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Space Infrastructure Resilience:
Reflections on Recovered Launch Debris

Regina Peldszus

On 4 June 1996, thirty-seven seconds after engine ignition on its inaugural flight as the first in a new generation of European launch systems, the Ariane 5 rocket veered off course, disintegrated, and self-destructed. Ripped apart by the powerful explosion, at an altitude of approximately 4,000 metres the launcher and its payload fragmented, scattering pieces across twelve square kilometres, close to its tropical launch site in Kourou, French Guiana. After the event, the debris was painstakingly recovered from the swamps and thick mangroves surrounding the launch pad. Together with data transmitted from the rocket itself and from radar stations tracking its trajectory, the fragments became the primary source material for the official inquiry that followed (Lions 1996: 2), allowing investigators to retrace all the strands leading to a single disruptive moment. In their granularity and immediacy, the images of the captured fragments – seemingly suspended in time – today testify to an instance when the interdependencies and entanglement inherent in large-scale systems led to momentary but consequential breakdown; they represent the ripple effects of human agency on the infrastructures we conceive, deploy, operate, maintain, dismantle, optimize, and try to safeguard.

Visual study on launch explosion fragments by ***Sascha Mikloweit****, created during a residency at the European Space Agency (ESA), after the pieces were archived for several decades. While the work was part of a multimedia installation at ESA's mission control centre, the images are here understood in their own right as points of departure for systems-theoretical considerations of the infrastructure they originated from.*

The debris of the Cluster I mission was archived at the European Space Agency, and captured afresh three decades later.
Image: © Sascha Mikloweit & VG Bild Kunst 2020.

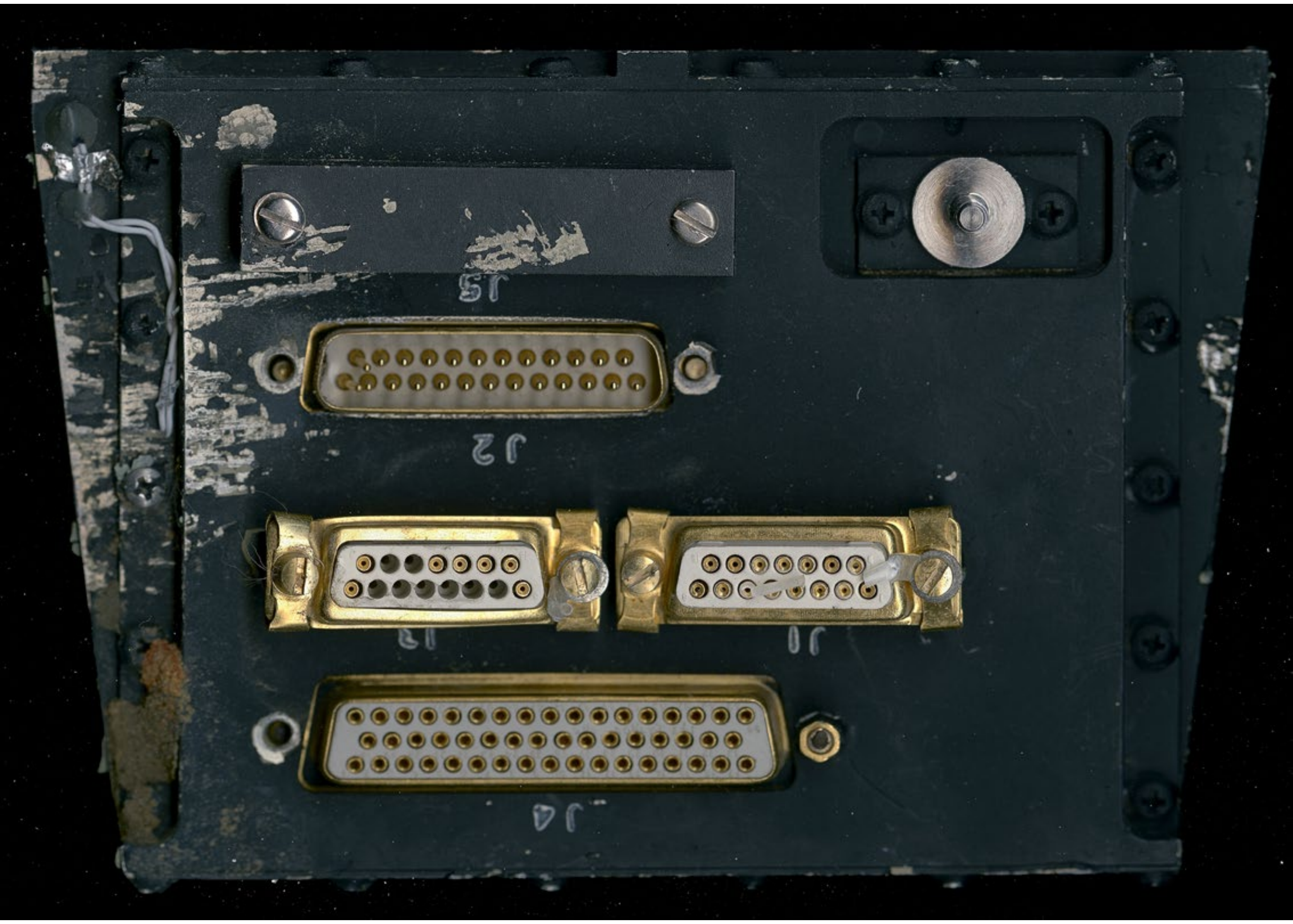
Failure as an inherent possibility of space infrastructure

