Human Factors for Space Operators-Leveraging Aviation Safety Frameworks for Enhanced Orbital Domain Resilience

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ABSTRACT

This paper examines the human factors parallels between Space Domain Awareness (SDA) occupations and other continuous (24/7/365) safety-critical services, offering insights into safety management successes and best practices. It draws on NASA's System-Wide Safety program in aviation, which addresses scaling safety management from human-centric operations to a digitally transformed, automation-integrated infrastructure. These findings are highly relevant to the evolving space domain, particularly as commercial space operations reshape orbital management and ground-based oversight.

The rise of commercial space operators and Space Situational Awareness (SSA) providers, coupled with increasing automation, highlights a gap: this emerging field lacks the institutional frameworks that guide human factors considerations in military or automation-reliant services like air traffic control. In contrast, aviation's decades of human factors research—encompassing Crew Resource Management (CRM), Threat and Error Management (TEM), and Fatigue Risk Management (FRMS) within a Safety Management System (SMS)—have driven continuous safety improvements, even amid rapid growth.

NASA's System-Wide Safety Project builds on this foundation to tackle challenges from autonomous aircraft, Advanced Air Mobility (AAM), and automation's growing decision-making role. Leveraging these efforts informs human factors risk management for space operators as their operational environments converge with aviation's. The shift from reactive to proactive and predictive safety intelligence hinges on the availability of safety risk data and a deeper understanding of human-autonomy teaming in increasingly automated settings. The 2018 National Academies report, *In-Time Aviation Safety Management*, underscores the need to collect human performance data, emphasizing "elevated risk states" (e.g., fatigue, inattention) and integrating behavioral psychology into safety systems.

Proactive safety reporting is vital for capturing human performance data, serving as an early warning system for threats, and measuring mitigation effectiveness. Yet, its success depends on a safety culture that encourages anti-error behaviors rather than punishing mistakes or reporting itself. Understanding the root causes of human error is as critical as analyzing the errors themselves—because satellites *don't have accidents in orbit; people fail on the ground.*

Unlike aviation, where human factors research often follows catastrophic events, the satellite operator community cannot afford a reactive approach. A single orbital mishap has lasting consequences for the domain's safety, underscoring the urgency of proactive human factors strategies.

1. INTRODUCTION

The intent of this paper is to introduce existing research on human performance in air traffic control to the commercial satellite operator and Space Situational Awareness (SSA) provider community. There are strong parallels in the human factor issues between these professions, including technology dependence, fluctuations in workload, attention and distraction, and fatigue. The body of research in the air traffic community is often internal to the government. Like aviation, discussions of human factors in commercial space quickly move to the topic of people on board. The study of accidents involving human spaceflight frequently includes human factor elements that occur within the ground-based portion of spaceflight, as well as those that arise in the decision-making chain associated with ground-based operations [1]. Economic pressures are frequently identified as creating risks that affect human decisions [2] [3]. Findings from these studies should be used to inform the commercial space sector.

It is important to look beyond human participants in flight and onboard spacecraft and consider the ground-based operators with critical safety responsibilities. As such, this paper focuses narrowly on those responsible for ensuring safe operation in orbit and does not include the impact of launch and reentry on civil airspace. Space sustainability considers the long-term viability of orbits with no human presence. Preventing collisions between space objects without humans on board is critical to preserve the space-based services that humans depend upon on Earth. The human operators responsible for that task, including satellite operators, space situational awareness, and space domain awareness providers, are required to maintain continuous watch and can benefit from existing research on human factors but may also have the opportunity to leapfrog concepts of safety management to embrace the emerging automation-dependent constructs developed for In-Time Aviation Safety Management Systems (IASMS) embraced by the National Academies.

2. LEARNING FROM FAILURE

The common perception that aviation models use learning from failure to develop safety standards has merit. However, notwithstanding high-profile events, the record of safety in commercial aviation could not have been achieved through a purely reactionary approach (Figure 1). The safety management approach in civil aviation is mature and includes an important focus on human factors that can be instructive for the commercial space industry.

