, ensuring, for example, that there is two-fault tolerance in system and sub-system hardware. However, safety oversight groups have been slow to recognize and address organizational and socio-technical risks, despite their indisputable contribution to accidents. There is a need for a permanent body linked to space operations which considers these risks and *ensures* that tools such as the one described in this paper are used to identify, monitor, and assess these risks on a periodic basis. Organizational and socio-technical risk assessment is too important to leave outside the system, subject to the vagaries of the moment.

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