Debris recovered after the launch failure and explosion of Ariane 5 on 4 June 1996.
Image: © Sascha Mikloweit & VG Bild Kunst 2020.

Failure is understood to be an intrinsic reality of highly complex domains – inevitable, normal even (Perrow 1999). In an almost Boolean logic, the largest and most consequential incidents are ideally characterized by their absence; yet this absence is only made possible through a continuous engagement with their potential emergence.[1] In the development, operation, and governance of large-scale complex sociotechnical systems or infrastructure, we hope to eclipse this emergence through a preoccupation with failure and anticipation of the factors contributing to it (Weick and Sutcliffe 2001). The ensuing adaptation instils resilience – less a property, but rather a constant practice of individuals, teams, and organizations acting within and upon a system (Reason 2008: 8).

Incidents of failure represent a “temporal inability to cope effectively with complexity” (Hollnagel, Woods and Leveson 2006: 3). They are effects of a combination of conditions and decisions, rather than of the failure of a single function or component: Although the Ariane report identified as an immediate cause of the launch failure the "complete loss of guidance and attitude information … due to specification and design errors in the software of the inertial reference system" of the launcher (Lions 1996: 12), it also recommended greater transparency in cooperation between different participating project entities and the inclusion of external experts for critical reviewing (Lions 1996: 14). Other analyses framed the underlying issue through a wider lens, suggesting the key to understanding this specific event lay in the application of systems engineering methods and their intersection with software development and its implementation in organizations (Le Lann 1996). Indeed, contemporary ideas on safety identify one particular area of potential for systems failure: software requirement flaws – that is, determining precisely the affordances, functions and constraints of software rather than software error per se – and their interaction with the overall system (Leveson 2011: 48).

The fragments pictured here were part of the payload, which consisted of four spacecraft in the Cluster I science mission. Image: © Sascha Mikloweit & VG Bild Kunst 2020.



Space infrastructure as product of constant human engagement

Remnants of the battery regulator unit of one of the spacecraft onboard the exploded launcher.
Image: © Sascha Mikloweit & VG Bild Kunst 2020.

In analyses of other catastrophic launch failures, problems with general organizational aspects of communication and joint decision-making in complex structures of space programmes were also highlighted as crucial contributing factors (compare Vaughan 2016). This potential is compounded by the fact that while launch systems are already highly complex undertakings, they slot into an even wider infrastructure with added interdependencies and nestled layers of complexity. The ground segments of space infrastructure – launch sites, tracking stations, mission control centres (Holdaway 2003) – constitute nodes in a network of command and control of any activity performed to access and utilize space. In order to design this distributed infrastructure, approaches to systems engineering evolved in the course of space activities since the 1950s (Booton 1984; Johnson 2006) that were able both to allow for, and leverage, high complexity, and can also be employed in promoting integrity and reliability (Leveson 2011).

At a scale where infrastructure is understood as a system-of-systems, design operations are only possible through the collaboration of large teams-of-teams. Here, human agency on a variety of levels (compare Vicente 2010) holds the key to resilience – from the individual designers or operators who may programme a scheduling tool to allocate time slots in a network of ground station antennae or command pre-planned manoeuvres on a satellite, to cross-disciplinary teams who jointly control a crewed mission. Despite the highly proceduralized field of mission control – and in contrast to automated agents that purely follow pre-programmed routines – these human operators intentionally vary their performance to suit the needs of an evolving situation, thus keeping a system within a boundary of safe operations (Hollnagel et al. 2008).