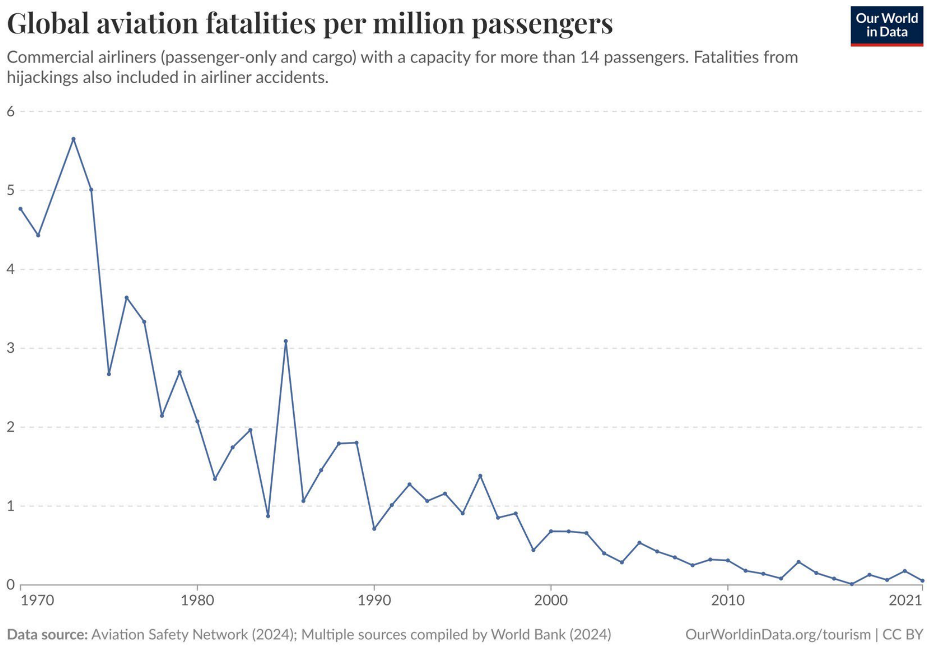

Figure 1: Aviation fatal accident rate [4]

Fatality is not an appropriate measure for commercial space operators that are not engaged in human spaceflight, but a parallel to the aviation goal of zero fatal accidents can be developed (i.e., zero debris-generating accidents). While this chart contains historical data, a discussion of commercial aviation safety in 2025 is incomplete without considering the January 29, 2025 crash between American Airlines flight 5342 and a Black Hawk helicopter. This accident in particular provides relevant parallels to the commercial space operator community and is an opportunity to learn from failure.

In applying delegated separation (visual) to the Black Hawk pilot, the air traffic controller was able to focus attention on other high workload tasks, assuming the responsible entity, the helicopter pilot, was equipped and able to perform the function. The Black Hawk pilot relied on information provided by automated systems in carrying out the task. Had the equipment functioned properly, the accident would not have occurred. However, in a critical safety system, the ability to identify and respond to system failures is crucial. This is where human factors in both design and environment come in. In the design of automated systems, it is necessary to answer the question, "is there a means for humans to detect failure? [5]" That is an important element, but this paper will assume there is a means to detect failure and focus on the human environment side of the equation - is the human operator in the physical and psychological condition to detect and respond to failure?

Like commercial space, the Federal Aviation Administration's (FAA) work on human factors has historically focused heavily on the human on board the aircraft (pilot and flight crew). This is true for both human factors in automation and fatigue risk management. The emergence of unmanned aircraft systems is bringing new attention to the role of human factors in automation-dependent systems [6] that may expand the discussion of ground-based staff in aviation. IASMS seeks to exploit faster and more comprehensive access to information from automated systems to detect and respond to safety threats. Dr. Valerie Gawron has published a collection of articles focused on the applicability of aviation research on human factors and autonomy in aviation that can be applicable to other fields [7].

3. SAFETY CULTURE

An effective safety culture is at the core of any organizational framework but is too often described in terms of the mechanics of a safety program. It is important to recognize that the safety culture requires that human error will occur and that detection and correction of human error is a constructive safety process that requires transparency and active intervention to encourage threat detection and reporting.

3.1 Threat and Error Management

Threat and Error Management (TEM) in aviation is a safety framework designed to prevent the development of an undesired state. It considers both external threats and human performance in safety management. Threats are external conditions that affect the safety environment, while errors are deviations or mistakes tied to human performance. In aviation, TEM is generally regarded as a component of Crew Resource Management (CRM) applied on the flight deck to ensure early recognition and correction of elements that can cause a safety event to escalate.

3.2 System Wide Safety and IASMS

NASA's System Wide Safety program (Figure 2) focused on aviation safety but has important implications for space operators. Ironically, the infrequency of accidents creates a specific challenge for safety management. Reactive safety systems depend on data collected from accidents and incidents. Proactive systems depend on safety reporting and increase the data available but require time to collect and analyze the data. Predictive safety management relies on data, technology, and analytics to predict future risk and allows organizations to take preventative measures [8]. It is designed to operate in environments where accident rates are low and other safety data is needed to identify risks.