Finally, it is an organizational aggregation of public and private actors in government, industry, science, and military that define and execute the functions of space infrastructure, that determine its overall purpose, appraise its merits as part of a regulatory process, and ultimately decide whether and how a large-scale programme,

Blown up honeycomb sandwich panels used as part of the spacecraft structure on which instrumentation was mounted.
Image: © Sascha Mikloweit & VG Bild Kunst 2020.

system, or infrastructure is set up, sustained, or discontinued. Spaceflight increasingly relies on this multilateral engagement (compare Zabusky 1995), due to the sophistication and global significance of the technology or missions involved. In turn, this cooperation drives the fundamental values imparted – deliberately and inadvertently – in the overall infrastructure, as a collage of converging or conflicting agendas, goals, demands. If collaborative practices in constructing or augmenting space infrastructure are both a means and an end in themselves (i.e. a raison d'être for embarking on a common space endeavour, but also way to achieve it, and thus by default a defining feature thereof), they are also both a source of and countermeasure against failure. Yet, today, ever more diverse actors with multifaceted interests, capabilities, and legacies engage in space activity together or in parallel (Al Rhodan 2012). Space infrastructure and its related policy developments are hence subject to a hitherto unseen "acceleration of technology proliferation and associated human networks" (Mineiro 2012: 34). In view of potentially conflicting interests and goals, how do the different stakeholders effectively govern and operate a set of global infrastructure(s)?

Close-up of the honeycomb panels of the Cluster I spacecraft. After the satellites were lost during the launch explosion, a fresh set was built and the mission relaunched in 2000 as Cluster II.
Image: © Sascha Mikloweit & VG Bild Kunst 2020.

The debris was retrieved immediately after the explosion from terrain surrounding the launch pad in French Guiana.
Image: © Sascha Mikloweit & VG Bild Kunst 2020.

What does this mean for the concept of failure, and our thresholds for the acceptance of risk? How do we weigh and interpret events and their scale, extent, and impact when our perspectives are determined by our levels of participation in the ownership of or access to infrastructure?

Space infrastructure as critical infrastructure

Three decades after the end of the Cold War, we find ourselves on the cusp of a paradigmatic change in the utilization of orbit. An unprecedented number of spacecraft are planned for launch as part of large satellite constellations by a new generation of spacefaring actors, along with a resultant proliferation of heterogeneous ground-based infrastructure (Lal et al. 2018). Space systems – particularly those affording position, navigation and timing, earth observation, and communication applications – are today considered critical infrastructure (Hesse and Hornung 2015).

In this new era of increased complexity, space infrastructure is exposed to new levels of risk, such as accidental collisions with other active satellites or orbiting debris (McCormick 2013), but also to potential deliberate disruption (Harrison et al. 2019). Ensuring the resilience of space infrastructure therefore necessitates a twofold approach; it is understood both as a means to ensure the reliability of space systems against the inadvertent hazards of a busy operating environment and as a means of dissuading potential adversaries from manipulating space assets (Peldszus 2019). As legacy systems that have been in operation for decades, both on the ground and in orbit, will need to be integrated with cutting-edge new systems, failure, and the preoccupation with it, will become more pertinent and even more impactful.

As a new reality of space gains momentum, what may the battered remnants of a twenty-year-old incident tell us today? Reviewed afresh, the fragments of the Ariane 5 launch failure are concrete markers of an otherwise intangible domain: Not only is orbit remote, but as a large, globally distributed assemblage of networks, the ground segment also remains distant from its human actors, who by default may only grasp and act upon either a comparably microscopic aspect of it in great detail, or its entirety but at a very coarse level of abstraction. The pieces of debris compel us to desist from the hubris of believing ourselves able to fully absorb and control a burgeoning class of infrastructure, in view of the inevitable and continuous entropy of degradation and breakdown.

Notes:

[1] Compare Weick (2011) for the notion of safety as “dynamic non-event.”

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Author:

Regina Peldszus is a senior policy officer with the German space agency, DLR Space Administration, where she works on the implementation of European capabilities in space situational awareness and handles studies on emerging issues at the intersection of space security, operations, and infrastructure. Until 2015, Regina was an Internal Research Fellow with the European Space Agency (ESA), European Space Operations Centre, Studies and Special Projects Division, addressing the resilience of mission control. Prior to this, she contributed to various future systems and safety projects, including at ESA's Astronaut Training Division, Special Skills and Exploration Unit.

Regina holds a PhD from Kingston University, London, on human systems integration and extreme environment analogues for exploration mission scenarios. Her interests focus on resilience, foresight, and governance of complex systems in dual use and high-reliability areas, including the space, polar, and nuclear domains.

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