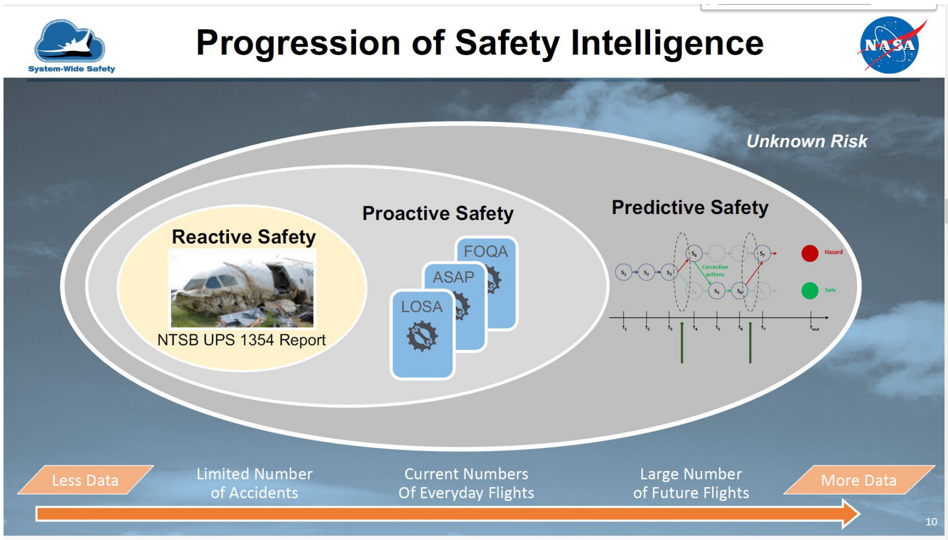

Figure 2: NASA In-Time Aviation Safety Management System (Source: NASA)

Access to safety intelligence is an essential part of safety management. Historically, this has been human generated data from accident investigations and safety reporting. The rapid development of the unmanned aviation sector has created a gap in the human intelligence but also opened opportunities for automated data collection, enabling predictive safety management – if the data is collected and used. The automation of operations and data collection does not exclude human factors from the safety equation. The shifting role of the human in increasingly automated processes eliminates certain risks but may introduce others. As the human becomes more responsible for systems monitoring, issues of physical and mental fatigue require attention.

The development of In-time Aviation Safety Management Concept (Figure 3) is endorsed by the National Academies in "In-Time Aviation Safety Management: Challenges and Research for an Evolving Aviation System" [9]. IASMS was developed to respond to emerging challenges in safety management from the growth in unmanned and autonomous aviation. The human factors challenges shift from active human operations (Human In The Loop (HITL)) to humans monitoring system operations (Human On The Loop (HOTL)). Safety data from operator detection and reporting becomes inadequate to drive mitigation approaches and greater reliance on machine derived data is needed. For the HOTL, they are moved further from active engagement with safety data and complacency becomes a new risk factor to be mitigated.

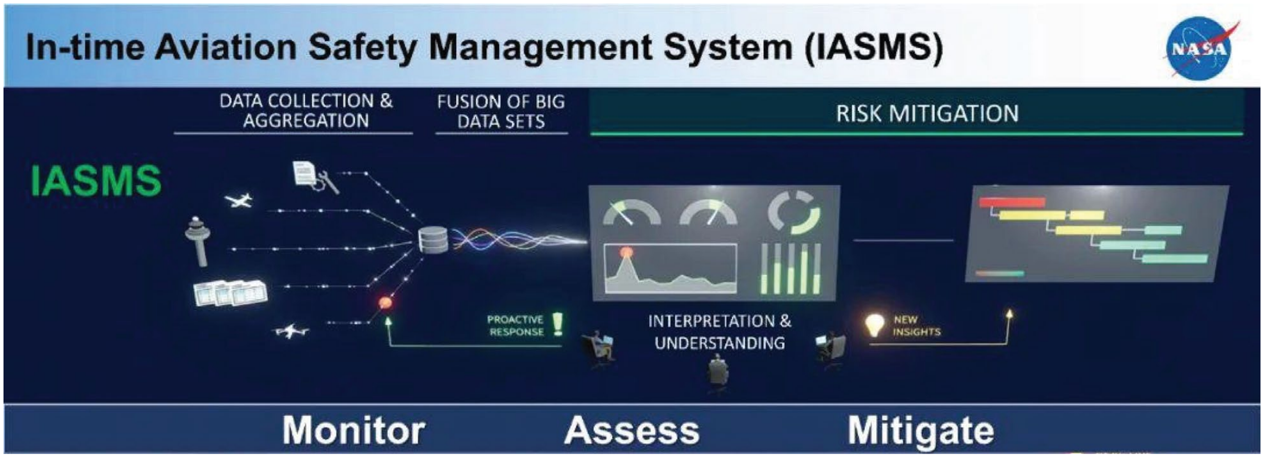

Figure 3: IASMS process (source:NASA)

4. FATIGUE RISK MANAGEMENT

Human fatigue is a physiological condition. In both civil and military aviation, it took considerable research and effort to shift the paradigm away from the view that fatigue is a character flaw to be managed by the individual and not a risk to be managed by the organization. It is important to note that fatigue is not a synonym for sleepiness. The Federal Aviation Administration offers the following:

> *"Fatigue is a complex state characterized by a lack of alertness and reduced mental and physical performance, often accompanied by drowsiness. Fatigue is objectively observed as changes in many aspects of performance, including increased reaction time, lapses in attention (i.e., reaction times greater than 500 milliseconds), reduced speed of cognitive tasks, reduced situational awareness, and reduced motivation"* [10]

Dr. Kim Cardosi at the US Department of Transportation Volpe Center has completed extensive research on the topic of fatigue and human performance in air traffic control and developed accessible and informative materials like "Human Factors for Air Traffic Control Specialists: A User's Manual for Your Brain" [11]. Fatigue is not limited to physical tiredness; it includes mental fatigue that can be temporary and task-related. Effective fatigue risk management requires an understanding of the different effects and causes.

4.1 Sleep Disruption/deprivation

Satellites do not stop orbiting at the end of a workday and need to be monitored on a continuous basis. The need for 24-hour-a-day, 7-day-a-week, 365-day-a-year (24/7/365) conjunction assessment monitoring by satellite operators and space situational awareness providers introduces specific risks to human awareness. The field of fatigue risk management (FRMS) has a considerable body of work on this topic that considers the effects of both sleep loss related to shift work and the role of circadian control of biological function that can help inform the commercial space sector. Fatigue risk is present in every profession involving shift work, as noted by the US Occupational Safety and Health Administration providing employer recommendations in “Long Work Hours, Extended or Irregular Shifts, and Worker Fatigue—Prevention.” [12]. However, generic recommendations based on work schedules too often create a box-checking compliance exercise and lack the detail necessary to inform a safety-critical professions with dynamic fluctuations in workload and stress. Instead of generic material, space operators facing emerging issues of fatigue risk management can look to professions with similar work profiles, like air traffic control, that can provide valuable parallels.

NASA recently concluded a study for the FAA, “Assessing Fatigue Risk in FAA Air Traffic Operations” [13] using the definition of fatigue adopted by the International Civil Aviation Organization, the United Nations specialized agency for aviation (ICAO):

> *“A physiological state of reduced mental or physical performance capability resulting from sleep loss or extended wakefulness, circadian phase, or workload (mental and/or physical activity) that can impair a crew member’s alertness and ability to safely operate an aircraft or perform safety-related duties* [14]*."*[1]

The study recognized short-term consequences of sleep loss and fatigue, including increased safety risk, burnout and poor behavioral health, and an increase in subclinical conditions. In addition to issues of sleep duration and quality for shift workers, the study reinforced the findings of decades of study on performance impairment and circadian misalignment.

4.2 Circadian Lows and Shift Work

There are identifiable physiological alterations attached to the human circadian rhythm, including body temperature, alertness level, and cognitive performance [10]. Awareness and recognition of circadian lows is an important part of identifying fatigue risk. In organizations without a mature safety culture, this can be difficult. Too often organizations rely on shift workers to self-manage sleep patterns to counteract circadian fatigue, but notwithstanding the work schedule, the average worker functions in a day-wake cycle based on societal, cultural, and family obligations. Recognizing the Window of Circadian Low (WOCL) allows for the introduction of fatigue countermeasures. For individuals in a normal day-wake, night-sleep pattern, there are two WOCL, approximately twelve hours apart and roughly between three and five in the afternoon and morning [10].

4.3 Time on task fatigue

Time on task fatigue has been studied by behavioral psychologists for decades. It is the measurable decline in human performance over time when conducting the same task, this occurs in both high intensity and low intensity tasks, but low intensity tasks like monotonous or partially automate tasks induce more significant measures of mental fatigue [15]. FAA research highlighted this finding in a study of air traffic controllers in a simulated environment in, “EEG Correlates of Fluctuation in Cognitive Performance in an Air Traffic Control Task” [16]. The recognition of time on task fatigue is not new to the watch community, during World War II radar operators saw a reduced probability of signal detection decreased with time on watch [17].

5. MILITARY EXPERIENCE AND APPLICABILITY TO COMMERCIAL CULTURE

[1] Even within this definition, the focus on crew member fails to recognize the importance of alert and unimpaired safety professionals operating in ground-based positions, however, the NASA study applied the definition to the controller duties.

With the rapid increase in volume and variety of operational activities, safety-related aspects of military space operations now touch not only operators and analysts of SSA data collection systems, but also C2 and watch center operators, satellite payload and bus operators, intelligence analysts, and others. The urgency of protecting national security interests drives a human factor culture that ensures operators are healthy, trained, rested, equipped, and ready to respond to both routine and contingency operations. Despite the shared risk, however, this human factor culture and operational posture may not translate directly to commercial space operations due to the difference in mission requirements and access to resources. As a result, commercial satellite owner/operators, SSA providers, or others performing some operational function, and especially those who face challenging or safety-related operational scenarios, must develop comparable human factor safeguards adapted to their unique operational approach.

6. WE ARE NOT ALONE

The discussion of human factors cannot remain confined to individual operators or single organizations. The orbital environment is inherently international, and the risks introduced by fatigue, workload, and operator error do not stop at national boundaries. Satellite conjunctions frequently involve spacecraft from multiple countries, and the safe resolution of these events depends on the ability of human operators to share data, trust one another's reporting, and coordinate mitigation actions across borders.

Recent work by NASA's Multi-Mission Automated Deep-Space Conjunction Assessment Process (MADCAP) underscores this reality. In cislunar and Martian orbits, there is no comprehensive catalog of debris or non-cooperative objects. Instead, conjunction assessment relies on self-reported ephemerides from mission teams. This dependence places exceptional weight on the human factors of vigilance, communication, and organizational transparency. Where trust is strong, as in the case of multinational missions to Mars, operators coordinate effectively. Where cooperation is absent, such as China's reluctance to share lunar ephemerides, blind spots emerge that increase risks for all. These challenges are not solely technical gaps; they also involve human factors on an international scale [18].

Existing governance mechanisms provide partial models. The United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) Long-Term Sustainability Guidelines encourage responsible operations but do not define common standards for managing operator fatigue or ensuring proactive safety reporting [19]. Similarly, the Inter-Agency Space Debris Coordination Committee (IADC) guidelines address debris mitigation but remain silent on the role of human operators [20]. By contrast, the European Space Agency's Space Safety Programme and the European Cooperation for Space Standardization (ECSS) take more explicit account of human factors, embedding operator training, fatigue considerations, and safety protocols into technical practice [21].Yet these approaches are not globally harmonized.

The path forward is to integrate human factors into international space safety frameworks with the same rigor that aviation applied through ICAO's Annex 19 Safety Management Systems. A global standard for fatigue risk management, a shared human factors curriculum for space operators, and a multinational safety data trust for anonymized reporting of performance metrics would strengthen the resilience of the orbital domain. These measures would recognize what practitioners already know: satellites do not collide in orbit by themselves. Collisions occur when human operators, working across different organizations and countries, fail to coordinate effectively. Embedding human factors into governance is thus not only a technical improvement but also a strategic imperative for sustaining the safety of shared space environments [9].

7. CONCLUSION

As the commercial space sector evolves, the imperative to proactively address human factors in Space Domain Awareness (SDA) and Space Situational Awareness (SSA) operations becomes increasingly clear. Drawing on decades of aviation safety management—particularly the transition from reactive to predictive frameworks and the integration of automation—space operators can avoid repeating historical missteps and instead leapfrog toward best practices. The lessons from Crew Resource Management, Threat and Error Management, and Fatigue Risk Management in aviation demonstrate that safety is not merely a technical challenge, but a fundamentally human one, shaped by organizational culture, vigilance, and international cooperation.

With the rise of continuous, automation-dependent operations and the international nature of orbital management, the risks posed by fatigue, workload, and communication failures are amplified. The absence of globally harmonized human factors standards for space operators represents a critical gap, one that must be addressed through the development of shared curricula, fatigue risk protocols, and multinational safety data trusts. As satellites themselves do not cause accidents, but rather the humans who operate and coordinate them, embedding human factors into both technical practice and governance is essential for sustaining the safety and long-term viability of the orbital domain.

By embracing proactive safety cultures, leveraging predictive analytics, and fostering international collaboration, the commercial space industry can set a new benchmark for safety management—one that recognizes the central role of human performance in preventing accidents and ensuring the sustainability of space operations. The path forward is clear: to secure the future of space, we must prioritize the people who safeguard it.

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